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Multi-gas emission pathways for stabilizing greenhouse gas concentrations

M.G.J. den Elzen
Netherlands Environmental Assessment Agency (associated with RIVM), Bilthoven, The Netherlands
M. Meinshausen
Swiss Federal Institute of Technology (ETH Zurich), Zurich, Switzerland

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ABSTRACT: This paper presents a set of multi-gas emission pathways compatible with different levels of ambition of avoiding long-term climate change, expressed in terms of different greenhouse gas concentration stabilization levels, i.e. 400, 450, 500 and 550 ppm CO_2-equivalent. Also the effect of different assumptions on the resulting emission pathways, such as different baselines and technological improvement rates is analyzed. The emission pathways are derived using a methodology to calculate the cost-optimal implementation of available reduction options over the greenhouse gases, sources and regions. The emission pathway is determined iteratively to match prescribed climate targets of any level. Stabilizing greenhouse gas concentrations 450 CO_2 equivalent or lower requires global emissions to peak within the next two decades, followed by substantial overall reductions by as much as 30 to 50% in 2050 compared to 1990 levels. Further delay in peaking of the global emissions leads to delayed, but much steeper reductions. The total emission reductions strongly depend on the emissions growth in the baseline scenario and the further improvements of the abatement potential and reduction costs for all greenhouse gases in the future.

1 INTRODUCTION

The aim of this study is to develop multi-gas abatement pathways of the set of the six greenhouse gases covered under the Kyoto Protocol, i.e. CO_2, CH_4, N_2O, HFCs, PFCs and SF_6 that aim for stabilization of greenhouse gas concentrations at 400, 450, 500 and 550 ppm CO_2-equivalent, along with an analysis of their global reduction implications. Earlier analysis of emission pathways leading to climate stabilization focuses mainly on CO_2 only. Reducing non-CO_2 emissions can have important advantages in terms of avoiding climate impacts (Hansen et al. 2000; Meinshausen et al. 2004). Recent studies exploring the impacts of including non-CO_2 gases in the analysis of the Kyoto Protocol have found that major cost reductions can initially be obtained through the relatively cheap abatement options for some of the non-CO_2 gases and the increase in flexibility (Hayhoe et al. 1999; Reilly et al. 1999). Multi-gas studies on long-term stabilization targets also show considerably lower costs for a multi-gas strategy than under a CO_2-only strategy (e.g., Manne and Richels 2001; van Vuuren et al. 2003; 2004b). However, the time-dependent share of non-CO_2 gases depends on the use of 100-year Global Warming Potentials (GWPs) (e.g., van Vuuren et al. 2005). Under a multi-gas strategy using the 100-year GWPs, the contribution of the non-CO_2 gases in total reductions is very large early in the scenario period (50-60% in the first two decades (e.g., van Vuuren et al. 2003), although CO_2 remains by far the most important human-induced radiative forcing agent in the long term. Not using GWPs (but instead determining the substitution on the basis of cost-effectiveness in realizing a long-term target) implies that the primary focus of mitigation in the near-term rests on CO_2 (e.g., Manne and Richels 2001)

Here, we follow for the development of the multi-gas emission pathways a multi-gas strategy using GWPs based on a cost-optimal implementation of available reduction options over the greenhouse gases, sources and regions (e.g. van Vuuren et al. 2003). We focus emission pathways meeting the greenhouse gas concentration stabilization targets 400, 450, 500 and 550ppm CO_2-equivalent (taking into account the radiative forcing of all greenhouse gases, tropospheric ozone and aerosols), so as to achieve more certainty in reaching the EU 2°C target above pre-industrial levels. Den Elzen and Meinshausen (2005) have shown that 550ppm CO_2-eq. stabilization is unlikely to meet the 2°C target, whereas stabilization at 450 ppm CO_2-eq. or below is likely (probability of more than 60%) to meet the 2°C target, if the 90% uncertainty range for climate sensitivity is believed to be 1.5 to 4.5°C. For the lower concentration targets, we assume a certain overshooting (or peaking), i.e. concentrations may first increase to an 'overshooting' concentration level up to 480, 500 and 525ppm then decrease before stabilizing at 400, 450 and 500ppm CO_2-eq., respectively. This overshooting is partially reasoned by the already substantial present concentration levels and the attempt to avoid drastic sudden reductions in the presented emission pathways.

2 METHOD FOR DEVELOPING EMISSION PATHWAYS

In order to assess the emission implications of different stabilization levels, this study presents new multi-gas emission pathways for the scenario period, 2000-2400, derived by a method for a cost-effective mitigation of emissions. This method calculates the cost-optimal mixes of greenhouse gas emission reductions for a given global emission pathway. The emission pathway is determined iteratively to match prescribed climate targets of any level, as described in detail below. It should be kept in mind though that this approach does not derive cost-effective pathways over the whole scenario period per se, but focuses on a cost-effective split among different greenhouse gas reductions for given emission limitations on GWP-weighted and aggregated emissions. For example, based on the current model version with static cost assumptions, we cannot make definitive judgments on how a delay in global action will affect overall mitigation costs over time. However, the model framework surely accommodates an analysis of the existing policy framework with preset caps on GWP-weighted overall emissions under the assumption of cost-minimizing national strategies. The emissions that have been adapted to meet the pre-defined stabilization targets include those of the six Kyoto greenhouse gases, ozone precursors (VOC, CO and NO_x) and sulphur aerosols (SO_2).

For our method we used the policy decision support tool FAIR 2.0 in combination with another climate policy tool called SiMCaP.

The FAIR (Framework to Assess International Regimes for the differentiation of commitments) 2.0 model (www.mnp.nl/fair) aims to assess the environmental and abatement costs implications of regimes for differentiation of post-2012 commitments (den Elzen and Lucas 2003; 2005). For the calculation of the emission pathways, only the (multi-gas) abatement costs model of FAIR is used. This model distributes the difference between baseline and global emission pathway over the different regions, gases and sources following a least-cost approach, taking full advantage of the flexible Kyoto Mechanisms (emissions trading) (den Elzen et al. 2005). For this purpose, it makes use of (time-dependent) Marginal Abatement Cost (MAC) curves for the different regions, gases and sources as described below. The model also uses baseline scenarios, i.e. potential greenhouse gas emissions in the absence of climate policies, from the integrated assessment model IMAGE (IMAGE-team 2001) and the energy model, TIMER (van Vuuren et al. 2004a).

The SiMCaP ('Simple Model for Climate Policy Assessment') (www.simcap.org) pathfinder module makes use of an iterative procedure to find emission paths that correspond to a predefined arbitrary climate target. The global climate calculations make use of the simple climate model, MAGICC 4.1 (Wigley 2003). More specifically, the pathfinder module makes use of an iterative procedure to find emission paths that correspond to a predefined arbitrary climate target.

The integration of both models, the ‘FAIRSiMCaP’ 1.0 model, allows the strengths of both models to be combined to: (i) calculate the cost-optimal mixes of greenhouse gas reductions for a global emissions profile under a least costs approach (FAIR) and (ii) find the global emissions profile that is compatible with any arbitrary climate target (SiMCaP).

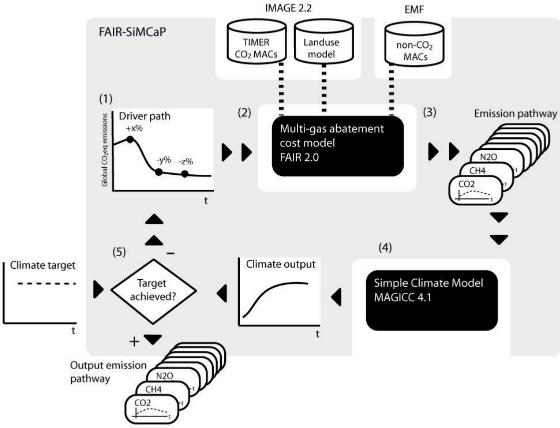

Figure 1. The FAIRSiMCaP model (den Elzen and Meinshausen 2005).

More specifically, the FAIRSiMCaP calculations consist of four steps (Figure 1):

1. Using the SiMCaP model to construct a parameterized global CO_2-equivalent emission pathway. This emission pathway is calculated using the emissions of the six Kyoto gases combined with the 100-year GWPs. One exception is formed by the LUCF (land use and land use change related) CO_2 emissions; this because no MAC curves are available for these, although the option of sink-related uptakes is parameterized in FAIR as one mitigation option. The LUCF CO_2 emissions are described by the baseline scenario. Up to 2012, the pathway incorporates the implementation of the Annex I Kyoto Protocol targets for the Annex I regions excluding Australia and the USA.

2. The abatement costs model of FAIR is used to allocate the global emissions reduction objective (except LUCF CO_2 emissions): i.e. the difference between the baseline emissions and the global CO_2-equivalent emission pathway (see Figure 2) of step 1. Here a least-cost approach (cost-optimal allocation of reduction measures) is used for five year intervals over the 2000-2100 period for the six Kyoto greenhouse gases; 100-year GWP indices, different numbers of sources (e.g. for CO_2: 12; CH_4: 9; N_2O: 7) and seventeen world regions are employed, taking full advantage of the flexible Kyoto Mechanisms. Figure 2 shows the contribution of the different greenhouse gases in the global emissions reduction to, in this case, reach the 450ppm CO_2-eq. concentration level. The figure clearly shows that up to 2025, there are potentially large incentives for sinks and non-CO_2 abatement options (cheap options), so that the non-CO_2 reductions and sinks form a relatively large share in the total reductions. Later in the scenario period, the focus is more on the CO_2 reductions, and the contribution of most gases becomes more proportional to their share in baseline emissions. The emission pathways of the different greenhouse gases can then be constructed in this way.

Different sets of baseline- and time-dependent MAC curves for different emission sources are used here. For energy- and industry-related CO_2 emissions, the impulse response curves calculated with the energy model, TIMER 1.0 are used (van Vuuren et al. 2004a). This energy model calculates regional energy consumption, energy-efficiency improvements, fuel substitution, and the supply and trade of fossil fuels and renewable energy technologies, as well as carbon capture and storage. A carbon tax on fossil fuels is imposed for constructing the TIMER MAC curves to induce emission abatements, taking into account technological developments, learning effects and system inertia. The response curves were calculated assuming a linear increase of the permit price, and in this way, they do take into account (as a first-order approximation) the time pathway of earlier abatement, although not dynamically. For CO_2 sinks the MAC curves of the IMAGE model are used (van Vuuren et al. 2004b).

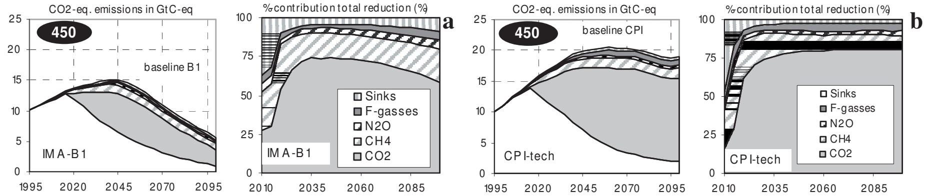

Figure 2. Contribution of greenhouse gases in total emission reductions for the emission pathways for a stabilization at 450ppm CO_2-eq. concentration of the IMA-B1 (a) and CPI+tech scenario (b).

For non-CO_2, exogenously determined MAC curves from EMF-21 are used. This set is based on detailed abatement options, and includes curves for CH_4 and N_2O emissions from both energy- and industry-related emissions and some agricultural sources, as well as abatement options for the halocarbons (Table 1). The non-CO_2 MAC curves were constructed mainly for 2010, over a limited costs range of 0 to 200 US$/tCeq, and do not include technological improvements in time. Furthermore, the curves were constructed against a hypothetical baseline that assumes that no measures are taken in the absence of climate policy ('frozen emission factors'). Therefore, the non-CO_2 MAC curves have been corrected for measures already applied under our baseline scenario. Finally, increases are assumed in the abatement potentials due to the technology process and removal of implementation barriers. Here, a relatively conservative value of an increasing potential (at constant costs) due to technology progress and removal of implementation barriers for all other non-CO_2 MAC curves of 0.4% per year is assumed (Graus et al. 2004). There are still some remaining agricultural emission sources of CH_4 and N_2O, where no MAC curves were available (e.g. for N_2O agricultural waste burning, indirect fertilizer, animal waste and domestic sewage). Here, we assumed a linear reduction towards a maximum of 35% compared to baseline levels within a period of 30 years. In addition to the end-of-pipe measures, as summarized in the non-CO_2 MAC curves, CH_4 and N_2O emissions can also be reduced by systemic changes in the energy system (for instance, the reduction in the use of coal and/or gas reduce CH_4 emissions during production and transport of these fuels). As seen in van Vuuren et al. (2004b) we account for these effects by a coupled analysis of the FAIR and TIMER models. However, the total impact of these indirect reductions is relatively very small and has therefore not been taken into account here.

Finally, it should be noted that the assumptions about the rate at which the MAC curves evolve in time, is highly uncertain. It will be crucial to extend research on non-CO_2 emission reduction options beyond 2010 and on the sources, where no MAC curves are available.

3. The greenhouse gas concentrations, and global temperature and sea level rise are calculated using the simple climate model MAGICC 4.1.

4. Within the iterative procedure of the SiMCaP model, the parameterizations of the CO_2-equivalent emission pathway (step 1) are optimized (repeat step 1, 2 and 3) until the climate output and the prescribed target show sufficient matches.

These emission pathways have been developed for three underlying baseline scenarios:

1. CPI: the Common POLES IMAGE (CPI) baseline (van Vuuren et al. 2003; 2004b) scenario with the fixed LUCF CO_2 emissions of this scenario (Figure 5) and with the default MAC curves. The CPI scenario assumes a continued process of globalization, medium technology development and a strong dependence on fossil fuels. This corresponds to a medium-level emissions scenario when compared to the IPCC SRES emissions scenarios (Figure 2b).

2. CPI+tech: the CPI baseline scenario with the fixed LUCF CO_2 emissions of the IMA-B1 scenario (less deforestation) and with MAC curves assuming additional technological improvements.

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As current studies (e.g., Nakicenovic and Riahi 2003; Azar et al. 2004) indicate that more technological improvements in abatement potential and reduction costs are possible than assumed in the CPI baseline, we have analyzed the impact of more optimistic assumptions. For this, we made the following, rather arbitrary, assumptions: (1) for the MAC curves of energy CO_2, an additional technological improvement factor of 0.2%/year; (2) for the MAC curves of the non-CO_2 gases, an improvement rate of 1%/year instead of 0.2%/year and (3) for the sources of non-CO_2 gases, where no MAC curves were available, a maximum reduction of 80% instead of 30% in 2040.

3. IMA-B1: the IMAGE IPCC SRES B1 baseline (IMAGE-team 2001) scenario with the fixed LUCF CO_2 emissions of this scenario and the default MAC curves. This scenario assumes continuing globalisation and economic growth, and a focus on the social and environmental aspects of life.

Table 1. Source of information on MAC curves (adapted from van Vuuren et al. 2004b).

Emission category (Non-CO_2 gases)	Source of information on marginal abatement costs	Reduction potential of sources (2010)	Assumed annual increase of potential
CH_4 and N_2O from agricultural sources	DeAngelo et al. (2004) and Graus et al. (2004) for development of potential in 2010-2050 period	N_2O soil: 7% CH_4 animals: 7% CH_4 rice: 20%* CH_4 manure : 17%	3.9% up to 2050 3.9% up to 2050 1.5% up to 2050 2.4% up to 2050; 0.4% 2050-2100 [x]
CH_4 and N_2O from industry and energy sources	Delhotal et al. (2004)	CH_4 total : 65% N_2O: 90-95%	0.4% [x]
CH_4 and N_2O emissions (no MAC curves available)	Den Elzen and Meinshausen (2005)	Maximum reduction of 35% in 2040 [x x]	0.4% [x]
Halocarbons	Schaefer et al. (2004); Den Elzen and Meinshausen (2005)	2010: around 40% 2100: 95% in 2100 [vv]	
Emission category (CO_2)	**Source of information on marginal abatement costs**	**Reduction potential of main sources**	**Assumed annual increase of potential**
CO_2 from energy use and production	Time-dependent MACs (van Vuuren et al. 2004a) [vvv]	2010: Around 50% 2100: Around 80%	- [x]
Sinks	Based on IMAGE calculations	Kyoto Protocol	Potential increases to 400 MtC/yr in 2050

* In DeAngelo et al. (2004) a reduction of 38% is given. This number has been scaled down for 2010 on the basis of Graus et al. (2004); [v] Van Vuuren et al. (2004b) assumed no reductions. [v v] Van Vuuren et al. assumed a 0.4% annual increase; [vvv] Van Vuuren et al. assumed a time-dependent MACs iterating between FAIR and TIMER; [x] CPI+tech baseline scenario assumes a 2.0% annual increase of potential for non-CO_2 emissions, and a 0.2% additional technological improvement for energy-related CO_2 emissions; [x x] CPI + tech baseline scenario assumes a 80% reduction in 2040.

3 MULTI-GAS EMISSION PATHWAYS

This section presents various global multi-gas emission pathways to bring about stabilization at CO_2-equivalence levels of 550ppm (3.65W/m^2), 500ppm (3.14W/m^2), 450ppm (2.58W/m^2) and 400ppm (1.95W/m^2). The latter three pathways are assumed to peak at 525ppm (3.40W/m^2), 500ppm (3.14W/m^2) and 480ppm (2.92W/m^2) before they return to their ultimate stabilization levels around 2150 (Figures 3). The emissions of the pathways for stabilization at 550, 450 and 400ppm CO_2-eq. concentrations are illustrated in Figure 4. Clearly, there are different pathways that can lead to the ultimate stabilization level. Here, we assume that the global emission reduction rates should not exceed an annual reduction of 2.5%/year for all default pathways (at least not over longer time periods). The reason is that a faster reduction might be difficult to achieve given the inertia in the energy production system: electrical power plants, for instance, have a technical lifetime of 30 years or more. Fast reduction rates would require early replacement of existing fossil-fuel-based capital stock, which may be associated with large costs. A maximum rate of 2%/year is hardly exceeded for the majority of the post-SRES mitigation scenarios, apart from some lower stabilization scenarios. As a result of this assumed condition the departure from baseline emissions, reduction takes place relatively early, and global emissions peak around 2015-2020. For all stabilization pathways, the global reduction rates remain below 2.5%/year for the whole scenario period, except for the pathways at 400ppm CO_2-eq., with maximum reduction rates of 2.5-3%/year over 20 years. A further delay in peaking of global emissions in 10 years doubles maximum reduction rates to about 5% per year, and very likely leads to high costs (den Elzen and Meinshausen 2005).

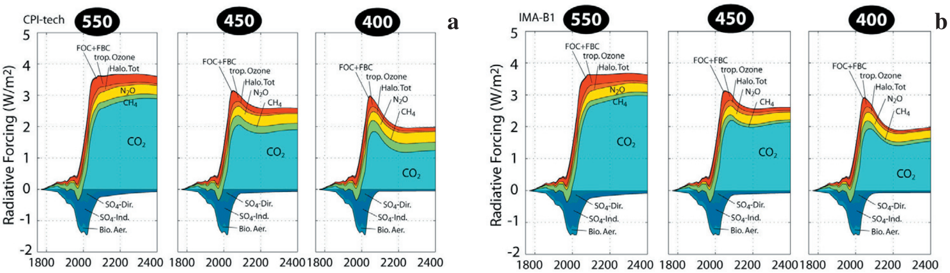

Figure 3. The contribution to net radiative forcing by the different forcing agents under the three default emission pathways for a stabilization at 550, 450 and 400 ppm CO_2-equivalent concentration after peaking at 500 and 475 ppm, respectively for the CPI+tech (a) and the B1 scenario (b). The upper line of the stacked area graph represents net human-induced radiative forcing. The net cooling due to the direct and indirect effect of SOx aerosols and aerosols from biomass burning is depicted by the lower negative boundary, on top of which the positive forcing contributions are stacked by CO_2, CH_4, N_2O, fluorinated gases (including the cooling effect due to stratospheric ozone depletion), tropospheric ozone and the combined effect of fossil organic and black carbon.

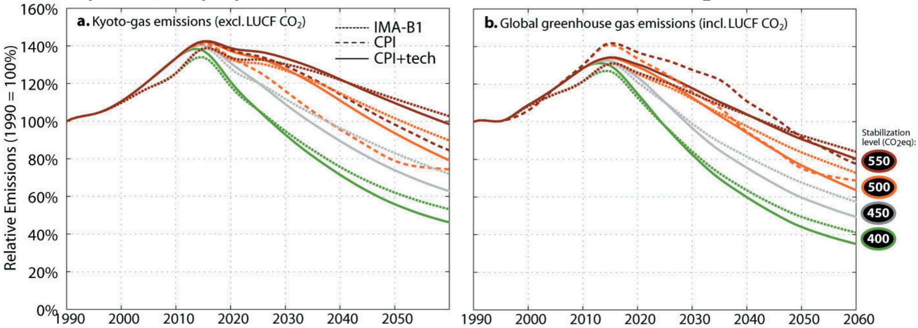

Figure 4. Global emissions excluding (a) and including (b) LUCF CO_2 emissions for the stabilization pathways at 550, 500, 450 and 400 ppm CO_2-eq. concentrations for the three scenarios.

Greenhouse gas emission reductions *excluding* and *including* LUCF CO_2 emissions are analyzed here (Figure 4). Given the assumption of these static LUCF scenarios with decreasing emissions, the quantified reduction requirements obviously differ, depending on whether the reduction requirements refer to all greenhouse gas emissions including LUCF CO_2 or Kyoto gas emissions (excl. LUCF CO_2). In general, emission pathways for the CPI+tech and B1 baselines have slightly higher greenhouse gas emissions (excl. LUCF CO_2) compared to the pathways under the CPI baseline for the same concentration target, because the LUCF CO_2 emissions for the CPI+tech and B1 scenario are assumed to be lower (see Figure 5).

By 2050, global greenhouse gas emissions (excl. LUCF CO_2) will have to be near 40-45% below 1990 levels for stabilization at 400ppm CO_2-eq. For higher stabilization levels, e.g. 450ppm CO_2-eq. stabilization, greenhouse gas emissions (excl. LUCF CO_2) may be higher, namely 15-25% below 1990 levels. For the CPI+tech scenario, the reductions for 400ppm (450ppm) CO_2-eq. are 50% (30%) in 2050 compared to 1990 levels. However, if LUCF CO_2 emissions do not decrease as rapidly as assumed here, but continue at presently high levels, an additional reduction of Kyoto-gas emissions (excl. LUCF CO_2) by around 10% are required up to 2050.

Global greenhouse gas emissions (incl. LUCF CO_2) will have to decrease to 5% to 10% below 1990 levels by 2050 for stabilization at 550ppm CO_2-eq. For stabilization at 500ppm CO_2-eq., Kyoto-gas emissions would need to be 15-25% below 1990 levels in 2050. The reduction requirements now become as high as 50-55% and 30-40% below 1990 levels in 2050 to reach the 400ppm and 450ppm CO_2-eq. target, respectively (instead of 40-45% and 15-25%, respectively). These reductions are about 10-15% higher than the reductions of the emissions excluding LUCF CO_2.

Figure 5 shows the emission pathways of the individual greenhouse gases for the stabilization pathways. The reductions for the fossil CO_2 emissions are in general somewhat higher than the reductions of all Kyoto gas emissions, as we assume less abatement potential for the non-CO_2 gases in particular from agricultural sources. The reduction requirements for the fossil CO_2 emissions are the highest for the CPI scenario, as this scenario assumes highest LUCF CO2 emissions.

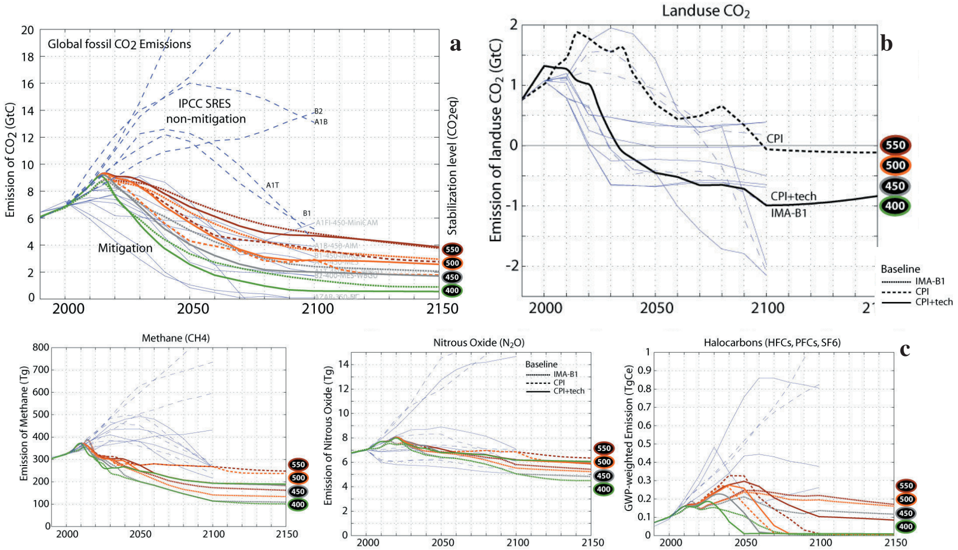

Figure 5. Global fossil CO_2 emissions (a), land-use CO_2 emissions (b) and methane, nitrous oxide and halocarbon emissions (c). For comparison, the emission implications of the IPCC-SRES non-mitigation scenarios (grey dotted lines) and a range of SRES mitigation scenario (grey solid lines) are also plotted.

4 CONCLUSIONS

This study describes a method to derive multi-gas pathways that closely reflects the existing international framework of pre-set caps on aggregated emissions and individual cost-optimizing actors. Thus, cost-optimal mixes of greenhouse gases reductions are derived for a given global emission pathway. The presented emission pathways stabilize long-term CO_2-equivalent concentration at 550, 500, 450 and 400 ppm. Here, we follow a ‘peaking strategy’, allowing concentrations to peak before stabilizing. In order to meet the EU 2°C climate target with more than 60% certainty, greenhouse gas concentrations need to stabilize at 450 (400) ppm CO_2-equivalent. This requires global emissions to peak before 2015-2020 in order to avoid global reduction rates exceeding more than 2.5%/year, followed by substantial overall reductions by as much as 50% (30%) under the CPI scenario (excl. LUCF CO_2 emissions) in 2050 compared to 1990 levels. The reduction requirements become as high as 35-55% below 1990 levels in 2050 for all greenhouse gas emissions (incl. LUCF CO_2). This study shows that the non-CO_2 gasses contribution to total reduction declines under stringent targets. Improving knowledge on how future reduction potential for non-CO_2 gasses could develop is in this context a crucial research question.

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