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Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios

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ABSTRACT

In 2010, the combined emissions of methane (CH_4), nitrous oxide (N_2O) and the fluorinated gasses (F-gas) accounted for 20–30% of Kyoto emissions and about 30% of radiative forcing. Current scenario studies conclude that in order to reach deep climate targets (radiative forcing of 2.8 W/m^2) in 2100, carbon dioxide (CO_2) emissions will need to be reduced to zero or negative. However, studies indicated that non-CO_2 emissions seem to be have less mitigation potential. To support effective climate policy strategies, an in-depth assessment was made of non-CO_2 greenhouse gas emission and their sources in achieving an ambitious climate target. Emission scenarios were assessed that had been produced by six integrated assessments models, which contributed to the scenario database for the fifth IPCC report. All model scenarios reduced emissions from energy-related sectors, largely resulting from structural changes and end-of-pipe abatement technologies. However, emission reductions were much less in the agricultural sectors. Furthermore, there were considerable differences in abatement potential between the model scenarios, and most notably in the agricultural sectors. The paper shows that better exploration of long-term abatement potential of non-CO_2 emissions is critical for the feasibility of deep climate targets.

1. Introduction

In the discussion of climate change and climate policy, most of the attention is focused on reducing carbon dioxide (CO_2) emissions. And indeed, CO_2 currently forms around two-thirds of equivalent emissions and forcing. Accordingly, the reduction potential for CO_2 emissions (as part of more comprehensive climate policy strategies) has been extensively looked at in several comparison projects using scenarios reaching 2 degrees (Kriegler et al., 2013; Riahi et al., 2013). Many of the deep mitigation scenarios use negative emissions technologies to mitigate CO_2. Interestingly, in these scenarios non-CO_2 emissions tend to have less mitigation potential (Clarke et al., 2014). As non-CO_2 emissions also contribute to climate change, it is very policy relevant to look deeper into the non-CO_2 emission reduction strategies.

Integrated assessment analyses show that mitigation of non-CO_2 greenhouse gas (GHGs) forms an important part of cost-efficient climate mitigation strategies (van Vuuren et al., 2006; Weyant et al., 2006). There are several reasons for this. First, the main non-CO_2 GHGs (CH_4, N_2O and the F-gasses) covered under the Kyoto Protocol contribute to about 20–30% of the total 2010 CO_2-equivalent emissions and to about 30% of the total radiative forcing (IPCC, 2007). Second, some non-CO_2 GHGs have relatively short lifetimes, thereby creating the option of a short-term climate benefits (see for instance Shindell et al., 2012). Third, some of the options to reduce non-CO_2 gases are relatively inexpensive, providing an option to reduce overall mitigation costs (Weyant et al., 2006; van Vuuren et al., 2006). Finally, a larger portfolio of

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mitigation options increases flexibility (van Vuuren et al., 2006; Weyant et al., 2006). Consistent with these findings, non-CO_2 GHGs are covered in most climate policies, including the Kyoto protocol and country pledges under the Cancun agreements (UNFCCC, 2005, 2009).

Still, non-CO_2 gases have received much less attention in multi-model studies. The last model comparison study to specifically address non-CO_2 gases was the EMF21 study (van Vuuren et al., 2006; Weyant et al., 2006). This study looked into the benefits of a multigas strategy over a CO_2-only reduction strategy. The study, however, paid little attention to comparing sectoral strategies across models, and only looked at relatively modest climate targets.

In this paper, we focus on the role of non-CO_2 emission reduction in state-of-the-art mitigation scenarios generated by integrated assessment models. These and similar scenarios form the basis of the analysis in the 5th Assessment Report by IPCC (Clarke et al., 2014). We go beyond the existing comparisons by (1) looking at more recent scenarios, (2) for the first time looking at the sectoral mitigation potential and (3) specifically address the role of the remaining non-CO_2 emissions (CH_4, N_2O and F-gases) in deep mitigation scenarios in order to discuss their relevance for climate policy. To show some of the relevant uncertainty, we use a set of different integrated assessment models (IAMs). The analysis uses the results of the recent LIMITS model comparison study (Kriegler et al., 2013) for six different IAMs. Appendix A provides a brief overview of the participating models: GCAM (Calvin, 2011), IMAGE (MNP, 2006; van Vuuren, 2007), MESSAGE (Riahi et al., 2007), REMIND (Luderer et al., 2011), TIAM-ECN (Kober et al., 2013; van der Zwaan et al., 2013; Rösler et al., 2014) and WITCH (Bosetti et al., 2006, 2009). Most of these models used information on mitigation potential based on the EMF21, but have updated the projections of driving forces and non-CO_2 gas emissions. In the LIMITS study, several scenarios were run by these models, including no policy scenarios and scenarios aiming at a 2100 forcing level of 2.8 W/m^2. Using the LIMITS scenarios that are also assessed in the most recent IPCC report (IPCC, 2014), this paper looks into the following questions:

(1) What is the role of the remaining non-CO_2 emissions for reaching ambitious climate targets?
(2) How do mitigation strategies compare across models in reducing non-CO_2 emissions at a sectoral level?

First, in Section 2, we discuss the methodology of the study. In Section 3.1, we compare the overall response for non-CO_2 emissions in the different models for deep mitigation scenarios. In a subsequent analysis, we look into the sectoral emissions sources (Sections 3.2–3.4) and regional results (Section 3.5). After which we compare emissions under similar conditions in Section 3.6. Finally, in Section 3.7 we look into the potential implications for climate change. Section 4 presents the conclusions.

2. Methods

2.1. Comparison of mitigation potential

The LIMITS study (Kriegler et al., 2013) developed different scenarios to look into the question what would be required to meet the 2 °C target. Here, we use two scenarios from the LIMITS project:

(1) *Baseline*: This scenario assumes that no new climate policies are implemented. Assumptions on the development of trends in socio-economic parameters, energy and land-use and derived emissions were left to the individual models teams, resulting in a range of 2100 emission levels of 90–110 $GtCO_2$-equiv./yr (Kriegler et al., 2013).
(2) The *450* scenario: This scenarios aims to achieve a radiative forcing target of 2.8 W/m^2 in 2100 by starting with immediate full global cooperative action. The scenario is regarded to have a likely (>70%) chance of reaching the 2 °C target (Kriegler et al., 2013). The policy target assumed for the depicted scenarios refers to the aggregate radiative forcing from the following substances: Kyoto gases (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6), Non-Kyoto gases (substances controlled under the Montreal protocol, i.e. chlorides, halons, bromine; tropospheric and stratospheric ozone; stratospheric water vapor), and aerosols (sulfate, black and organic carbon from fossil fuel and biomass burning, indirect aerosol forcing).

All six IAMs included in this study have partly based their information on mitigation potential and costs on the US-EPA MAC curves (Weyant et al., 2006) to estimate the marginal abatement costs of non-CO_2 GHGs. This includes the information presented by Delhotal et al. (2006) for methane and nitrous oxide emissions from waste, energy and industry, DeAngelo et al. (2006) for methane and nitrous oxide mitigation from agriculture, and Schaefer et al. (2006) for emissions from the f-gases (HFCs, PFCs, and SF6). IMAGE and REMIND use a set of MAC curves that also try to capture dynamic changes over time as described in Lucas et al. (2007). This set combines information from the US-EPA curves with information taken from Graus et al. (2004) and extends the abatement potential over time using a technological development factor. The abatement potential is reformed with first-order estimates on future maximum attainable reduction potentials combined with an inertia effect representing implementation barriers. GCAM and MESSAGE have implemented the information underlying the US-EPA MAC curves, but at the level of underlying technologies. The MAC curves in these models are held constant over time. TIAM-ECN uses a combination of DeAngelo et al. (2006) and Lucas et al. (2007).

In the analysis, we compare models for three different Kyoto non-CO_2 gases in different sectors and regions. In implementing a multi-gas strategy, all models considered here use Global Warming Potential (GWPs) as reported by IPCC's Fourth Assessment Report (AR4) (IPCC, 2007) to determine the relative value of reducing 1 kg of each gas. Here, we report the emissions of all sources in terms of CO_2-equiv. using AR4 GWPs. For the sectoral comparison, we compared the models with respect to the emission trends for the following sectors: (1) energy production; (2) energy end-use; (3) livestock production; (4) rice production; (5) fertilizer use; (6) deforestation, including savannah burning; (7) solvents; and (8) waste. Specific definitions can be found in Appendix B. In order to compare in the regional dimension, we defined a set of 5 aggregated world regions for comparison: OECD90, Asia, Latin America, Middle East and Africa, and the reforming economies of Eastern Europe and the Former Soviet union, see Appendix C for specifics.

Finally, it should be noted that the two scenarios above do not provide information on the underlying marginal abatement curves across the models–as they will use different carbon taxes to achieve a similar climate target (2.8 W/m^2). In order to systematically compare the potential across the models, we have therefore also look into non-CO_2 emission reduction using scenarios with the same carbon tax. For the comparison we have used diagnostic scenarios developed in the AMPERE project (Kriegler et al., 2015). One of the scenarios in this set starts with US$12.50/ton CO_2 equiv. in 2010, increasing 4% per year to around $426/ton CO_2-equiv. in 2100. The scenarios used harmonized population and GDP data (OECD, 2012) and are therefore very suitable to compare emission reductions across the models. We look at the reductions in this scenario compared to the baseline, plotting the value of the tax against the emission reduction.

2.2. Simple climate model runs exploring implications of non-CO_2 reduction potential

In order to get further insight into the importance of the findings regarding non-CO_2 abatement we have performed an additional set of experiments using the MAGICC model (version 6) (Meinshausen et al., 2011). In the experiments we used different assumptions on the mitigation potential of non-CO_2 gases, by either assuming: (1) no further reductions than the *Baseline*, (2) using the non-CO_2 results of the different models in combination with a standard CO_2 scenario (IMAGE), (3) assuming that emissions can be reduced to zero and (4) by combining the different assumptions of the non-CO_2 gases with perturbed IMAGE output of the *450* scenario in which the negative CO_2 emissions were removed in order to compare the impacts of non-CO_2 assumptions against the influence of negative CO_2 emissions.

3. Results

3.1. Non-CO_2 impact on global emissions

In the six LIMITS models, non-CO_2 Kyoto gas emissions account for 26–29% of global GHG emissions in 2005, i.e. consistent with the estimate of historic emission (JRC/PBL, 2014) (Fig. 1). In the *Baseline* scenario, the share declines to 16–27% in 2100 as a result of a more rapid increase of CO_2 emissions (98–181%) compared to non-CO_2 (23–148%). A key reason for this difference in growth rates is that the main driver of CO_2 emissions (energy use) is expected to grow faster than the combined drivers of non-CO_2 emissions (partly the energy sector, but for a significant part also land-use). This will be discussed further in the sectoral analysis.

Interestingly, for the 450 scenario an opposite trend can be noted (Fig. 1). As discussed by van Vuuren and Riahi (2011); and Kriegler et al. (2013), in deep mitigation scenarios, CO_2 emissions tend to be reduced to negative numbers (by using bio-energy in combination with carbon capture and storage (CCS)). At the same time, reductions of non-CO_2 gases are assumed to be constrained (see Sections 3.2–3.4). In total, across the different models the non-CO_2 Kyoto gas emissions in a 450 scenario are reduced by 16–47% compared to the *Baseline* scenario in 2050 and further reduced by 46–72% 2100. This means that by 2100, the non-CO_2 Kyoto emissions amount to 11–14 Gt CO_2-equiv./yr across the models, which are comparable to 2005 levels (12–13 Gt CO_2-equiv./yr). A remarkable result is that in the mitigation scenario (*450*) the contribution of non-CO_2 gases in emissions tend to increase over time (assuming the reduction of CO_2 emissions is implemented) – even going to levels above 100% of total emissions, as a result of total emissions becoming net negative. At the same time, in terms of forcing, CO_2 remains the most important contributor to climate change. Fig. 1 thus emphasizes that assumptions on the mitigation of non-CO_2 gases become increasingly important over time. Certainly if the option to further create negative emissions from CO_2 is constrained (due to limitations on bio-energy availability or CCS), assumptions on the non-CO_2 gases thus become critically important in achieving low concentration targets.

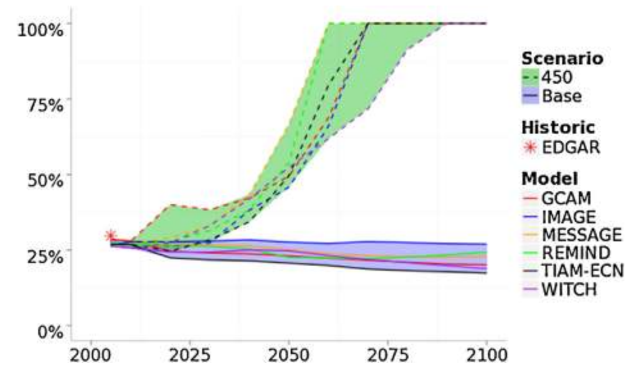

Fig. 1. Non-CO_2 emissions as fraction of total Kyoto gases in *Baseline* and *450* scenario.

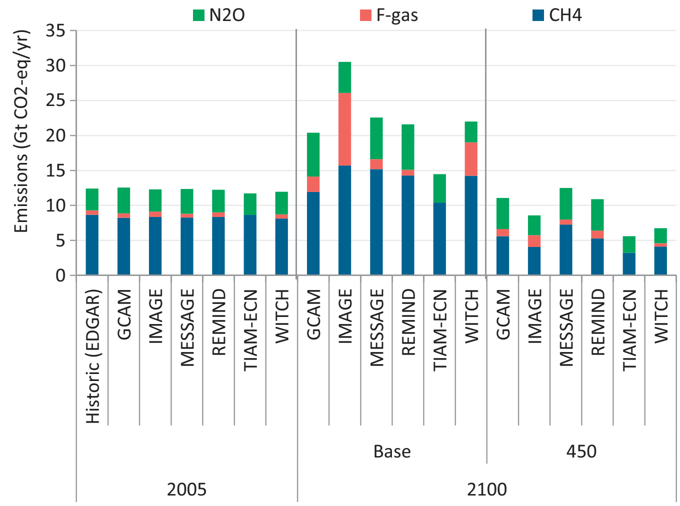

Fig. 2. Contribution of CH_4, N_2O and F-gases to total non-CO_2 emissions for the *Baseline* and *450* scenarios in the year 2005 and 2100.

In Fig. 2, we have broken down the emissions by gas. Across the different LIMITS models, the 2005 methane emissions account for approximately 66–74% of the non-CO_2 emissions, the N_2O emissions for 26–29% and the emissions of F-gasses for 5–6%. The breakdown of emissions in all models is in line with historic data. The overall growth of 23–148% by 2100 in the *Baseline* scenario is a result of a growth of methane emissions of 20–88%, for N_2O 8–101% and for F-gases 19–1269%. The reduction in the *450* scenario results from a reduction of all gases: the emission reductions of methane range from 52% to 74% compared to the *Baseline* scenario in 2100. For N_2O, the numbers are 46% and 72% and for F-gases 50% and 90%. This implies that across all models an overall reduction potential is seen comparable to Lucas et al. (2007). At the same time, however, large differences can be noted across the models at a sectoral level which we will discuss in more detail in Sections 3.2–3.4.

3.2. Methane emissions

3.2.1. Overall trends in emissions

In 2005, methane emissions in the models are 8–9 Gt CO_2-equiv./yr. Similar differences have been reported for historical inventories (Höglund-Isaksson, 2012; JRC/PBL, 2014), so the range is consistent with the uncertainty in emission data (the EDGAR data is shown for comparison in Fig. 3). In the *Baseline* scenario, the models project an increase to 10–16 Gt CO_2-equiv./yr in 2100 (Fig. 3) (38–79% increase over 2005). In all cases, first a faster increase in the 2005–2050 period is noted, followed by relatively small changes in the 2050–2100 period (except for REMIND, which even shows a relatively rapid decline in the second period).

Methane emissions in the *450* scenario shows a reduction across models ranging from 13–58% in 2050 and 35–71% in 2100 compared to the *Baseline* scenario. This implies that, on average, compared to 2005 the models show a slow decline with some model showing nearly constant emissions (MESSAGE) and other models showing a >50% reduction. Fig. 4 shows that the most important sectoral emissions sources in 2005 are the energy supply (24–30%), agricultural livestock (31–35%), agricultural rice

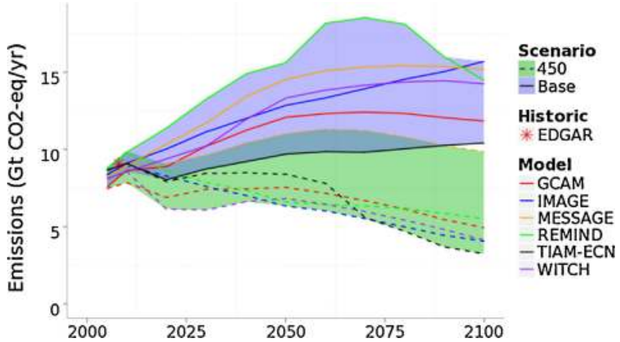

Fig. 3. Global CH_4 emissions for *Baseline* and *450* scenario.

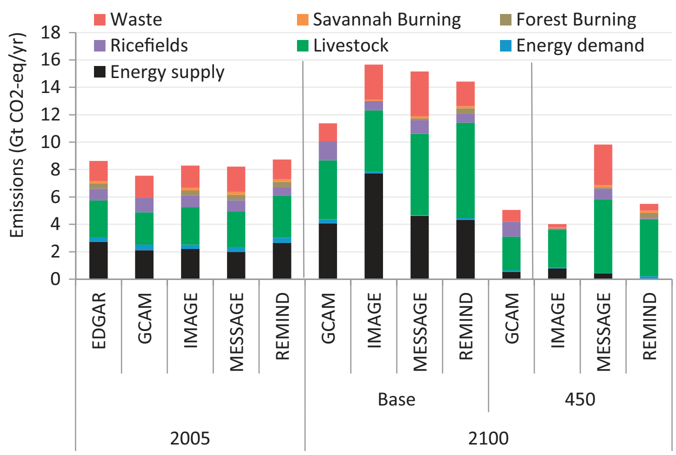

Fig. 4. Sectoral source CH_4 emissions in 2005 and 2100 in *Baseline* and *450* scenario.

fields (8–14%) and the waste sector (17–23%), reasonably consistent with recent estimates of historical emissions (the model slightly underestimate emissions coming from the energy sector). Of the remaining emissions in 2100 in the *450* scenario (Fig. 4), the livestock sector is the most important remaining methane source (49–76%).

3.2.2. Detailed discussion by sector

Fig. 5 shows how sectoral emissions develop over time for the *baseline* and *450* scenario. By far the largest increase in emissions in the baseline scenario occurs in the energy supply and livestock sectors. The mitigation scenarios show a quite different picture: the potential for emission reductions in the energy supply sector are considerable. Across the models, a reduction potential for the *450* scenario can be noticed of 87–99% compared to the *Baseline* scenario in 2100 (Fig. 5). Within this category, the two main sources are coal mining and oil and gas production emissions. Emission reductions in this sector occur as a result of (1) specific reduction of methane emissions by end-of-pipe measures and (2) reduction of fossil fuel use as a result of climate policy. Together these factors explain the large part of the emissions reduction. For underground mining, a key "end-of-pipe" measure is methane recovery (Hendriks and de Jager, 2001). There is a trend toward more surface mining, which is harder to mitigate but for the baseline scenario emits less methane emissions (factor 10) compared to underground mining. The abatement options taken into account for oil and gas production are better leakage management and co-production of gas and flaring (US-EPA, 1999; Hendriks and de Jager, 2001). Most emissions sources in energy supply can be mitigated at low cost.

The agricultural livestock sector shows significantly lower reduction potential ranging from 9% to 43% across the models. Three models (IMAGE, REMIND and GCAM) show a reduction of 39–43% while MESSAGE shows a more constrained reduction of only 9%. The two sources in this sector are enteric fermentation and animal waste emissions. Abatement options to reduce enteric fermentation emissions are dietary change and the use of more productive animal types (Riemer, 1999; Graus et al., 2004). The animal waste abatement option is the capture and use of methane emissions through anaerobic digesters (Graus et al., 2004).

Emissions from agricultural rice fields show a very large uncertainty range for reduction potential across the models ranging from 22% to 88%. While all models include emission reductions in this sector based on assumed changes in rice varieties and changing water management (see also Lucas et al. (2007)), they vary with respect to assumptions on the future technical improvements in these mitigation options and the degree with

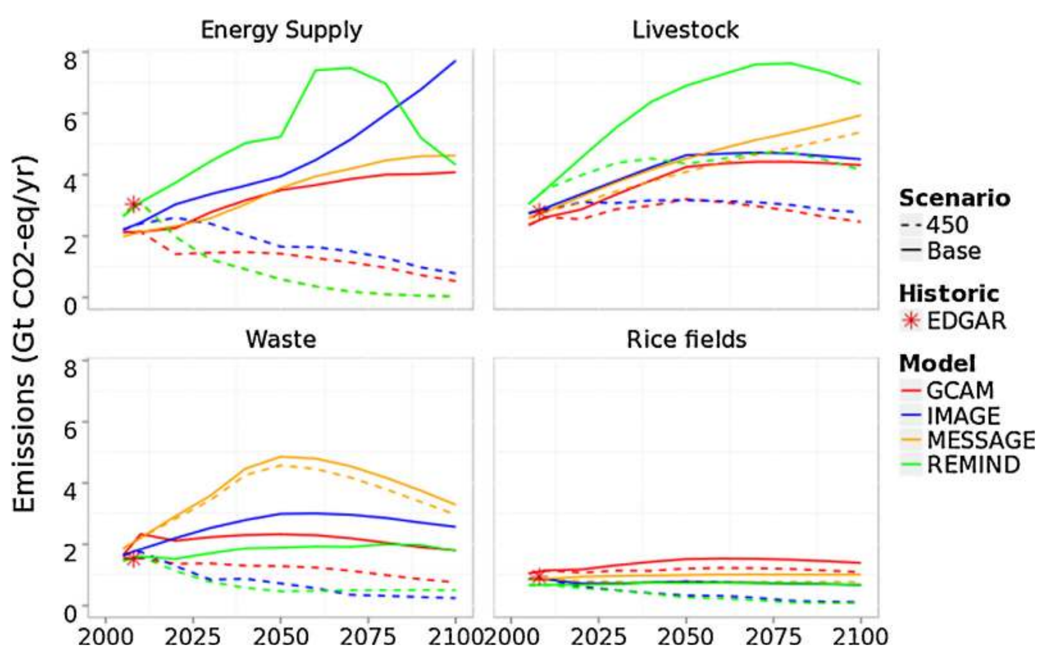

Fig. 5. (a) CH_4 emissions from energy supply sector. (b) CH_4 emissions from agricultural livestock sector. (c) CH_4 emissions from the waste sector, (d) CH_4 emissions from agricultural rice fields. Note the TIAM-ECN and WITCH model lack sectoral detail to be included in this analysis.

which these technical measures can be implemented (given the large amount of actors involved). Some models (IMAGE/REMIND) assume significant changes in the potential of these options – in particular related to the potential to implement existing options. Two models (MESSAGE/GCAM) only show a reduction of 21–24%. Clearly, agricultural rice emissions are strongly regionally related, with 80–93% of global emissions occurring in Asia throughout the century (see Section 3.5).

The waste sector shows very large differences across the models. The MESSAGE model shows a reduction potential of only 10% (starting from a high *Baseline*), while the IMAGE and REMIND models show 90% and 72% reduction potential in 2100 compared to the *Baseline*. GCAM shows a 34% reduction. The two sources in this sector are landfill and sewage and waste water emissions. Landfill emissions can be abated by either the reduction of organic material in landfills or by landfill gas recovery (Bates, 2001). Sewage and waste water emissions can be abated by more waste water treatment plants in combination with methane recovery and aerobic waste water treatment (Lucas et al., 2007). For MESSAGE, the *baseline* scenario already is very gas intensive leading to relatively low significance of the low cost gas available from mitigation from land fills. Earlier runs, however, have showed significant land fill mitigation in scenarios with more restricted gas supply.

3.3. N_2O emissions

3.3.1. Overall trends in emissions

In 2005, N_2O emissions in the models are 3.0–3.6 Gt CO_2-equiv./yr. Estimates of current emissions show that there is a large uncertainty regarding N_2O emissions, the IPCC AR5 estimates for current anthropogenic emissions range from 1.3 to 5.2 Gt CO_2-equiv. (IPCC, 2014; JRC/PBL, 2014) (the sum of natural and anthropogenic emissions is more constrained). In the *Baseline* scenario, the models project a growth of 32–108% by 2100, except for WITCH that shows a decline in the second half of the century to 8% in 2100 compared to 2005 (Fig. 6). In the *450* scenario, three models (IMAGE, TIAM-ECN and WITCH) show a reduction of 9–34% by 2100 compared to 2005 emissions, while the three other models (GCAM, MESSAGE and REMIND) show an increase of 26–42%. In terms of reduction compared to *Baseline* in 2100 the range is 10% (MESSAGE) to 42% (TIAM-ECN). The overall reduction potential for N_2O is, thus, smaller than for CH_4 (35–71%), partly related to the much smaller role of the energy sector. The most important sectoral source for N_2O emissions in 2005 is the agricultural sector that consists of the livestock (37–77%) and fertilizer sector (27–49%) (Fig. 7). Similar to the uncertainty in historical data, also the models show a relatively large range for base year emissions which is further discussed in the section below.

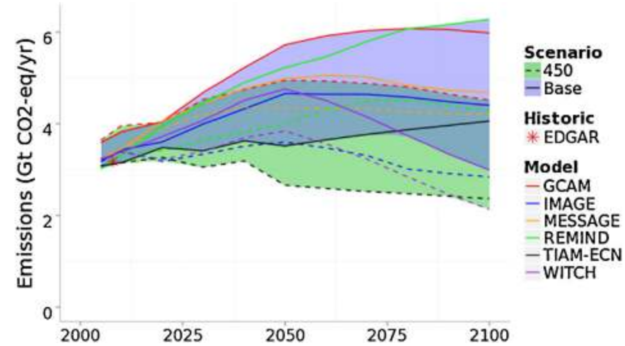

Fig. 6. N_2O emissions for *Baseline* and *450* scenario.

3.3.2. Detailed discussion by sector

The N_2O emissions from the agricultural sector originate from the livestock and fertilizer sector (Fig. 8). This comparison shows that uncertainties on a sectoral level are substantial, both between the models and historically. The IPCC AR5 points out that most of the uncertainty in N_2O emissions is, in fact, due to uncertainty in the agricultural sector (0.8–2.2 Gt CO_2-equiv.) (IPCC, 2014). Agricultural livestock emissions are projected to increase by 59–130% in the *Baseline* scenario in the 2005–2100 period compared to 2005, driven by increasing demand for dairy products and meat. The emission reduction in the *450* scenario in 2050 ranges from 16% to 35% compared to the *Baseline* scenario and from 26% to 45% in 2100. Abatement options for the livestock

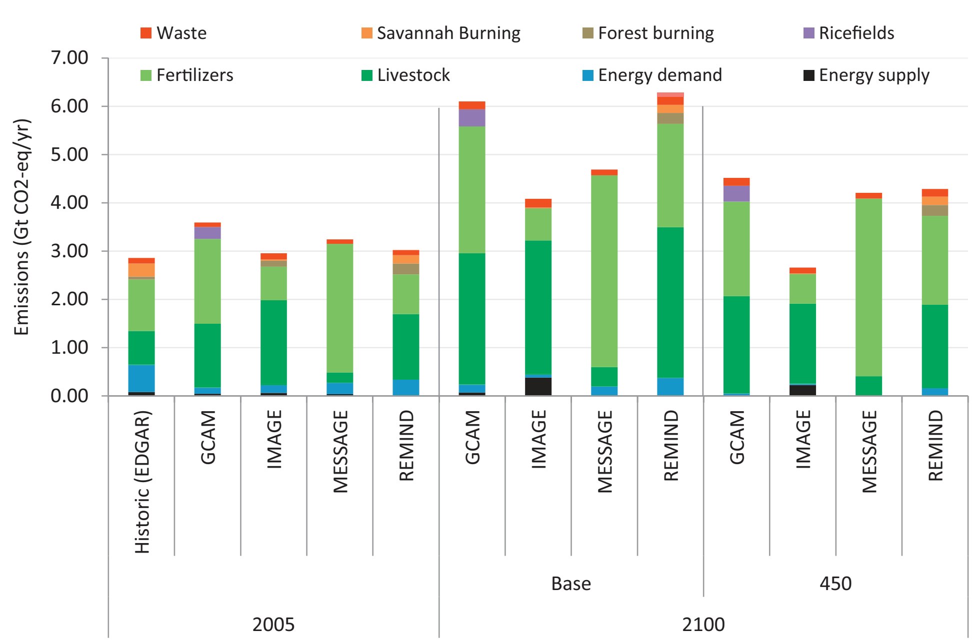

Fig. 7. Sectoral source N_2O emissions in 2005 and 2100 in *Baseline* and *450* scenario. *Note*: Manure management emissions for the MESSAGE model are accounted for in the fertilizer sector.

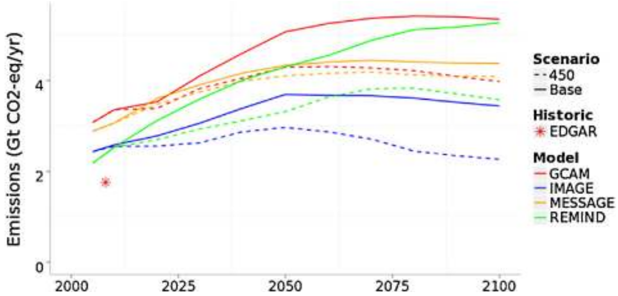

Fig. 8. N_2O emissions from the agricultural sector (livestock and fertilizer).

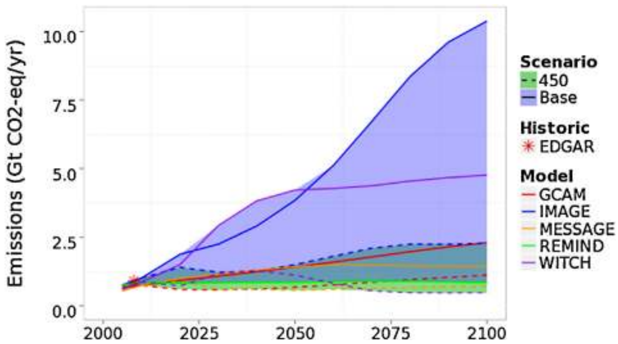

Fig. 9. F-gas emissions for *Baseline* and *450* scenario.

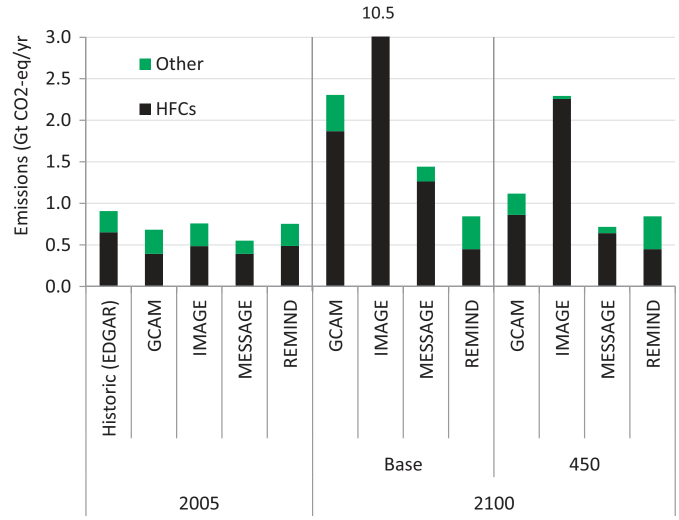

Fig. 10. Sectoral source F-gas emissions in 2005 and 2100 in *Baseline* and *450* scenario. In REMIND, F-gas emissions are implemented exogenously and show, therefore, no change as a result of carbon tax. IMAGE F-gas emission are 10.5 Gt CO_2-equiv. in total, of which the majority (97%) are HFC emissions.

sector are dietary changes, increasing animal productivity, optimizing manure management and limiting the free–grazing share of livestock (Clemens and Ahlgrimm, 2001; Brink, 2003). Most of the emissions are projected in the Asia and OECD region, together around 70% of global 2010 emissions. The emissions from agricultural fertilizer increase by 49–160% in 2100 in *Baseline* compared to 2005 for most models, only the IMAGE model projects a slight decline of 4%. The sector shows relatively low emission reduction potential in the *450* scenario compared to *Baseline* with ~7% in 2100 for MESSAGE and IMAGE, and 14–25% for REMIND and GCAM. Abatement options for this sector are improving fertilizer use efficiency, restricting the use of fertilizer in time, using fertilizer-free zones and replacing current fertilizer with new types with lower emissions (Hendriks et al., 1998; Mosier et al., 1998; Graus et al., 2004).

3.4. F-gases

In 2005, F-gas emissions in the models are 0.5–0.8 Gt CO_2-equiv./yr. In the *Baseline* scenario, they are projected to increase to 0.8–10 Gt CO_2-equiv./yr in 2100 (12–1269% increase over 2005) (Fig. 9). Two models (IMAGE and WITCH) project significantly higher increase of emissions (1269% and 677%) than the other models (GCAM 237%, MESSAGE 162%). REMIND shows an increase of 11%. The *450* scenario shows reduction across models ranging from 52% to 90% in 2100 compared to *Baseline.* In REMIND, F-gas emissions are exogenous and show, therefore, no change in the mitigation scenario as a result of a carbon tax. The projections are left out of further analysis.

In 2005, HFCs account for 57–71% of total F-gas emissions (Fig. 10). The models seem to slightly underestimate the HFCs compared to historic data (JRC/PBL, 2014). Most of the growth in the F-gas emissions over the century is driven by HFC gases. As a result their share increases over time to 81–97% in 2100 in *Baseline* scenario due to a growth of 222–1968% in 2100 compared to 2005. HFC emissions in the IMAGE model follow projections developed by Velders et al. (2007) suggesting significant emission growth without policy intervention. The main driver for growth is the refrigeration and air conditioning industry. In the 450 scenario strong reduction of 49–77% are seen for the HFC emissions. Abatement options are (1) thermal destruction of HFC emissions during production (Irving and Branscombe, 2002; Klein Goldewijk et al., 2005), (2) better sealed applications to prevent leakages (Schwarz and Leisewitz, 1999), (3) HFC recovery of disposed products, and (4) substitution by substances with zero GWP (Heijnes, 1999).

The "other" F-gases consist of mainly PFC and SF6 gases that are used in the semiconductor, magnesium, aluminum, foam and solvent industry. In 2005, combined PFC and SF6 emissions consist of 29–43% of total F-gas emissions. In the *Baseline* scenario, emissions increase by 13–50% in 2100. Their relative contribution to the total F-gas emissions becomes smaller due to the strong growth of HFC emissions. Reductions in the *450* scenario compared to *Baseline* range between 41% and 58% in the year 2100. For PFC, the abatement options are (a) the use of modern process technology for aluminum production (Heijnes, 1999); (b) emission capture and (thermal) destruction in semiconductor manufacture (Heijnes, 1999); and (c) replacing the use of PFCs as solvents. For SF6 the abatement options are (a) improved recovery; (b) minimization of leakage; and (c) optimization of use (Heijnes, 1999; Wartmann and Harnisch, 2005).

3.5. Regional distribution of emissions

In 2005, 31–44% of global methane emissions come from Asia (see Table 1). This is mainly due to emissions from rice production that is much more prominent in Asia. Also methane emissions from energy supply and livestock play a role but these are more evenly spread across the regions. In the *Baseline* scenario, in 2100, the share in global methane emissions increases in the Middle East and Africa and decreases in Asia, compared to their 2005 shares, in particular due to an increase in the energy supply and livestock sector. In three models (MESSAGE, IMAGE and GCAM) Asia will remain the most important methane emitter (37–44%), while the other models (WITCH and REMIND) show that the Middle East and Africa region would become the largest emitting region. In the *450* scenario, in 2100, the share of global methane emissions is not much different than in the baseline scenario for most regions. Methane emissions decrease in all regions except the Middle

Table 1
Regional share in percentages of global emissions per gas, in 2100 for the *Baseline* and *450* scenario.

		Asia	Latin America	Middle East and Africa	OECD90	Reforming economies
CH_4	2005	39 [31–44]	13 [13–14]	16 [13–20]	19 [15–24]	10 [9–14]
	2100 base	35 [24–44]	11 [8–16]	27 [18–36]	17 [10–22]	9 [6–11]
	2100 450	37 [23–47]	15 [8–25]	31 [23–42]	12 [6–16]	5 [2–9]
N_2O	2005	34 [25–41]	14 [13–16]	18 [14–25]	25 [23–30]	7 [4–9]
	2100 base	32 [29–36]	14 [12–16]	30 [25–37]	17 [13–21]	6 [2–10]
	2100 450	27 [18–37]	15 [12–18]	32 [19–46]	17 [11–27]	6 [3–13]
F-gases	2005	25 [18–30]	5 [3–6]	5 [2–7]	55 [47–62]	7 [6–9]
	2100 base	42 [30–57]	7 [3–11]	17 [2–29]	26 [12–50]	5 [3–8]
	2100 450	41 [30–57]	7 [3–12]	17 [2–29]	27 [11–50]	5 [3–8]

East and Africa region (92%-189%), where emissions from livestock still increase significantly.

For N_2O emissions, both Asia (25–41%) and the OECD90 region (23–30%) were the largest emitters in 2005, with no clear difference in sectoral sources. Similar to methane, also the N_2O share of the Middle East and Africa in global emissions increases compared to 2005, in both the *Baseline* and the *450* scenario.

For the F-gas emissions the OECD90 region is clearly the largest emitter (47–62%). Toward 2100, however, the share in global F-gas emissions in the OECD90 region decreases significantly, while the share of Asia and the Middle East and Africa increases. The increase of F-gases in the latter two regions is largely related to increased use of air conditioning by their increasing and more affluent populations. For the *450* scenario, most regions would still see an increase compared to 2005 levels. Reduction levels are similar across the regions, leaving the global distribution almost unchanged.

Fig. 11 shows the share of non-CO_2 emissions in total regional GHG emissions. This share is around 23–50% in 2005, except for OECD90 where it is much smaller (14–23%). For most regions, the high share of CH_4 emissions come from land-use sources, while in the Reforming Economies the energy supply sector is dominant. Also for N_2O the land-use sector is a dominant source, except for the OECD90 region in which the transport sector is also important. In the *Baseline* scenario in 2100, the shares of CH_4 and N_2O in total emissions compared to 2005 levels decreases significantly in Asia and, to a lesser extend, also in Latin America and the Middle East and Africa. The share, however, increases in OECD90 and the Reforming Economy regions. This is mainly due to a large increase in CO_2 emissions in the developing regions. F-gas share are only small and only decrease slightly toward 2100.

In the *450* scenario, in 2100, the share of the non-CO_2 GHG emissions in total emissions (excluding the negative emissions from bio-energy combined with carbon capture and storage, bio-CCS) is much higher than in the *Baseline*, also compared to levels observed in 2005. The CO_2 emissions from energy production are reduced much more than the non-CO_2 emissions (and even go negative due to the use of bio-CCS), while for CH_4 and N_2O there are several sources that are hard to abate (see Section 3.1).

3.6. Overall marginal abatement curves

As discussed in Appendix C, the models use different methods to determine the costs of non-CO_2 GHG abatement. For the first 10–20 years, most models use the estimates of the EMF21 study, but for the period beyond 2030 other assumptions (in particular technological rates) play a role. The models clearly differ in the assumed improvement rates and the sectors covered by mitigation action. Fig. 12 shows the total non-CO_2 emission reduction (CH_4, N_2O and F-gas) in the harmonized scenarios from the AMPERE project (see methods) against the value of the carbon tax, giving an indication of the underlying MACs. Consistent with the earlier results, the figure shows that GCAM and MESSAGE show considerable less reductions for a given carbon price. This is in particular the case for methane and F-gas emissions. For N_2O, only GCAM shows relatively low reductions. The differences result from different assumptions on technological learning and maximal technical reduction feasibility (see Appendix C).

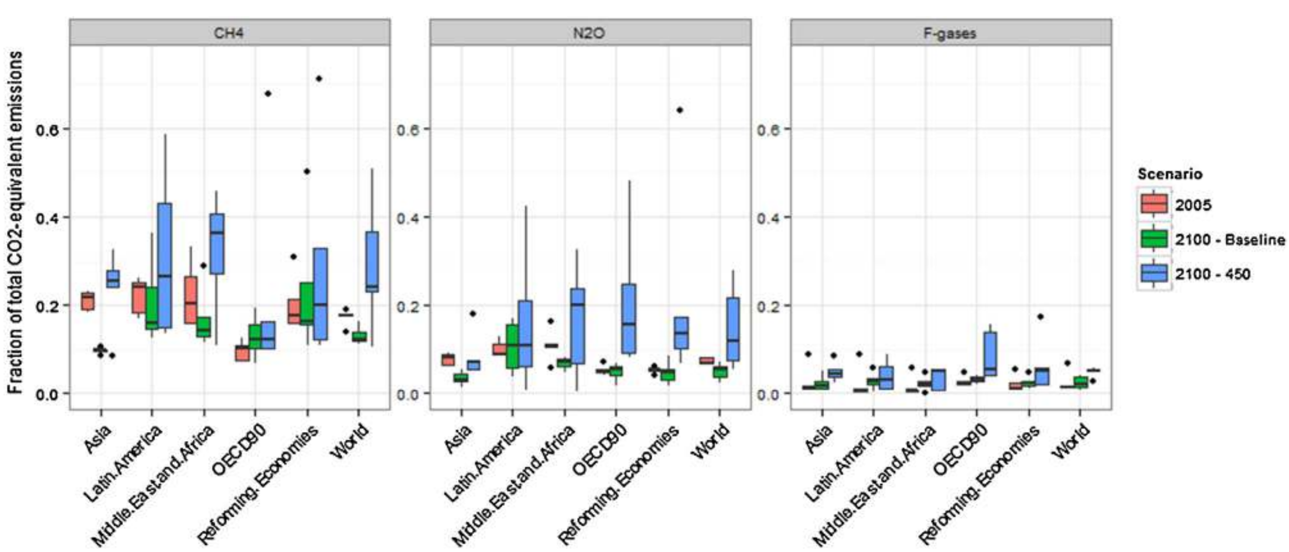

Fig. 11. Regional shares of non-CO_2 emissions. For the 450 scenario bio-CCS is excluded from the total regional emissions.

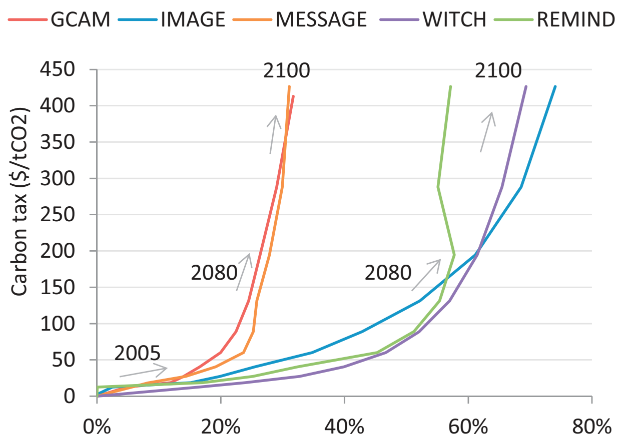

Fig. 12. Increasing carbon tax (4% per year) versus non-CO_2 reduction compared to baseline. Data is taken from the diagnostic runs of the AMPERE project (Kriegler et al., in press). Here, the carbon tax in 2005 is $0 per ton CO_2 increasing to $12.50 in 2010, reaching approximately $200 in 2080 and $426 in 2100.

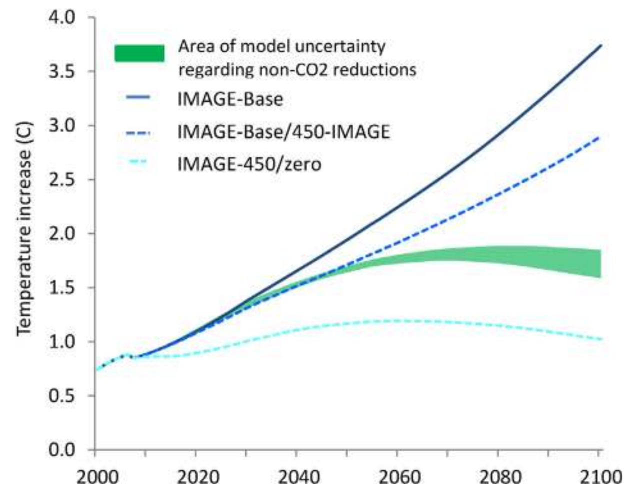

Fig. 13. Temperature increase (based on MAGICC) for different non-CO_2 emission levels for the period 2000–2100 (see Table 2 for scenario definitions). The green area indicates the model uncertainty regarding non-CO_2 reductions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Overall, higher emission reduction levels are seen in the *450* scenario (MESSAGE 39%, GCAM 46%, WITCH 70%) compared to the diagnostic scenario (MESSAGE 31%, GCAM 46%, WITCH 69%), with the exception of the IMAGE model. This latter is related to the spread of carbon taxes in the LIMITS scenarios (relatively low for IMAGE).

Recently, the USA-EPA published an update on the non-CO_2 MACs (US-EPA, 2013). Analysis shows that for the short-term the reduction potential in the new curves is slightly higher for low carbon taxes than the 2006 estimates, but less overall reductions in higher cost range. As in the emission reductions in the models are determined by long-term estimates these updates will not affect the results presented here in a significant way (will certainly not affect the conclusions of this paper). Nevertheless, updating the models with the latest insights will be important, including estimates on emissions reductions beyond 2030.

3.7. Implications for climate change

In the previous sections, we have seen that in all integrated assessment models the reduction potential of non-CO_2 gases is significantly constrained compared to CO_2. At the same time, the results also show that there is quite some uncertainty in the reduction potential for non-CO_2 gases. A key question that emerges from this is the implication of these findings for the feasibility of stringent climate targets, such as the 2 °C target.

In order to explore this, we have calculated the impact of the different non-CO_2 emission projections on temperature increase. We have made different combinations of the outcomes of the scenarios discussed in the previous sections (see Table 2). Because we focus on the impacts of non-CO_2 gas assumptions, we use IMAGE model results for CO_2 as default. Clearly, by combining the outcomes of different models and scenarios we create rather inconsistent sets of assumptions. However, these pathways can still provide good insights into the role of assumptions on the reduction potential for non-CO_2 gases for achieving low climate target.

We assess the impact of the non-CO_2 emission reductions by comparing the temperature differences between the *IMAGE-Base* and the *IMAGE-base/450* pathway. This comparison shows a 0.8 °C reduction in 2100 temperature (from 3.7 °C to 2.9 °C).

The impact of the uncertainty in emission reduction potential of the different models can be assessed by comparing the temperature differences between the pathways that combine the CO_2 emissions from the *IMAGE-450* scenario with the non-CO_2 emissions from the *450* scenarios of the various models. Fig. 13 shows a range of 1.9 to slightly below 1.6° in 2100 (thus around 0.3 °C difference). Three models (IMAGE, TIAM-ECN and WITCH) show an early peak (1.7–1.8 °C) around 2070 followed by a decline to 1.6–1.7 °C in 2100, while the other models (GCAM, MESSAGE and REMIND) show a later and higher temperature peak (1.8–1.9 °C) around 2085 followed a slower decline to 1.8–1.9 °C in 2100. The differences across the models might be important for conclusions on the feasibility of the 2 °C target given the 0.3 °C range.

Finally, we compare the temperature outcomes between the normal *IMAGE-450* scenario with the *IMAGE-450/zero* pathway that immediately reduces non-CO_2 emissions to zero in 2010. This shows the potential impact of completely phasing out of non-CO_2 emissions (if it would be possible to increase reduction potential by e.g. new technologies or lifestyle changes). Assuming an immediate phase-out of non-CO_2 GHG the 2100 temperature decreases by 0.8 °C compared to the *IMAGE-450* scenario, resulting in an increase of the global mean temperature of only 1 °C compared to pre-industrial levels. Thus, further reductions of non-CO_2 GHG increase the likelihood of reaching the 2 °C target and

Table 2
Pathway definitions used for climate experiments.

Pathway	CO_2	Non-CO_2
IMAGE-base	IMAGE baseline	IMAGE baseline
IMAGE-base/450-IMAGE	IMAGE baseline	IMAGE 450
IMAGE-450/450-X (x-name model)	IMAGE 450	450 from the different models
IMAGE-450/Base-IMAGE	IMAGE 450	IMAGE baseline
IMAGE-450/zero	IMAGE 450	Zero non-CO_2 emissions
IMAGE-NoNeg450/base-IMAGE	IMAGE 450 restricting emissions to go negative	IMAGE Baseline
IMAGE-NoNeg450/450-IMAGE	IMAGE 450 restricting emissions to go negative	IMAGE 450

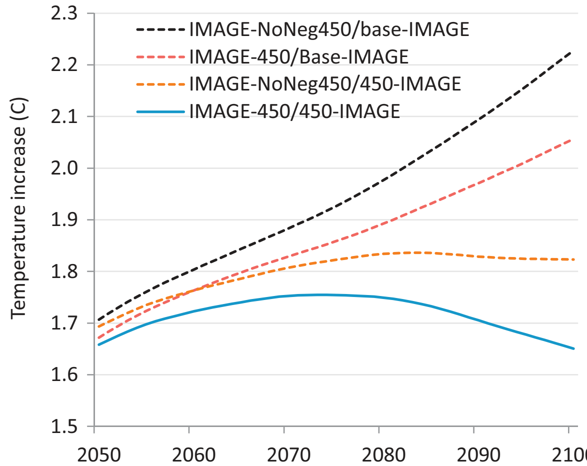

Fig. 14. Temperature increase for three experiments (IMAGE-450/Base, IMAGE-NoNeg450/Base and the IMAGE-NoNeg450/450) compared to the normal IMAGE-450/450-IMAGE scenario.

reduce the requirement of steep long-term CO_2 emission reductions from the energy system.

It should be noted that the temperature development toward the end of the century (and later) is determined by both the remaining non-CO_2 emissions and level of the negative CO_2 emissions (via bio-CCS). In order to illustrate this further, we compare the impact of the negative CO_2 emission on the global temperature increase with that of the non-CO_2 emission reductions (Fig. 14). Comparing the normal IMAGE *450* scenario with a scenario that excludes negative CO_2 emissions (IMAGE-NoNeg450/450-IMAGE) result in a difference of temperature of 0.2 °C. Interestingly, the impact of not considering non-CO_2 emission reductions in climate mitigation (IMAGE-450/Base-IMAGE) (0.4 °C) is stronger than the impact of excluding negative emissions (0.2 °C).

4. Conclusions

In this paper, we have assessed the sectoral mitigation effort of non-CO_2 emission sources (CH_4, N_2O and F-gases) in a scenario aiming for long-term stabilization of the global mean temperature of 2 °C compared to pre-industrial levels. To cover some of the uncertainty we have used a model comparison approach that includes results for six different integrated assessment models that have contributed to the set of scenarios assessed in the latest IPCC report. The questions we look into are: (1) What is the role of the remaining non-CO_2 emissions in deep mitigation scenarios? and (2) How do mitigation strategies compare across models for the reduction of non-CO_2 emissions at a sectoral level? The following conclusions can be drawn:

In scenarios with deep mitigation targets, non-CO_2 emissions could become a lion's share of remaining greenhouse gas emissions. In deep mitigation scenarios CO_2 emissions tend to be reduced to negative numbers, by using bio-energy in combination with CCS. At the same time, reductions of non-CO_2 gases are assumed to be constrained, particularly in the land-use sectors. Interestingly, this implies that in all models looked at, non-CO_2 emissions become increasingly important over time in terms of the remaining share in total emissions and that they are compensated by strong reductions of CO_2 emissions from the energy system.

In general, the model results show that strong emission reductions for non-CO_2 gases can be achieved in the energy supply sector but much less in the agricultural sectors. The energy supply sector shows a consistent reduction potential of CH_4 across models for the *450* scenario of 87–99% compared to *Baseline* scenario in 2100. This reduction is driven by both end-of-pipe mitigation assumptions, such as gas flaring and CH_4 recovery, and reduced fossil fuel use. On the contrary, the livestock sector shows both less overall reduction potential and considerable differences between the models, resulting in a wider range of 9–43% reduction for CH_4 in 2100 and 26–45% for N_2O. This results first of emphasize the importance of mitigating energy sector non-CO_2 emissions in mitigation strategies. At the same time, for further emission reduction it would be important to assess options to reduce land-based non-CO_2 GHGs further.

At the levels of sectors considerable differences can be noted across the models. There are considerable differences between the models due to different baseline and abatement costs assumptions. Reductions from the livestock sector range for CH_4 emission from 9% to 43% and for N_2O from 26% to 45%. These differences can add up significantly, for example CH_4 emission reductions from the waste sector shows a range of 10–90% by 2100, which is approximately 3 Gt CO_2-equiv./yr difference. The same holds for CH_4 emission reductions from the livestock sector with a range of 9–43% by 2100, resulting in a difference of approximately 2 Gt CO_2-equiv./yr. Differences between model results with respect to the non-CO_2 emission projection and reductions are especially high for the F-gases, where the lowest and highest projections differ a factor 6.
Assumptions on abatement potential and costs for non-CO_2 greenhouse gases are critically important in reaching low temperature targets. Overall, the non-CO_2 emission reductions for the 450 scenario differ between 46% and 72% compared to *Baseline* in 2100 across the different models. Around 0.3 °C can be attributed to this uncertainty for non-CO_2 mitigation potential. Furthermore, assuming an immediate phase-out of non-CO_2 emissions would reduce climate change by 0.8 °C. Obviously, this is not possible according to current estimates of technology and lifestyle patterns, but the experiments emphasize the importance of better exploring the potential for further non-CO_2 emission reductions in all sectors.

This paper has derived information on mitigation strategies for non-CO_2 gases on the basis of the state of the art in integrated assessment models. We indicate that further improvement of the insight in non-CO_2 emissions abatement is a key step to (1) address the considerable uncertainties and (2) to explore additional mitigation options that address the remaining non-CO_2 emissions, specifically in the agricultural sectors.

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Appendix A. Overview participating models

Model	Model category	Abatement cost	Non-CO_2 implementation	Technological learning and inertia	CH_4 sectors	N_2O sectors	F-gas sectors
IMAGE	Recursive dynamic partial equilibrium model.	Carbon tax	US-EPA MAC curves based on Lucas et al. (2007)	Constant sectoral technological development factor and first-order estimates on future maximum attainable reduction potentials and costs.	Losses and leakages of energy production for coal, oil and gas; Landfills; domestic sewage; wetland rice production; enteric fermentation and animal waste.	Transport; adipic acid production; fertilizer use; animal waste and domestic sewage.	HFC, PFC and SF6. No specific sectors addressed, only total emissions.
GCAM	Recursive dynamic partial equilibrium model.	Carbon tax	US-EPA MAC curves based on DeAngelo et al. (2006)	No further technological change assumed for MACs.	Losses and leakages of energy production for coal, oil and gas; Landfills; domestic sewage; wetland rice production; enteric fermentation and animal waste.	Nitric and adipic acid production, fertilizer use, wastewater treatment, other sources.	HFC, PFC and SF6. Aluminum, Foams, Solvents, Fire Extinguishers, Semiconductors.
MESSAGE	Intertemporal optimization general equilibrium model.	Carbon tax	US-EPA MAC curves based on DeAngelo et al. (2006)	No further technological change assumed for MACs.	Losses and leakages of energy production for coal, oil and gas; Landfills; domestic sewage; wetland rice production; enteric fermentation and animal waste.	Nitric and adipic acid production, fertilizer use, other sources.	HFC (only modeled as HFC134-a equiv.), PFC and SF6. Refrigeration & Air conditioning, semiconductors, Magnesium, Aluminum, Foams, Solvents.
REMIND	Intertemporal optimization general equilibrium model.	Carbon tax	Baseline emissions source-based for energy sector, econometric estimate for waste, exogenous for others. MAC curves based on Lucas et al. (2007)	Time-dependent maximum attainable reduction potentials and costs.	By source, MACs: Fugitive emissions for coal, oil, gas; solid waste disposal on land, wastewater handling, waste incineration, other waste handling Exogenous baseline, MACs: Enteric fermentation, manure management, rice cultivation Fully exogenous, no MACs savanna burning, agricultural waste burning, forest fires, grassland fires, peat fires and decay of drained peatland.	By source, MACs: wastewater handling, waste incineration, other waste handling Exogenous baseline, MACs Transport; Adipic and nitric acid production; Manure management, direct soil emissions, manure in pasture/range/paddock, indirect N_2O from agriculture Fully exogenous, no MACs savanna burning, forest fires, grassland fires, peat fires and decay of drained peatland, forest fires-post burn decay	HFC, PFC and SF6. No specific sectors addressed, only total emissions. Exogenously implemented.
TIAM-ECN	Intertemporal optimization partial equilibrium model.	Carbon tax	MAC curves based on DeAngelo et al. (2006) and van Vuuren et al. (2007) [in line with Lucas et al. (2007)]	Exogenous learning rates for energy conversion technology.	Losses and leakages of energy; Landfills; domestic sewage; wetland rice production; enteric fermentation and animal waste.	Transport; adipic & nitric acid production; fertilizer use and other agricultural emissions.	No F-gases.
WITCH	Intertemporal optimization general equilibrium model.	Carbon tax	Baseline emissions sources: US-EPA (2005–2030) + growth rates from the IIASA-MESSAGE-B2 scenario (2030–2100) abatement cost sources: US-EPA MAC curves	The abatement shares associated to the MACs are multiplied by an exogenous Technical Progress factor linearly increasing by 1/7 every 5 years from 1 in 2005/2010, with an upper bound for the maximum abatement share fixed to 90%.	No specific sectors addressed, only total emissions.	No specific sectors addressed, only total emissions.	No specific sectors addressed, only total emissions. Distinction between Short-Lived Fluorinated (HFCs w/lifetime $<$ 100 years) and Long-Lived Fluorinated (HFCs w/lifetime $>$ 100 years, PFCs, SF6, NF3).

Appendix B. Sectoral definitions

Variable	Definition
Energy Supply	Emissions from Extraction and Distribution of Fossil Fuels (including fugitive Emissions, IPCC category 1B); Electricity production and distribution, district heating and other energy conversion (e.g. refineries, synfuel production)
Energy Demand	Emissions from all energy end-use sectors, including industry emissions
Land Use	Total anthropogenic emissions from land use
Land Use|Agricultural Waste Burning	Emissions from on-field Burning of Agricultural waste including Stubble, Straw etc. (IPCC category 4F)
Land Use|Forest Burning	Emissions from Deforestation
Land Use|Savannah Burning	Emissions from Savannah burning (IPCC category 4E)
Land Use|Agriculture	Emissions from Fertilizer use, Enteric Fermentation, manure management, Use of pesticides (IPCC categories 4A, 4B, 4C, 4D)
Land Use|Agriculture|Livestock	Emissions from agricultural livestock, including manure management
Land Use|Agriculture|Ricefields	Emissions from agricultural rice production
Land Use|Agriculture|Fertilizers	Emissions from fertilizer use
Solvents	Emissions from Solvent and other Product Use (IPCC Category 3)
Waste	Emissions from Landfills, wastewater treatment, human wastewater disposal and waste incineration (non-energy) (IPCC category 6)

Appendix C. Regional definitions

OECD90 = Includes the OECD 90 countries.

Australia, Austria, Belgium, Canada, Denmark, Fiji, Finland, France, French Polynesia, Germany, Greece, Guam, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Caledonia, New Zealand, Norway, Portugal, Samoa, Solomon Islands, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States of America, Vanuatu

REF = Countries from the Reforming Economies of Eastern Europe and the Former Soviet Union.

Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Malta, Poland, Republic of Moldova, Romania, Russian Federation, Slovakia, Slovenia, Tajikistan, TFYR Macedonia, Turkmenistan, Ukraine, Uzbekistan, Yugoslavia

ASIA = The region includes most Asian countries with the exception of the Middle East, Japan and Former Soviet Union states.

Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China, China Hong Kong SAR, China Macao SAR, Democratic People's Republic of Korea, East Timor, India, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Singapore, Sri Lanka, Taiwan, Thailand, Viet Nam

MAF = this region includes the countries of the Middle East and Africa.

Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Cote d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran (Islamic Republic of), Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Oman, Qatar, Reunion, Rwanda, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Syrian Arab Republic, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Yemen, Zambia, Zimbabwe

LAM = this region includes the countries of Latin America and the Caribbean.

Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela

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