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Long-term reduction potential of non-CO_2 greenhouse gases

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ABSTRACT

A methodology is presented here to assess the potential long-term contribution of non-CO_2 greenhouse gases in mitigation scenarios. The analysis shows the future development of the mitigation potential of non-CO_2 gases (as a function of changes in technology and implementation barriers) to represent a crucial parameter for the overall costs of mitigation scenarios. The recently developed marginal abatement cost curves for 2010 in the EMF-21 project are taken as the starting point. First-order estimates were made of the future maximum attainable reduction potentials and costs on the basis of available literature. The set of MAC curves developed was used in a multi-gas analysis for stabilising greenhouse gas concentrations at 550 ppm CO_2-equivalent. Including future development for the non-CO_2 mitigation options not only increases their mitigation potential but also lowers the overall costs compared to situations where no development is assumed (3–21% lower in 2050 and 4–26% lower in 2100 in our analysis). Along with the fluorinated gases, energy-related methane emissions make up the largest share in total non-CO_2 abatement potential as they represent a large emission source and have a large potential for reduction (towards 90% compared to baseline in 2100). Most methane and nitrous oxide emissions from landuse-related sources are less simple to abate, with an estimated abatement potential in 2100 of around 60% and 40%, respectively.

1. Introduction

In the past, the focus in climate mitigation studies was mainly on CO_2 from energy-related sources, with many studies using a single gas approach (see Hourcade and Shukla, 2001; Morita et al., 2001). In the last few years, however, non-CO_2 greenhouse gases (GHGs) have been rapidly gained attention. Studies that consider both CO_2 and non-CO_2 mitigation options generally report important advantages of so-called multi-gas mitigation strategies,[1] including: (1) major cost reductions compared to a CO_2-only strategy due to relatively cheap abatement options for several of the non-CO_2 GHG sources (Blok et al., 2001; Harmelink et al., 2005; US-EPA, 1999); (2) an increase in the flexibility in abatement options (Hayhoe et al., 1999; Hyman et al., 2002; Jensen and Thelle, 2001; Lucas et al., 2005; Manne and Richels, 2001; Reilly et al., 1999; Tol, 1999; Van Vuuren et al., 2003); and (3) the fact that non-CO_2 GHGs can contribute to a more rapid response in avoiding climate impacts by focusing on short-lived gases (Hansen et al., 2000). Moreover, it has been suggested that reduction in methane emissions is nearly twice as effective in radiative forcing (i.e. 2/3 larger) than its Global Warming Potential (GWP) value suggests. This is due to its indirect effects via tropospheric ozone and stratospheric water vapour (Shindell et al.,

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[1] This set of greenhouse gases includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the so-called fluorinated gases (hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6)).

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2004). Hansen et al. (2005) estimate total effective forcing from direct and indirect methane for 1750–2000 at about 50% of the CO_2 forcing in that period. Van Amstel (2005) computes a 0.5 °C temperature decrease in 2100 when a maximum reduction of methane is attained. The effectiveness of methane in short-term emission reductions compared to CO_2 result from both the limited lifetime of methane and the fact that the impacts of CO_2 emission reductions are partly offset in the short term by simultaneous reduction of energy-related aerosol emissions. In fact, policy-makers already acknowledged the contribution of other greenhouse gases through the GHG basket approach adopted in the Kyoto Protocol targets and the US Administration GHG intensity strategy, thereby allowing full substitution among six different types of GHGs (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6).

To analyze the potential contribution of non-CO_2 gases in overall reduction strategies, information is needed about the abatement potential for the different gases and sources and the cost at which the different abatement options can be implemented. In addition, information is needed on other barriers than costs, which might prevent mitigation measures being implemented and how both these barriers and the mitigation measures themselves change over time. This paper focuses on long-term non-CO_2 mitigation potential and its role in the construction of multi-gas mitigation scenarios.

The Energy Modelling Forum (EMF) has recently organised a model comparison study to further enhance the understanding of multi-gas abatement strategies (EMF-21). The study was aimed at providing a consistent set of abatement potentials and costs for the major non-CO_2 GHGs and their sources, and to provide an opportunity to compare results of multi-gas mitigation scenarios across a range of different models. Furthermore, the study aimed to explore how a multi-gas strategy differs from a CO_2-only approach. Overall, they concluded that – on average and across all models – a multi-gas strategy could lead to a cost reduction of 30–60% compared to focusing on CO_2 only (Van Vuuren et al., 2006; Weyant and De la Chesnaye, in press). The set of abatement potentials and costs provided within the EMF-21 project in the form of marginal abatement cost (MAC) curves concentrated on the year 2010. That implies that their work on MAC curves left the question open of how to deal with changes in reduction potential after 2010.[2] The focus on 2010 in the EMF-21 set also resulted in two other limitations. First, the data set focuses particularly on the emission sources for which currently available technologies could be identified and for which implementation was foreseeable; abatement potential was not identified for all emission sources. Second, the potential reduction measures have only been identified for a maximum cost level of 200 US$/tCeq (2000 US$). In the longer term, however, it is very reasonable to assume that new technologies could emerge and implementation barriers might become less important, certainly under the high carbon prices that are currently foreseen (above 200 US$/tCeq) for more ambitious climate policy scenarios (see Van Vuuren et al., in press-a). This would result in larger possible cuts in emissions of non-CO_2 gases. Several individual modelling groups within the EMF-21 project already included technology developments in their analysis (see for instance Van Vuuren et al., in press-b). These studies, however, only applied some general rules for technology development, focused on sources reported in the EMF-21 MAC curve set and did not include abatement potential above 200 US$/tCeq.

In this paper, we focus heavily on the importance of changes in the non-CO_2 reduction potential in the longer term. Given the fact that technology development has also been shown to be very important for long-term CO_2 emission reduction (Weyant, 2004), this is a very topical issue. Gallaher et al. (2005) have constructed MAC curves using the EMF-21 set, including technology development based on changes in input costs, productivity and reduction efficiency of abatement options. Although their MAC curves set incorporates better differentiation over the different world regions and explicitly include drivers for future development, the curves run towards 2030 only and require regional assumptions on price and productivity developments. Furthermore, they do not include landuse-related sources. These factors made them less applicable in our modelling framework, as we aim to cover the whole range of non-CO_2 emission sources and their extension towards 2100 in a relatively flexible and transparent framework. Therefore, to investigate the influence of technology development we first performed a literature survey on future non-CO_2 abatement potentials and costs to see whether information on potential technology development and reduction of implementation barriers (Section 2) was available. Since information on the development of non-CO_2 abatement potential (and existing implementation barriers) is still relatively scarce, some estimates need to be made that are based on interpretation of only a few studies. Nevertheless, we used this information to extend the non-CO_2 EMF-21 MAC curves to 2100 (Section 3). Through these ''best-guess'' estimates, we hoped to explore the importance of changes in non-CO_2 MAC curves. For this purpose, we combined this set with cost estimates for energy-related CO_2 emissions and assessed the role of the non-CO_2 GHGs and technology development, including the reduction of implementation barriers, in the construction of multi-gas mitigation scenarios (Section 4). We used the FAIR 2.1 model (den Elzen and Lucas, 2005) for the analyses, which includes a multi-gas abatement costs model with the newly developed set of non-CO_2 MAC curves as described here.[3] We also analyzed the sensitivity of our model results to the main assumptions on the non-CO_2 MAC curves extension, and explored uncertainties with respect to different multi-gas emission scenarios and emission pathways for stabilising the GHG concentration (Section 5). The paper ends with our results and general conclusions (Section 6).

[2] Although the EMF-21 data set includes both 2010 and 2020 numbers, relative reductions are the same for both years.

[3] The FAIR 2.0 model is a policy decision-support tool developed to explore and evaluate the environmental and abatement cost implications of various international climate regimes for the differentiation of future commitments for meeting long-term climate targets. The FAIR 2.1 model is an updated version of FAIR 2.0, differences being the marginal abatement cost curves and baseline emissions, as described briefly here.

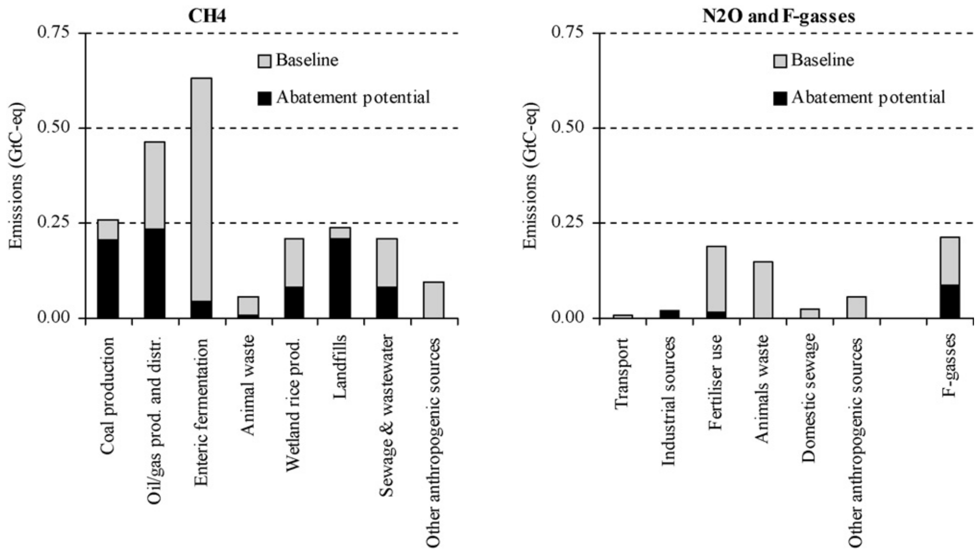

Fig. 1 – Emission baseline and reduction potential in 2010 according to the extended EMF-21 set of MAC curves by Van Vuuren et al. (in press-b).

2. Non-CO_2 abatement potential and costs

The most extensive set of abatement potentials and costs currently available for non-CO_2 GHGs is the EMF-21 data set. The EMF-21 set of MAC curves includes estimates of sector and option-specific technical mitigation potentials and costs for CH_4 and N_2O emissions from industrial and energy-related sources (Delhotal et al., in press), CH_4 and N_2O emissions from agricultural sources (DeAngelo et al., in press) and for industry-related fluorinated gases, i.e. HFCs, PFCs and SF_6 (Schaefer et al., in press). Marginal abatement costs are determined by the break-even carbon price, where the revenues from the options equal the costs of the options. In their analysis within the EMF-21 project, Van Vuuren et al. (in press-b) extended the above set with curves for CH_4 domestic sewage and N_2O transport from Graveland et al. (2002). They also included a technological development factor to extend abatement potential in time and, following Graus et al. (2004), included implementation barriers for the agriculture-related MAC curves, extending them towards 2050. While the work of Graus et al. provided a very useful extension of the EMF-21 MAC curves, their work covered only a limited set of emission sources.

Fig. 1 indicates the global 2010 emission levels and the maximum abatement potentials identified according to the "extended" EMF-21 set.[4] A large share of emissions can be abated for several sources. This is particularly the case for CH_4 emissions from landfills and coal production, and for N_2O emissions from adipic and nitric acid production, for which more than 80% can be abated world-wide. For most other sources, a more modest reduction potential is identified, such as for CH_4 emissions from wetland rice production and for the F-gases (approximately 40%). Furthermore, there are some sources that can (almost) not be abated according to this set: in particular, CH_4 emissions from sewage, enteric fermentation and animal waste, and N_2O emissions from animal waste, domestic sewage and fertiliser use. The figure also shows baseline emissions for the category other sources, which includes all anthropogenic sources assumed to be difficult to abate or too small compared to other sources to be of any significance.

Given these limitations in reduction potential for some very important sources of non-CO_2 gases, a crucial question is how the reduction potential can develop in the future, and at what (possibly higher) costs. In this section, we focus on the information available in the literature on technical and long-term (2050 and 2100) reduction potentials, and abatement costs of the non-CO_2 gases. The information on post-2010 abatement is obviously to some degree speculative. This is amplified by the fact that in comparison to CO_2, a very limited number of studies have looked into their long-term potentials. For some sources, available information is sufficient to provide a reasonable estimate. For other sources, however, information is much scarcer. For these sources too, available information is used to provide a first-order estimate of reduction potential. In contrast, we do not intend to provide a final answer to the question of reduction potential for each individual source. The results of this study may be used in subsequent studies to analyze reduction potentials in more detail (if found relevant).

In assessing future reduction potential, we have estimated reductions against current technologies—and focused on technological potential and rough costs levels. We assume that specific implementation barriers such as limited capital turnover rates and lack of information in developing countries would disappear over the assessment period (2010–2100) as an effect of increasing globalisation. The reduction potentials that were obtained from the literature assessment (presented in Table 1) are expressed as percentage reductions compared to baseline emission levels and the marginal costs are

[4] The baseline used is the one reported in the EMF-21 database, which was constructed mainly on the basis of National Communications in combination with expert judgement (US-EPA, 2006).

Table 1 – Estimated maximum reduction potential and the accompanying marginal price in 2050 and 2100

	2050		2100	
	Maximum possible reduction compared to baseline (%)	Marginal price of maximum reduction (US$/tCeq)	Maximum possible reduction compared to baseline (%)	Marginal price of maximum reduction (US$/tCeq)
CH_4				
Coal production[a]	90	500	90	500
Oil/gas production and distribution	75	300	90	500
Enteric fermentation	50	1000	60	1000
Animal waste	50	1000	60	1000
Wetland rice production	80	1000	90	1000
Landfills	90	500	90	500
Sewage and wastewater	80	500	90	500
Other anthropogenic sources	–	–	–	–
N_2O				
Transport	85	500	85	500
Adipic acid production	98	5	98	5
Nitric acid production	90	5	95	5
Fertiliser use	35	1000	40	1000
Animal waste	35	500	45	500
Domestic sewage	20	500	35	500
Other anthropogenic sources	–	–	–	–
F-gas				
HFC-23 as by-product	90	1	98	100
HFC use	90	500	95	500
PFC from aluminium production	80	200	90	500
PFC use	80	100	95	200
Sulphur hexafluoride	80	100	90	250

[a] This only accounts for underground coal production.

expressed in 1995 US$/tCeq. For studies providing credible information on reduction potential, but no available cost estimates, we used the upper boundaries for marginal costs (as for our costs model, namely 1000 US$/tCeq or 500 US$/tCeq where we could assume that lower costs estimates were relevant). Measures with costs clearly above a 1000 US$/tCeq, or those requiring a scientific breakthrough that is not foreseeable today, have not been considered; for example, we did not include possible systemic changes in food production. As such, our estimates should be considered as rough, lower boundary estimates of the maximum potential. Especially for the landuse-related sources, habits can play a very important role in whether certain abatement action is taken, as several options require a significant change in farming practices. However, as we focus on maximum attainable potentials and costs aiming to include them in an economic framework to determine the most cost-effective mix of options, we assume that price incentives and ongoing globalisation can overcome these barriers. In the second half of this paper we present a sensitivity analysis of our estimates on the overall annual costs of long-term multi-gas mitigation scenarios.

2.1. *Long-term emission reduction potential for methane*

2.1.1. *Methane emission reductions from coal mining*

Emission reductions for methane emissions from coal production are based on maximising methane recovery (up to, on average, 70% to 90%) from underground mining of hard coal only (no reduction options exist for other hard coal and brown coal). In the OECD and for economies in transition (EIT) about 6% of the methane emissions is currently recovered (Olivier et al., 2002). Potentially, about 90% reduction is technically possible, of which around 70% at relatively low costs (Hendriks and de Jager, 2001), e.g. about 30 US$/tCeq (US-EPA, 1999). In addition, the trend towards more surface mining is expected to continue; this reduces emissions per tonne of coal mined by a factor of 10 when compared to underground mining. However, it is uncertain to what extent resources close to the surface will continue to be available for surface mining for the next 100 years. Based on this, we assume that, overall, around 90% of the methane emissions from underground mining can be reduced in both 2050 and 2100 (notably hard coal) at a cost of about 500 US$/tCeq. No reduction potential is assumed for surface mining.

2.1.2. *Methane emission reductions from oil and gas production and distribution*

Methane emissions in oil and gas production and distribution originate mainly from fugitives, from equipment and pipeline leaks, and from venting of emissions during maintenance and repair. The key abatement options are: (a) the reduction of fugitives by reducing gas leakage from production by more frequent direct inspection and better maintenance; (b) in oil production more utilisation of co-produced ''associated'' gas as fuel (onsite or elsewhere) instead of venting; and (c) flaring of the remainder of the associated gas. In oil and gas production about 75% reduction of fugitives and gas venting may be achieved (on average) by better maintenance of pipe joints and valves and more re-use of the gas, respectively; a further reduction to 95% is possible by flaring the remainder (Hendriks and de Jager, 2001; US-EPA, 1999). The costs are highly dependent on the location: offshore flaring instead of venting may cost about 50–300 US$/tCeq, whereas onshore flaring instead of venting, would cost much less, e.g. 5–15 US$/tCeq (US-EPA, 1999). In conclusion, we estimate that globally 50% reduction can be achieved at 50 US$/tCeq (on average), and reductions up to 95% at costs up to 300 US$/tCeq. The key reduction options for natural gas distribution are replacement of old leaky pipelines and more frequent leak search and repair. For gas distribution systems, it is estimated that replacing the leakiest parts will reduce the emissions globally by about 75% on average at a cost of about 150–300 US$/tCeq (Hendriks and de Jager, 2001). More frequent leak detection and repair will reduce emissions inverse proportional to the frequency change, for example, by doubling the inspection frequency at an additional cost of about 300 US$/tCeq (Hendriks and de Jager, 2001) emissions will be halved, i.e. both options together may result in reductions up to about 90%. It should be noted that although practically all current natural gas distribution networks will be replaced by 2100, also new pipelines degrade over time; therefore more frequent inspection and maintenance of the network remains important. Riemer (1999) state that it would be technically possible to prevent over 70% of present-day emissions, considering only present-day technology, which could increase to 80% by the year 2010 and to even higher percentages as technology continue to develop. We assumed, for the total oil and gas production and distribution sector, a reduction potential of 75% in 2050 at 300 US$/tCeq and 90% reduction in 2100 at 500 US$/tCeq.

2.1.3. *Methane emission reductions from enteric fermentation*

Methane emissions from enteric fermentation are dependent on the animal type, age, function and production level, but also on the type, amount and digestibility of the animal feed. The key reduction options are changing animal diets and the use of more productive animal types. However, the most important implementation barrier of these reduction options is the lack of market incentives and the lack of knowledge of farmers. Riemer (1999) estimates a maximum reduction up to 75% by increasing fodder digestibility, although its applicability is limited to indoor-housed animals. Graus et al. (2004) performed an extensive study to identify and quantify different implementation barriers, thereby extending the EMF-21 curves for methane emission reductions from enteric fermentation towards 2050. They estimate a world-wide emission reduction potential of 6% in 2020 and 32% in 2050 (ranging between 30% for developing countries and 50% for North America). Most of these reductions could be attained at negative costs in the developing regions and Western Europe, while for North America costs are much higher (up to 1000 US$/tCeq). As suggested but not applied by Graus et al., we assume that farming practices all over the world develop towards the feeding operations applied in North America. Taking the North American practices as the maximum attainable, we can assume a maximum reduction potential of 50% by 2050. Taking into account the difficulties for developing countries to attain these standards the maximum attainable costs of less than 1000 US$/tCeq are used as a conservative estimate. Furthermore, assuming ongoing technology development and further increasing globalisation, while taking into account the difficulties addressed by Graus et al., we can assume a small increase in the abatement potential of current technologies towards 60% in 2100, again at costs less than 1000 US$/tCeq.

2.1.4. *Methane emission reductions from animal waste*

For methane emissions from animal waste the key reduction option is the capture and use of methane emissions through anaerobic digesters, which can be farm-scale digesters for the extensive agricultural zones and centralised digesters for the intensive agricultural zones (mainly OECD Europe). Graus et al. (2004) state that the implementation barriers are expected to be larger in developing countries than in the developed world. They estimate a world-wide emission reduction potential of around 15% in 2020 and 44% in 2050 (ranging between 30% for developing countries and 48% for the developed world), with costs mainly below 200 US$/tCeq for developing regions and below 1000 US$/tCeq for developed regions. Again, taking the North American practices as the maximum attainable, and taking into account the difficulties for developing countries to reach these standards, we assume a maximum reduction potential of 50% by 2050 at costs less than 1000 US$/tCeq. Assuming ongoing technological development and further increasing globalisation, while taking into account the difficulties addressed by Graus et al., we can assume a small increase in potential towards 60% in 2100, again at costs less than 1000 US$/tCeq.

2.1.5. *Methane emission reductions from rice production*

Methane emissions from rice production are mainly produced in the last step of the anaerobic breakdown of organic matter in wetland rice soils, where Asia accounts for 94% of total rice production. Most of the abatement options involve changes in the water management regime to reduce the time over which anaerobic conditions in flooded fields occur, or to alter the amendments to soils to inhibit methanogenesis (Graus et al., 2004). The barriers for mitigation include the lack of financial incentives and insurance facility, and uncertainty regarding the potential and the lack of knowledge on the impacts on yields and alternative techniques (Lantin et al., 2003). Riemer (1999) estimates the maximum reduction potential in 2020 at 40% at costs less than 250 US$/tCeq, which is largely dependent on the social support of the different measures to be taken. Graus et al. (2004) estimate the world-wide emission reduction potential to be limited to only 16% of total emissions in 2020, while for 2050, a maximum reduction potential is estimated at 80%, with maximum costs between 200 US$/tCeq (East Asia) and more than 1000 US$/tCeq (south Asia). We assume this maximum reduction potential of 80% by 2050, using 1000 US$/tCeq as a conservative estimate. For 2100 we assume 100% implementation (compared to 70% in 2050), resulting in an abatement potential of 90%, again at costs around 1000 US$/tCeq.

2.1.6. Methane emission reductions from landfills

Key reduction options for methane emissions from landfills are: (a) reduction of the amount of organic carbon deposited in landfills (by prevention or incineration of organic municipal waste) and (b) energetic use or flaring of landfill gas. Another low-emission waste-treatment technology to prevent dumping of organic waste is composting (e.g. aerobic treatment, anaerobic digestion). In most OECD countries about 20% of the landfill gas is currently recovered (Olivier et al., 2002), while in most other countries no recovery and almost no incineration exists. By 2050, a reduction potential of 70% can be achieved in OECD and EIT countries by methane recovery at costs around 10 US$/tCeq (when flared; costs are negative with energetic applications) and a maximum of 90% at costs up to 500 US$/tCeq (compared to a no recovery case) (Bates and Haworth, 2001). The 90% reduction potential could be achieved by either reducing the amount of organic waste deposited in landfills by modifying the waste management system (e.g. by incineration or composting with recovery) or by improved oxidation of (remaining) fugitive emissions in the landfill cap. In developing countries, an initial reduction of 25% could be achieved at costs of around 10 US$/tCeq when methane recovery is installed at major sites, while another 25% reduction would be possible if a similar fraction of the organic waste were not dumped into landfills, but treated by incineration or composting with CH_4 recovery, at a cost of 100–200 US$/tCeq (Bates and Haworth, 2001). As the EMF-21 project already reports abatement potential around 85–90% in 2010 for all world regions at marginal costs above 200 US$/tCeq, we assume that for both 2050 and 2100, a maximum of 90% reduction could be achieved globally at a cost less than 500 US$/tCeq. The relatively high costs of the high-end reductions are due to the fact that low flow rates, both during start-up of a landfill and in the "tail" of emissions after the closure, are much more expensive to capture. The same holds for a landfill that changes its composition and becomes a "low emitter" due to methane collection or lower fractions of organic waste being dumped.

2.1.7. Methane emission reductions from sewage and waste water

Key reduction options for sewage and wastewater methane emissions are: (a) more wastewater treatment plants in preference to using latrines and direct wastewater disposal, where all methane is dispersively generated and emitted into the air; (b) aerobic wastewater treatment, for example by aeration; and (c) recovery of methane from wastewater treatment plants. Most OECD countries have methane recovery systems in place in their wastewater treatment plants, but the recovery rates can still be increased. Most developing countries have limited wastewater treatment plants, mostly latrines and direct disposal of waste water through open sewers. Almost half of the global CH_4 emissions from waste water stem from latrines and another 30% originate in open sewers. Other sources are septic tanks and industrial and residential wastewater treatment (Doorn and Liles, 1999). Wastewater treatment plants have much lower methane emission factors than emissions from latrines and polluted surface water disposed of through open sewers due to recovery of most of the methane (typically around 80%) (Olivier and Berdowski, 2001). Thus, the maximum technically feasible emission reduction consists of replacing the use of latrines and open sewers with sewerage systems connected to wastewater treatment plants with high recovery in non-OECD regions, and further improving the recovery rate of wastewater treatment plants in OECD countries. However, installing closed sewage and wastewater treatment plant systems in developing countries are done to improve sanitary and health conditions rather than for greenhouse gas mitigation. Furthermore, large-scale wastewater treatment in rural areas may be unrealistic, where septic tanks, with significant methane emissions, may be more appropriate. However, also for septic tanks abatement technologies are in principle available.

As assessments on the long-term abatement potential and costs of this source of methane emissions are very scarce we assume a reduction of 50% to be possible in OECD and EIT countries at tentative costs less than 250 US$/tCeq and about 75% at a cost of 500 US$/tCeq. In developing countries a reduction of 80% is possible in 2050, and 90% in 2100, if wastewater treatment plants are installed that include enhanced methane recovery, both at costs of less than 500 US$/tCeq. It should be noted that although climate policy would not be the main driving force behind wastewater treatment plants installation, we have included their reduction potentials and costs in our estimates. Overall, we assume a global reduction potential in 2050 of 80% and 90% in 2100, both at a tentative cost of 500 US$/tCeq, assuming replacement of latrines and open sewers in developing countries by wastewater treatment plants.

2.1.8. Other methane emission sources

Other methane-emitting sources relate to land clearing for agricultural extension, and the use of traditional biomass for energy production and cooking. Furthermore, some methane emissions occur in industry, mainly iron and steel production and the chemical sector. As the first source is rather difficult to abate and the last two are relatively small compared to total methane emissions, no reduction potential has been assumed for these sources.

2.2. Long-term emission reduction potential for nitrous oxide

2.2.1. Nitrous oxide emission reductions from transport

Nitrous oxide emissions from road transport are mainly due to catalyst-equipped petrol cars, where the key reduction option is the application of low-N_2O catalytic converters. Present catalytic converters are only designed to reduce emissions of ozone precursors such as NMVOC, CO and NO_x, thereby increasing N_2O emissions with respect to uncontrolled emissions (for example, from 0.6 to 4.2 g/GJ) (Olivier et al., 2002). However, improved catalysts that can at least prevent the increase of N_2O emissions keep N_2O emissions at very low levels.

A substantial increase in N_2O emissions is expected as a result of further penetration of catalytic converters for use in all petrol-fuelled cars outside North America and Japan (where these are already in common practice). Since the emission factors differ according to car and engine type, a reduction of

50% should be feasible when limiting new catalytic converter-equipped cars to technology that has the lowest N_2O emission factor. However, at present, no catalytic converter manufacturer has optimised its design for both ozone precursors and N_2O. Development and implementation of new catalysts, optimised for N_2O, would limit the N_2O emissions trend to the increase in fuel use only. The emission reduction for petrol cars would be about 85% (Olivier and Berdowski, 2001; Olivier et al., 2002).

Assuming a global fraction of petrol in road fuel use of 65% (i.e. the same as in 1995; down from 80% in 1970), we estimate that in 2050 about 50% can be reduced globally at very limited extra costs and about 85% (i.e. reduction of the emissions to the level of petrol cars without catalytic converters) at costs less than 500 US$/tCeq. However, regionally, this fraction will differ; for example, in the USA today virtually no diesel is used by passenger cars. This results in a share of petrol in total road transport of 80%, whereas in OECD Europe and Japan this is about 50% (source: EDGAR 3.2). We assume similar numbers for the year 2100. Technological breakthroughs such as the fuel cell will also largely reduce emission levels, but these have not been taken into account here due to the large uncertainties on feasibility and costs.

2.2.2. *Nitrous oxide emission reductions from industrial sources*

Nitrous oxide emission reductions from industrial sources originate mostly from adipic and nitric acid production, where the key reduction option for adipic acid production is (thermal) N_2O destruction, and for nitric acid production catalytic reduction of N_2O. Industrial N_2O emissions can be largely abated: 98% for adipic acid (Reimer et al., 1999; WBCSD/WRI, 2005) and 80–90% (WBCSD/WRI, 2005) and even up to 90–95% (Van den Brink et al., 2002) for nitric acid. The additional costs of these options are quite low; 1 US$/tCeq for adipic acid and 1–5 US$/tCeq for nitric acid (COHERENCE, 1999; De Beer et al., 2001). Therefore we assume 90% reduction potential in 2050 and 95% in 2100 for nitric acid and 98% for both years for adipic acid production. All reductions can be achieved at costs less than 5 US$/tCeq. This, in fact, implies that the 2050 and 2100 abatement potentials and costs for both sources are almost equal to the 2010 potential of the EMF-21 database, which are already 89% and 96%, respectively (compared to uncontrolled emissions).

2.2.3. *Nitrous oxide emission reductions from fertiliser use*

There are several options to reduce N_2O emissions from fertiliser use. These include: (a) improving fertiliser use efficiency; (b) restricting use of fertiliser in time; (c) using fertiliser-free zones; and (d) replacing current fertiliser with new types with lower emissions (Graus et al., 2004; Hendriks et al., 1998; Mosier et al., 1998). An important factor determining the total reduction potential is the baseline application of some of these options and the implementation barriers. Kroeze (1995) estimates a maximum emission reduction potential of 60%. Graus et al. (2004) estimate the reduction potential to be about 32% in 2050 at costs ranging between gains and more than 1000 US$/tCeq (dependent on differences in regional crop prices, fertiliser prices and labour costs). We assume 35% (the potential in the OECD regions) as maximum abatement potential in 2050, at 1000 US$/tCeq. Assuming ongoing technological development and further increasing globalisation, we assume a small increase in potential, towards 40% in 2100, again at 1000 US$/tCeq. These estimates are also used for indirect emissions from fertiliser use (as defined by the IPCC), as they are linked to their direct emissions.

2.2.4. *Nitrous oxide emission reductions from animal waste*

There are several options to reduce N_2O emissions from animal waste. Measures include: (a) dietary changes to reduce nitrogen excretion from animals (e.g. improving the protein quality of the diet and reducing nitrogen intake); (b) reducing the number of animals by increasing their productivity; and (c) optimising manure management and limiting grazing (Brink, 2003; Clemens and Ahlgrimm, 2001). While many studies mention these measures as a way to reduce N_2O emissions, few actually quantify potential, most probably reflecting the uncertainty in implementing several of these measures. Brink (2003), based on Hendriks et al. (1998) and Bates (1998), estimated the potential for 2010 to be about 35–45% for Western Europe. This potential is achieved mostly by measures with medium to relatively high costs. Given the reluctance of other studies to quantify potentials for this source, we assume that a maximum of 35% can be attained for 2050 and 45% for 2100. In all cases these reductions are assumed to be fully attainable at 500 US$/tCeq. These estimates are also used for indirect emissions from animal waste (as defined by the IPCC), as they are obviously linked to their direct emissions.

2.2.5. *Nitrous oxide emission reductions from domestic sewage*

Reduction of N_2O emissions from waste water is possible by controlled nitrogen removal at wastewater treatment plants (Gerbens and Zeeman, 2000). Optimising the N-removal process to achieve a more complete reduction to N_2 emissions instead of N_2O emissions can reduce emissions by 50% (Hendriks et al., 1998). In addition, emissions can also be reduced by N-enriched wastewater in crop production as an alternative to fertilisers (thus reducing fertiliser emissions). The total reduction potential is strongly determined by the possibility of implementing technical measures, i.e. the existence of wastewater treatment plants. Graveland et al. (2002) assume: (1) 35% of the wastewater being treated in OECD countries and only 0–8% in non-OECD countries in 2010; (2) emission reduction ranging between 10% and 20%; and (3) an implementation degree of 10–30%. This results in a total emission reduction of 1% in OECD countries and 0–0.3% in non-OECD countries. Assuming a large increase in wastewater treatment plants, technology and implementation degree all over the world, we assume an increase in overall reduction potential towards 20% in 2050 and 35% in 2100. Although according to Hendriks et al. (1998), the measures can be applied against low or zero costs, we assume medium high costs of 500 US$/tCeq for both years, since large extensions in wastewater treatment plants and technology have to be obtained.

2.2.6. *Indirect nitrous oxide emission reductions from non-agricultural sources*

Apart from indirect N_2O formation from agricultural sources, NO_x (and some NH_3) emissions from combustion sources and industrial processes give rise to these emissions. Using the IPCC methodologies, these indirect N_2O emissions are estimated at about 0.6 Tg N_2O for 2000 (Olivier et al., 2005), which is approximately 5% of global total other anthropogenic N_2O emissions that are accounted for in this paper. The reduction potential for N_2O is the same as for reducing NO_x emissions as air pollutant. NO_x reduction options in road transport are similar to reductions in the application of catalytic converters and in power plants and large industrial combustion plants where such deNOx technologies as Selective Catalytic Reduction (SCR) or Non-SCR can be applied (see Sections 2.2.1 and 2.2.2). However, although reducing emissions of these air pollutants will result in a proportional reduction of related indirect N_2O emissions, we do not include them in our analysis, because their abatement would occur outside the framework of climate policy.

2.2.7. Other emissions of nitrous oxide

Other N_2O emitting sources relate to land clearing for agricultural extension, and traditional biomass use for energy production and cooking. No mitigation potential has been assumed for these sources, considering that most of them are rather difficult to abate and relatively small compared to the other sources.

2.3. Long-term abatement potential for fluorinated gases

2.3.1. Hydrofluorocarbon emission reductions

Hydrofluorocarbon (HFC) emissions can be distinguished into HFC-23 by-product emissions, emissions from the use of both HFC-134a and other HFCs. Globally, each of these three had a share of about one-third in 2000, but the third source is increasing very fast while HFC-23 by-product emissions remain approximately constant (Olivier et al., 2005). A key reduction option is the thermal destruction of HFC-23 generated as a by-product of HCFC-22 production, which is technically feasible up to 98% (Irving and Branscombe, 2002; Klein Goldewijk et al., 2005): 90% at costs of around 1 US$/tCeq (Harnisch and Gluckman, 2001) and up to 98% at costs less than 100 US$/tCeq.

Key reductions for using HFCs are: (a) better sealed applications, notably in commercial refrigeration and in mobile air-conditioning, which could reduce current annual leakage rates of about 20% and 10%, respectively, to about 0.5% (Schwarz and Leisewitz, 1999); (b) HFC recovery when products are disposed of, which may reduce these emissions by about 25%; and (c) substitution of HFCs by substances with zero GWP, notably in commercial refrigeration and for foam blowing (e.g. hydrocarbons) (Heijnes et al., 1999). Overall reduction of emissions from HFC use may be about 95%, if HFCs are only applied in closed applications and with maximum recovery during maintenance, and when old equipment is disposed of (Harnisch and Gluckman, 2001). In practice, however, about 90% may be achieved due to actual non-optimised handling of the appliances. On the basis of Heijnes et al. (1999) and cost estimates from Harnisch and Hendriks (2000) and Harnisch and Gluckman (2001), we conclude that for stationary refrigeration, 80–90% reduction could be achieved with HFC use in 2050 at costs less than 250 US$/tCeq, and 95% reduction in 2100 at costs up to 500 US$/tCeq. For foam blowing 80–90% reduction in 2050 may be achieved and 100% in 2100 at costs less than 50 US$/tCeq for both years. Furthermore, emissions from mobile air-conditioning can already be reduced by 100% in 2050 at costs less than 200 US$/tCeq. Overall, we assume 90% reduction in 2050, and 95% in 2100, both at costs less than 500 US$/tCeq.

2.3.2. Perfluorocarbon emission reductions

Perfluorocarbon (PFC) emissions (CF_4 and C_2F_6) are generated as a by-product of primary aluminium production. Other emissions result from PFC use in semiconductor manufacturing and from PFC use as solvent (in some world regions). Key reduction options include: (a) the use of modern process technology for aluminium production (Point-Feed Prebake, PFPB); (b) optimising use and emission capture and (thermal) destruction in semiconductor manufacture; and (c) replacing the use of PFCs as solvents.

At present, one-third of the total aluminium is produced using old Vertical and Horizontal Søderberg (VSS, HSS) technologies, which, however, account for three-quarters of total PFC emissions from this source, mostly from VSS. The global emission reduction from aluminium production may be roughly around 80% (Heijnes et al., 1999) if we assume the same process mix and emission factors as in 2000. In fact, the global aluminium industry has committed itself to reducing the global average PFC emissions in 2010 by 80% compared to 1990 (Marks et al., 2005). Costs for VSS conversions are about 200 US$/tCeq. For conversions or retrofitting of Side Work and Center Work Prebake (SWPB, CWPB) processes, the costs are negative (Harnisch and Hendriks, 2000). We assume that all old Søderberg plants will have been discontinued by 2050 and the additional costs refer to either switching from CWPB and SWPB to PFPB or to further optimisation of the process control (e.g. computer-controlled anode effect detection) that may also reduce emissions by half. Overall, we assume a global reduction potential in 2050 of 80% by switching all plants to PFPB at costs of 200 US$/tCeq and 90% in 2100 with full optimised process control at costs less than 500 US$/tCeq.

The semiconductor industry is aiming at substantially reducing its global PFC emissions by 90% in 2010 compared to uncontrolled emissions (WSC, 2005). By capturing all F-gas emissions and using thermal destruction, virtually all emissions could be eliminated (Heijnes et al., 1999). Since PFCs are not used as solvents in many regions, alternative compounds with a lower GWP value or alternative processes are actually used and thus technically feasible, so a complete phase-out in all countries should be possible. For semiconductor manufacturing, 50–80% reduction can be achieved at costs less than 100 US$/tCeq and 100% at costs up to 200 US$/tCeq (Harnisch and Hendriks, 2000). We assume that the same holds for solvents. Overall we assume 80% reduction from PFC use in 2050 at a cost of 100 US$/tCeq, taking into account a number of other lesser uses of which the reduction potential is assumed to be similar to that of applications discussed here, and 95% in 2100 at costs less than 200 US$/tCeq (Harnisch and Hendriks, 2000).

2.3.3. Sulphur hexafluoride emission reductions

Key reduction options for sulphur hexafluoride (SF_6) production and use are: (a) improved recovery; (b) minimisation of leakage; and (c) optimisation of use. SF_6 emissions from manufacturing and decommissioning make up for most of the reduction potential; emissions from the ''use'' phase account for only less than 20%. Emissions from Gas Insulated Switchgear (GIS) manufacture and use may be reduced by 80% by 2020 at costs less than 100 US$/tCeq and possibly up to 90% in 2100 at costs up to 250 US$/tCeq (Heijnes et al., 1999; Wartmann and Harnisch, 2005). Emissions from magnesium production and magnesium die casting may be reduced by about 90% at costs less than 200 US$/tCeq, whereas emissions from semiconductor manufacture and miscellaneous applications could be reduced by 90% in 2050 at costs less than 100 US$/tCeq and almost 100% at costs less than 400 US$/tCeq (Harnisch and Hendriks, 2000; Heijnes et al., 1999). Military emissions may be reduced by 95% or more by using SF_6 in closed instead of open applications (e.g. AWACs) (Plöger, 2005, personal communication). Overall, we assume that 80% reduction can be achieved for SF_6 use in 2050 at costs less than 100 US$/tCeq, and 90% in 2100 at costs less than 250 US$/tCeq, considering that most of the reduction comprises reducing emissions from GIS manufacture and use.

3. Modelling non-CO_2 greenhouse gases

3.1. *Construction of the time-dependent non-CO_2 MAC curves*

Given the quality and current status of the EMF-21 data set on reduction options, we aimed here to develop a set of long-term MAC curves that dynamically link the short-term potentials to the long-term potentials discussed in Section 2. This implies taking future technological developments and cost reductions into consideration. We assume that technological developments lead to improvements in reduction efficiency and a decrease of costs. Several steps have been taken to construct the MAC curves in time (see also Fig. 2). First, we expressed the EMF-21 MAC curves (over the cost range of 0–200 US$/tCeq) in relative reductions against frozen efficiency (i.e. current, 2000 technology). As abatement technologies become slowly cheaper over time, we assume that the whole curve moves outward (point A in the left part of Fig. 2). The literature survey, as presented in Section 2, is used to identify time-dependent maximum reduction potentials and costs, which change over time as a function of changing implementation barriers and technology development. For 2010, this maximum is equal to the potential per source included in the EMF-21 database, while the values summarised in Table 1 are used for 2050 and 2100. These time-dependent maximum reduction potentials and costs are used to extend the MAC curves, including changing implementation barriers and technology developments above 200 US$/tCeq, assuming a linear increase from reduction potential at 200 US$/tCeq towards the tabulated maximum reduction potentials and costs (see point B on the left-hand side of Fig. 2). Finally, to avoid double counting in abatement options, improvements in emission factors under the baseline scenario (representing abatement measures already implemented for other reasons than climate policy) are subtracted from the low-cost side of the MAC curve (see point C on the right-hand side of Fig. 2). The resulting relative MAC curves can then be projected on different baseline emission scenarios to determine the absolute MAC curves. By doing so we assume that there are no real differences between technologies used in different baseline scenario. Further to this, we assume that there are only volume differences in total sectoral emissions and, with this, abatement potential differences due to differences in population and economy size and efficiency levels.

3.2. *The three sets of non-CO_2 MAC curves*

Three sets of non-CO_2 MAC curves are constructed to assess the impacts of the different steps described above on the overall reduction potential. In Fig. 3, the maximum abatement potentials in 2100 for these three sets are presented per source. The first bar presents the maximum reduction potential

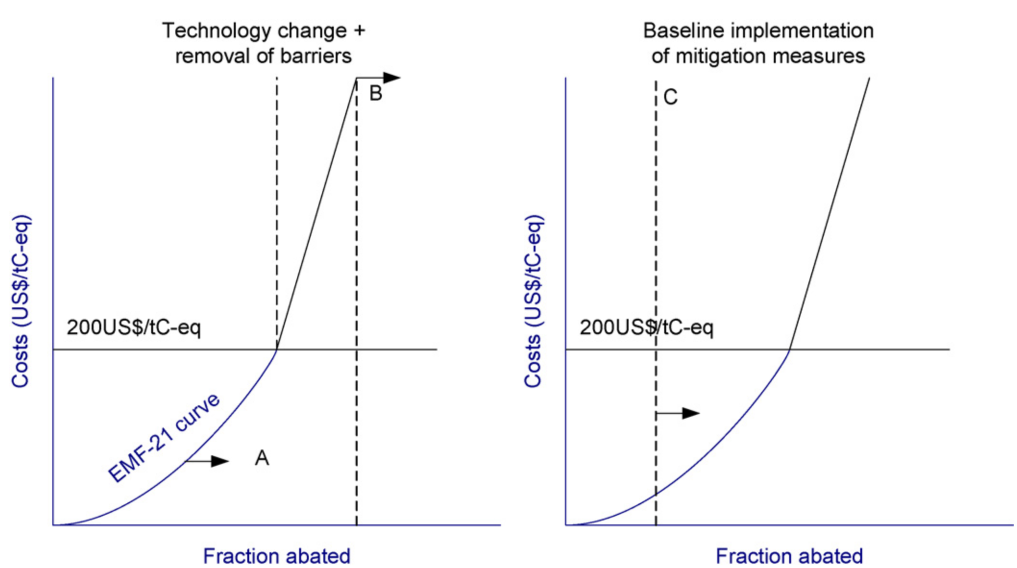

Fig. 2 – Construction of non-CO_2 MAC curves in time from the EMF-21 data set, including technological change (A), extension of curves above 200 US$/tCeq (B) and action already taken in the baseline (C). For detailed description see text.

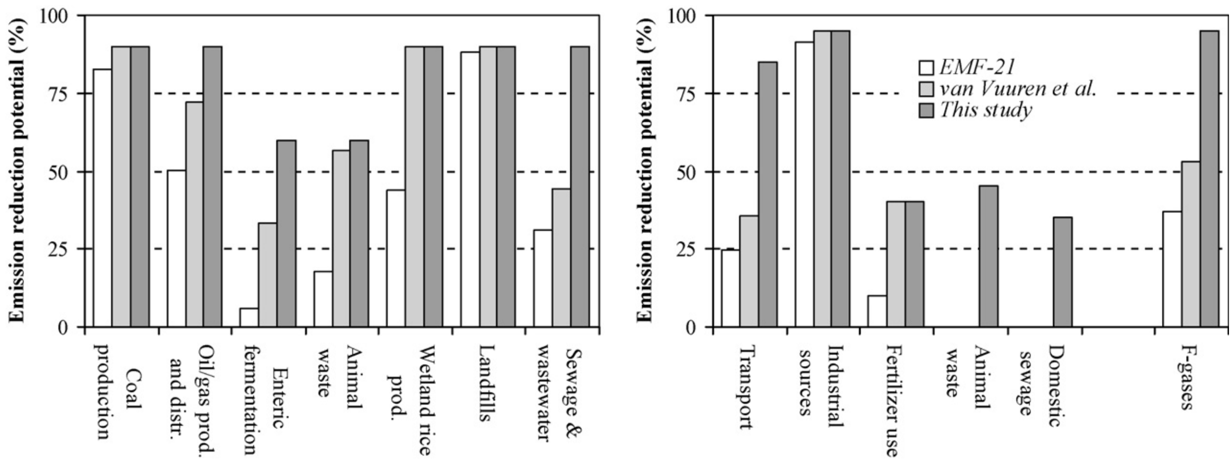

Fig. 3 – Maximum relative abatement potentials compared to baseline level, for methane emissions (left) and nitrous oxide and the fluorinated gases (right) for the three non-CO_2 MAC curve sets compared to 2100 emission levels. EMF-21 refers to the potentials as published by Delhotal et al. (in press), DeAngelo et al. (in press) and Schaefer et al. (in press); van Vuuren et al. refers to the data used by Van Vuuren et al. (in press-b).

(reduction at 200 US$/tCeq) of the original EMF-21 data set, assuming no technological development whatsoever (this set is further referred to as *EMF-21*). In the second bar, this set was extended with curves for CH_4 domestic sewage and N_2O transport from Graveland et al. (2002) and a technological development factor to extend abatement potential in time, as in Van Vuuren et al. (in press-b) (this set is further referred to as *van Vuuren et al.*). *Vuuren et al.* was included for reference purposes only. For the third bar, the *van Vuuren et al.* set was further extended using the maximum reduction potentials and accompanying marginal costs, as presented in Table 1 (further referred to as *this study*). For CH_4 emissions from enteric fermentation, animal waste and wetland rice production and for N_2O emissions from fertiliser use we used the MAC curves from Graus et al. (2004) from 2010 towards 2050 for the whole 0–1000 US$/tCeq range, which are based on the EMF-21 set. They thereby already include technology development for this period. The maximum attainable potentials of Section 2 are used here as an absolute maximum. After 2050 we used the same technological development factor as applied to the other sources. Furthermore, MAC curves for N_2O animal waste and N_2O domestic sewage, which are not present in the EMF-21 data set, were added to the set based on Brink (2003) for N_2O animal waste and Graveland et al. (2002) for N_2O domestic sewage. Fig. 4 presents aggregated MAC curves, including all non-CO_2 GHGs, as developed in *this study* for different years. The figure shows the different steps in constructing the curves, clearly distinguishing between the exogenous technology development factor (which can increases the abatement potential in time below 200 US$/tCeq) and the assumed maximum reduction potentials and accompanying marginal costs (which can increases the abatement potential in time above 200 US$/tCeq). The maximum 2010 reduction potential (at 1000 US$/tCeq) is approximately 35% of the total non-CO_2 baseline emissions (original EMF-21 potential). By including technology development and the breakdown of implementation barriers, this potential is more than doubled in 2100 to approximately 75% of the total non-CO_2 baseline emissions.

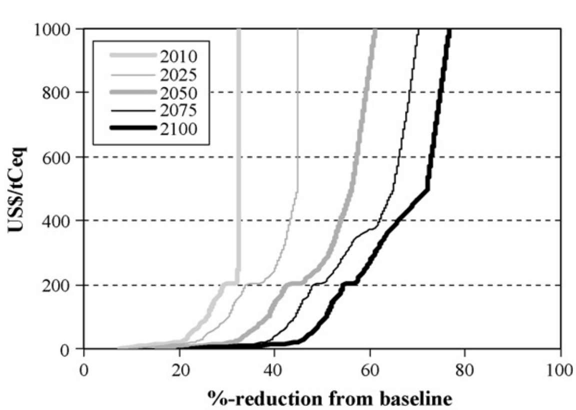

Fig. 4 – Aggregated MAC curves in time for the non-CO_2 GHGs including full technology development and the breakdown of implementation barriers.

3.3. Substitution among gases

To allow for substitution among the different GHGs we make use of Global Warming Potentials (GWPs) with a 100-year time-horizon. Although 100-year GWPs are suggested by the IPCC, several researchers point out that the choice of time-horizon is arbitrary and the results can change significantly by switching to GWPs with a 20-year or 500-year time-horizon (Reilly et al., 1999). Furthermore, the concept can only partly take into account the impacts of the different lifetimes of the various gases, or the economic efficiency of reducing them. Different metrics for comparison have been proposed. Fuglestvedt et al. (2003) provide a comprehensive overview of the different methods proposed, and the advantages and disadvantages of using them, while Van Vuuren et al. (2006) provide a comparison of stabilisation scenarios studies that use GWPs or substitute on inter-temporal optimisation. Despite this continuous scientific debate, the concept is regarded as convenient and to date no alternative measure has attained a comparable status. Within the proposed methodology the focus is on abatement action for individual non-CO_2 GHG emission sources, although there can be several interactions between the different sources. Such interactions can be, for example, that N_2O abatement from wastewater could result in more CH_4 emissions. However, these interactions were not included in the EMF-21 set. Furthermore they cover only a very small share of the non-CO_2 abatement potential, and are therefore not taken into account. Nevertheless, indirect linkages via the activity levels in the energy system (e.g. climate change reduces coal use and therefore methane emissions from coal use) are included by the coupling to the TIMER energy model (see Section 4).

4. Stabilisation scenarios under different assumptions for the development of reduction potential

In this section we will analyze the role of the non-CO_2 GHGs in long-term stabilisation scenarios. We will also analyze the role of technology development and reductions of implementation barriers on the marginal price of reduction and the overall global costs, as well as the contribution of the different emission sources to total abatement effort. For this purpose, we use the MAC curve sets as described in the previous section and combine them with MAC curves for energy and industry-related CO_2 emissions, and curves describing the potential and costs of carbon plantations for CO_2 sequestration. See Van Vuuren et al. (in press-b) for the applied methodology.

The MAC curves of *energy- and industry-related CO_2 emissions* were determined with the energy model TIMER 2.0 (Van Vuuren et al., in press-a). This energy model calculates regional energy consumption, energy-efficiency improvements, fuel substitution, the supply and trade of fossil fuels and the application of renewable energy technologies (including the use of biofuels), as well carbon capture and storage. The TIMER MAC curves were established by imposing a carbon tax and recording the induced reduction of CO_2 emissions, taking into account technological developments, learning effects and system inertia. There are several responses to a carbon tax in TIMER. In energy supply, options with high carbon emissions (such as coal and oil) become relatively more expensive than options with low or zero emissions (such as natural gas, carbon capture and storage and renewables). The latter options therefore gain in market shares, while investments in efficiency become more attractive in the context of energy demand.

The MAC curves for *carbon plantations* were derived using the IMAGE 2.3 model. In this model, the potential carbon uptake of plantation tree species is estimated for land that has been abandoned by agriculture (using a 0.5×0.5 grid), and then compared to carbon uptake by natural vegetation. Only those grid cells are considered where the sequestration by plantations exceeds sequestration by natural vegetation. On the basis of grid cells that are potentially attractive for carbon plantations, carbon sequestration supply curves are established and converted into MAC curves by adding land and establishment costs (see Graveland et al., 2002; Strengers et al., submitted for publication).

A baseline emission scenario and a multi-gas emission pathway (leading to stabilisation of the GHG concentration in the atmosphere) have been chosen alongside the constructed MAC curves. The difference between the total baseline emissions (CO_2 plus non-CO_2 emissions) and the emission pathway is the global emission reduction objective, i.e. total CO_2-equivalent emissions which need to be abated yearly to reach the global CO_2-equivalent concentration objective associated with the stabilisation profile. To determine abatement action and costs, we make use of the multi-gas cost module of the FAIR 2.1 model (den Elzen and Lucas, 2005). This model uses aggregated permit demand and supply curves derived from the MAC curves for the different regions, gases and sources to determine the market equilibrium permit price (henceforth known simply as ''permit price'') on the international trading market, the shares of the different abatement options in total abatement and the accompanying global abatement costs, by applying a least-cost approach.[5]

4.1. *The global emission reduction objective*

The baseline scenario used in this study is the updated IMAGE B2 scenario, which represents an implementation of the corresponding IPCC SRES scenario (Nakicenovic et al., 2000) (hereafter referred to simply as the B2 scenario). This scenario is seen as a continuation of present-day trends—with medium assumptions for population growth, economic growth and more general trends such as globalisation and technology development. In terms of quantification, the scenario roughly follows the reference scenario of the World Energy Outlook 2004 (IEA, 2004)—and after 2030, economic assumptions converge to the B2 trajectory (Nakicenovic et al., 2000). The long-term UN medium population projection (UN, 2004) is used for population trends. Trends in agricultural production (production levels and yields) are based on the Adaptive Mosaic scenario of the Millennium Ecosystem Assessment scenarios (MEA, 2005), which were elaborated for these parameters by the IMPACT model (Rosegrant et al., 2002). All other assumptions are based on the earlier implementation of the B2 scenarios (IMAGE-team, 2001).

The above described scenario, as presented in Fig. 5, distinguishes between CO_2 and non-CO_2 emissions. The CO_2 emissions originate mainly from the combustion of fossil fuels. The energy- and industry-related carbon dioxide emissions increase sharply and continue to be the major source of GHG emissions. For the non-CO_2 GHGs, total CH_4 and N_2O emissions increase up to 2050, after which they remain more-or-less constant. Over the century, their contribution in total greenhouse gases drops since their growth rate is slower than that of CO_2. This is caused by the fact that most landuse-related drivers of these emissions have strong saturation tendencies. For CH_4, only emissions from animal husbandry, gas production and landfills are likely to increase rapidly in the absence of climate policies. For coal and oil production, changes in production levels and capture of methane for economic or safety reasons already reduces some CH_4

[5] See den Elzen et al. (2005) for a discussion on the strengths and limitations of this cost methodology.

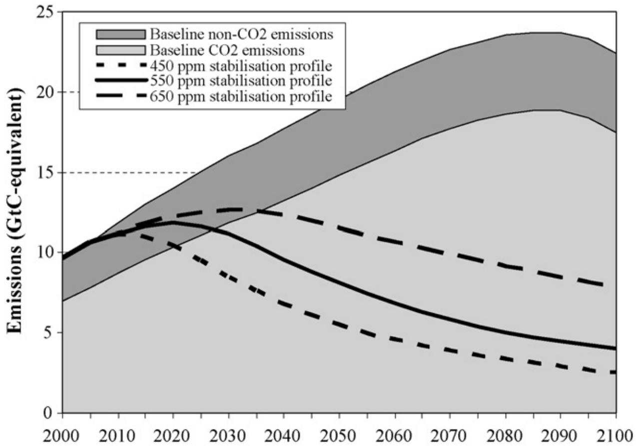

Fig. 5 – Baseline emissions and the 450, 550 and 650 ppm emission stabilisation pathways.

emissions. Wetland rice emissions remain more-or-less constant, as not much expansion is assumed to occur and yields improve. For N_2O, only increases in fertiliser use and animal waste are expected to lead to increasing N_2O emissions. Fluorinated gases form by far the fastest growing category. The reasons for their increase include replacement of ozone-depleting substances by HFCs and rapid growth rates of major emitting industries (semi-conductor and electricity production). It should be noted that despite the rapid increases, F-gas emissions in absolute terms remain relatively small compared to the other sources.

The baseline emissions are compared to constrained multi-gas emission pathways, corresponding to a stabilisation of total GHG concentration at a level of 550 ppm CO_2-equivalent, as developed by den Elzen et al. (in press) (see the solid line in Fig. 5). These emission pathways take into account constraints on the rate of the emission reductions because technical and political inertia prevents the global GHG emission levels from changing dramatically from year to year or from decade to decade. Fast reduction rates would require the early retirement of existing fossil-fuel-based capital stock, which may be associated with high costs.

4.2. *Results for the 550 ppm stabilisation profile*

In the analysis of the mitigation cases, we first analyzed the impacts of a CO_2 only versus a multi-gas approach on the overall costs of reaching the concentration stabilisation target. Furthermore, we used the different sets of non-CO_2 MAC curves, as developed in Section 3.2, to assess the impacts of technological development of the non-CO_2 reduction potential over time on the overall costs. The marginal price of the reductions and total abatement costs as percentage of GDP for the four sets of MAC curves are shown in Fig. 6. Obviously, both the marginal price and the overall costs are much higher when taking only CO_2 emission reductions into account, as this lowers the total abatement potential, i.e. the supply of emission reductions. For the three multi-gas cases we see an increase in the marginal price towards 2060 for *this study* and 2070 for *EMF-21*. Differences in the peak can be explained by the differences in abatement potential increase, which are the largest for *this study*. Technology development and the breakdown of implementation barriers not only lower the marginal costs but also increase the reduction potential. After 2060 and 2070 the respective increases in reduction potential (both CO_2 and non-CO_2) are larger than the increase in the reduction objective, resulting in a decrease in the marginal price. The overall costs for the three multi-gas cases increase in all scenarios towards 2060, arriving at abatement costs between 1.1% and 1.3% of world-wide GDP; after this the costs decrease towards 0.4–0.5% in 2100. Including the full set of future non-CO_2 abatement developments (*this study*) results in approximately 15% lower costs in 2050 and 17% lower costs in 2100 compared to the case where no development is assumed (*EMF-21*). The costs for the CO_2-only cases are much higher, amounting to approximately 1.7% of world GDP in 2060 and still rising afterwards. The decrease in the overall costs after 2060 in the three multi-gas cases is partly the result of dropping marginal prices, while the large increase in the global GDP also has considerable influence. In short, switching from a CO_2-only to a multi-gas approach can decrease the overall costs of climate policy by approximately 85% in 2010 and up to 25–35% in 2050 (depending on the level of future non-CO_2 abatement development).

The shares of the non-CO_2 emission reductions pertaining to the three multi-gas cases in total reduction are presented in

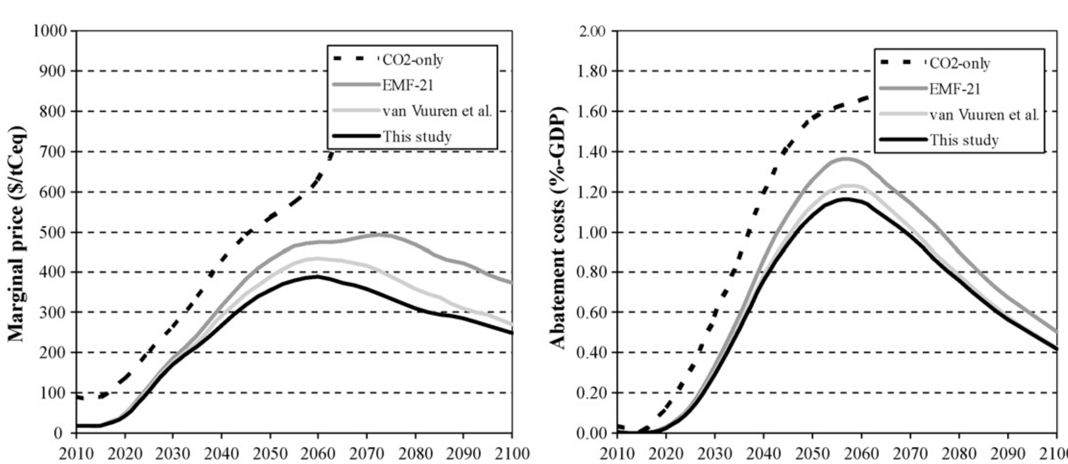

Fig. 6 – Marginal prices (left) and relative abatement costs as a percentage of GDP (right) for the four cases considered.

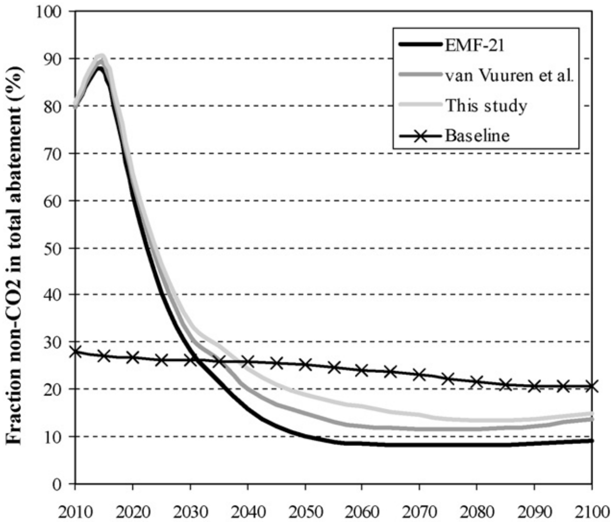

Fig. 7 – Non-CO_2 reduction share in total emission reductions (right) for the three multi-gas cases. The baseline represents the share of non-CO_2 GHGs in total baseline emissions.

Fig. 7. The share of the non-CO_2 emission reductions in the short term (up to 2035–2040) is larger than their baseline emission shares (80% reduction share and 30% baseline share in 2010). This can be explained by the fact that most non-CO_2 emission reduction options are relatively cheaper than reductions taken in the energy system and are therefore taken first. The share of non-CO_2 reductions even slightly increase towards 2015, as the potential of non-CO_2 emission reductions increases more than the CO_2 reduction potential from the energy system. Towards 2100, the share of the non-CO_2 emission reductions drops below the baseline share of these reductions (10–15% reduction share and 20% baseline share). In part, the overall shift simply reflects the fact that non-CO_2 emissions represent approximately one-fourth of total GHG emissions, and that reduction becomes more proportional to the emission shares. In addition, however, it also reflects the underlying reduction potential estimates. There is obviously a large difference in the future non-CO_2 abatement shares for the three multi-gas cases. When no technological developments are assumed, the potential of non-CO_2 reductions only increases when the baseline increases (*EMF-21*). For the other two cases, technological developments are assumed to result in much larger future potentials and therefore also larger shares.

Table 2 presents absolute non-CO_2 emission reductions and their shares in total non-CO_2 reductions using the MAC curve set from this *study*. Taken over the whole century, the largest share of abatement comes from CH_4. The share of the fluorinated gases is also considerable, while the share of N_2O emission reductions remains rather small. The table shows a declining increase in time of the overall reductions, where the largest increase comes from CH_4 landfills and enteric fermentation, N_2O fertiliser and HFC emissions. The increase in emission reductions shows both a baseline effect (increase in emissions due to increasing purchasing power and population) and a development effect (a breakdown of implementation barriers and an increase in abatement technology and thereby abatement potential). The dynamics in coal, oil and gas production can be explained from the baseline. Until approximately 2050 most of the increase in coal mining is surface mining, with much less CH_4 emitted, while after 2050 underground coal mining increases, raising total emissions and thereby also the abatement potential. For oil and gas, some mitigation already takes place in the baseline by flaring the CH_4 emissions. This is already done in most industrialised countries and is assumed to increase in most developing countries, resulting in a decrease of emissions, and thereby reduction potential, in the second half of the century.

5. Sensitivity analysis

Here, we analyze to what extent the non-CO_2 share and the global abatement costs depend on key assumptions related to the mitigation and policy options for the non-CO_2 emission sources. Besides assumptions on technology developments, and maximum achievable reduction potentials and costs, this sensitivity analysis also includes the choice of the baseline scenario and the concentration stabilisation target. The B2 baseline and the 550 ppm CO_2-equivalent concentration stabilisation target are used as the reference case, as already seen in the previous section. The key assumptions and variance levels of these can be found in Table 3. A high emission growth scenario (updated IMAGE A1b scenario) and a low emission growth scenario (updated IMAGE B1 scenario) are used to assess the influence of the baseline scenario.[6] The multi-gas emission pathways aiming at the low 450 ppm and the high 650 ppm CO_2-equivalent concentration stabilisation targets, as developed by den Elzen et al. (in press) are used to assess the influence of the concentration stabilisation targets (see dotted lines in Fig. 5). To assess the sensitivity of the assumptions on maximum abatement potentials and accompanying costs, the maximum potentials, as presented in Table 1, are increased by 20% to represent a more optimistic estimate and decreased by 20% to represent a more pessimistic view. The accompanying costs are also increased or decreased by 20% to represent respective pessimistic and optimistic views. To assess the sensitivity of the technology development, this parameter is set at 0%/year for the pessimistic case to 0.8%/year for the optimistic case.

Results of this sensitivity analysis are presented in Fig. 8 for the year 2050 as percentage change with respect to the reference case. With respect to the non-CO_2 share in total abatement, the methodology is most sensitive for assumptions on the concentration stabilisation target and the potential maximum reduction, where the range differs according an increase or a decrease of approximately 15%. Looking at the effort rate the largest sensitivity seen is towards

[6] The A1b scenario is characterised by very high economic growth and rapid technology transfer, and a leading consumer trend is towards a fast-food, high-meat, Western-style diet. The B1 scenario is characterised by rapid economic growth, an emphasis on quality-of-life and a rapid decline in energy- and material-intensive economic activities. The quantification of both scenarios is described in Van Vuuren et al. (in press-a).

Table 2 – Absolute sectoral non-CO_2 emission reductions and their shares in total non-CO_2 emission reductions for stabilising at 550 ppm CO_2-equivalent using the MAC curve set as developed in this study

	2025		2050		2075		2100	
	Emission reductions (GtC-eq.)	Share in emission reductions (%)	Emission reductions (GtC-eq.)	Share in emission reductions (%)	Emission reductions (GtC-eq.)	Share in emission reductions (%)	Emission reductions (GtC-eq.)	Share in emission reductions (%)
CH_4								
Coal production	231	21	296	14	484	20	627	24
Oil/gas production and distribution	214	19	344	16	112	5	97	4
Enteric fermentation	76	7	247	11	294	12	325	13
Animal waste	7	1	20	1	23	1	23	1
Wetland rice production	51	5	130	6	133	6	138	5
Landfills	227	20	439	20	449	19	379	15
Sewage and wastewater	71	6	97	4	110	5	119	5
Total	877	79	1573	72	1605	67	1709	66
N_2O								
Transport	1	0	5	0	6	0	5	0
Industrial sources	33	3	31	1	25	1	35	1
Fertiliser use	64	6	128	6	152	6	173	7
Animal waste	17	2	55	2	56	2	47	2
Domestic sewage	1	0	5	0	6	0	4	0
Total	116	10	217	10	246	10	264	10
F-gases								
HFCs	77	7	260	12	405	17	478	18
PFCs	25	2	79	4	99	4	77	3
SF6	21	2	59	3	54	2	58	2
Total	123	11	398	18	558	23	614	24
Total	1061	100	2188	100	2409	100	2587	100

Table 3 – Key assumptions and their variance levels as used in the sensitivity analysis

	Reference scenario	Optimistic scenario	Pessimistic scenario
Baseline scenario	B2	B1	A1b
Emission stabilisation target	550 ppm CO_2-equivalent	450 ppm CO_2-equivalent	650 ppm CO_2-equivalent
Max price	See Table 1	Table 1 −20%	Table 1 +20%
Max reduction potential	See Table 1	Table 1 +20%	Table 1 −20%
Technology development	0.4%/year	0.8%/year	0.0%/year

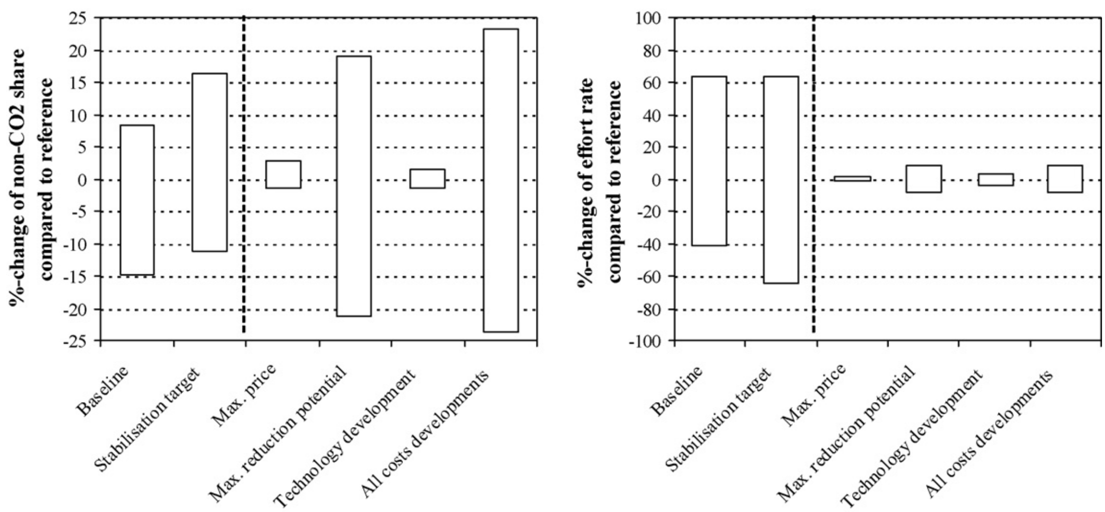

Fig. 8 – The impact of the key parameters on the non-CO_2 share in total abatement (left) and on the global effort rate (right) in 2050 (see also Table 3).

the baseline scenario and the concentration stabilisation target. Here, the range difference, from decrease to increase is 60% to 80%. The effects of assumptions for the technology developments, including maximum abatement potentials and accompanying costs, are relatively low, i.e. only around 5% from the reference case. However, compared to a case where no development is assumed, including the full set of development results in 3–21% lower costs in 2050 and 4–26% lower costs in 2100.

Thus, the non-CO_2 share seems rather robust over the different baseline scenarios. Nevertheless, as the costs are determined relative to the baseline scenario, scenarios with higher emission levels obviously result in higher costs. The concentration stabilisation targets influence the non-CO_2 share much more, while the overall costs are, moreover, in the same range. Both effects are the results of a lower (650 ppm) or higher (450 ppm) concentration stabilisation target and thereby reduction objective. A lower reduction objective results in a larger share of cheap non-CO_2 emission reductions, and obviously a lower price. A higher reduction objective works the other way around. The influence of technology developments, including maximum abatement potentials and accompanying costs, is partly outweighed by opposite changes in the non-CO_2 share.

6. Discussion and conclusions

In various studies it has been found that reducing non-CO_2 emissions along with CO_2 emissions from the energy system form a bare necessity to construct emission stabilisation scenarios which can accommodate stringent climate targets. Including non-CO_2 abatement options not only lower the overall abatement costs, but also bring the lower concentration stabilisation target more within reach. In this analysis, we extended the work done within the EMF-21 project, by emphasizing the importance of assessing the long-term reduction potential of non-CO_2 GHGs. The information on mitigation potential in the EMF-21 database only focuses on technologies that can be used in 2010 (for which fairly robust information is available). The database provides abatement potential of only 30% for the CH_4 emissions and less than 20% for the N_2O emissions. The reason for this is that the potential is limited by the focus on technologies that could be implemented around 2010. In the long term, technology development and removal of implementation barriers are likely to increase this reduction potential (similar to the reduction potential for CO_2 from energy consumption). It was for this reason that we looked into the existing literature to assess the long-term reduction potential of the different gases and present a methodology to extend the short-term MAC curves to 2100 for the most important non-CO_2 GHGs and their emission sources. The methodology uses a technological development factor and further extends the curves using maximum potential reductions and accompanying costs. These factors, potentials and cost estimates, are differentiated in time and over the different emission sources, but are the same for the different world regions. In our analysis, we first assessed the impacts of including non-CO_2 mitigation in reaching long-term GHG concentration stabilisation targets.

We then compared the impacts of assuming no progress in abatement potential to a situation in which potentials increase in time due to technology developments and the breakdown of implementation barriers.

Using the rough estimates made in this study it can be concluded that switching from a CO_2-only to a multi-gas approach can decrease the overall costs of climate policy by approximately 85% in 2010 and up to 25–35% in 2050 (depending on the level of non-CO_2 abatement potential development). Including non-CO_2 mitigation options not only increases the potential emission reductions, but the costs of these abatement options are significantly lower than most options in the energy sector. Furthermore, developments in abatement potential are most important for landuse-related sources, since according to present-day technology their potentials are still small. Including the full set of development, taking into account the uncertainties discussed, results in 3–21% lower costs in 2050 and 4–26% lower costs in 2100 compared to a case where no development is assumed. Next to non-CO_2 mitigation potential development, overall abatement costs are also sensitive to the baseline scenario (future socio-economic developments) and the concentration stabilisation target, as the combination determines the overall reduction objective.

Next to the diminishing role of non-CO_2 abatement in the overall costs in the long term, the non-CO_2 abatement share in total abatement also decreases in time. Up to 2035–2040, the share of non-CO_2 abatement is relatively large. This relatively large share can be explained by the fact that most non-CO_2 abatement options are cheaper than the CO_2 reduction effort in the energy system; the global reduction objective is still relatively small. In the long term, CO_2 emission reductions from the energy system become more and more important, lowering the non-CO_2 share to 10–15% in 2100, due to the limited potential of non-CO_2 reductions and the rapidly increasing global reduction objective. The non-CO_2 abatement share is most sensitive for assumptions on the concentration stabilisation target and the potential maximum reduction, which relates to a faster or slower non-CO_2 abatement potential depletion, respectively.

Methane emission reductions form the largest share in non-CO_2 abatement as the overall methane emissions are the largest and most of its emission sources (mainly from fossil fuel production and landfills) are relatively easy to abate. A high rate of reduction can also be reached for fluorinated gases, but their share in total emissions is much smaller. Nitrous oxide is a less important gas; both because the baseline emissions are relatively small and because the relative maximum potentials are much lower. The last point holds mainly for the landuse-related sources such as fertiliser use and animal husbandry, for which the maximum achievable reduction potential is assessed to be about only 40%.

The MAC curve set as developed in this paper has several attractive properties. First, of all, it is completely consistent with the EMF-21 set, as it uses the EMF-21 project as its starting point in 2010. As such, it embodies the information that was developed in the EMF-21 project and discussed among a large group of experts. The rules used to make these curves dynamic are relatively simple and transparent, and the effects can be easily assessed. Finally, using maximum potential reductions from the literature for relatively high marginal prices includes technology advances, which can already be foreseen; however, the timing and effects are not yet fully known. Next to these advantages, the methodology also has several disadvantages. The main disadvantage is that the maximum potentials are uniform for all regions and therefore assume that all regions have the same access to these new technologies and start from the same technology base, which is certainly not the case. This can obviously be improved if regional information is available. Furthermore, one could argue that the maximum potentials could be dependent on the concentration stabilisation target as a higher reduction objective increases the need to invest in abatement potential, i.e. technology. The estimates are based on known and foreseeable technologies. A technological breakthrough, especially in the agricultural sector, could significantly increase this potential. This mainly holds for animal husbandry as this is the main emitting source for both CH_4 and N_2O. Nevertheless, as the share of total non-CO_2 emissions remains small over the whole century, in spite of possible technological breakthroughs, their share in total reductions and therefore in overall costs reduction remains limited.

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