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Long-term marginal abatement cost curves of non-CO_2 greenhouse gases

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ABSTRACT

This study presents a new comprehensive set of long-term Marginal Abatement Cost (MAC) curves of all major non-CO_2 greenhouse gas emission sources. The work builds on existing short-term MAC curve datasets and recent literature on individual mitigation measures. The new MAC curves include current technology and costs information as well as estimates of technology development and removal of implementation barriers to capture long-term dynamics. Compared to earlier work, we find a higher projected maximum reduction potential (MRP) of nitrous oxide (N_2O) and a lower MRP of methane (CH_4). The combined MRP for all non-CO_2 gases is similar but has been extended to also capture mitigation measures that can be realized at higher implementation costs. When applying the new MAC curves in a cost-optimal, integrated assessment model-based 2.6 W/m^2 scenario, the total non-CO_2 mitigation is projected to be 10.9 Mt CO_2 equivalents in 2050 (i.e. 58% reduction compared to baseline emissions) and 15.6 Mt CO_2equivalents in 2100 (i.e. a 71% reduction). In applying the new MAC curves, we account for inertia in thline implementation speed of mitigation measures. Although this does not strongly impact results in an optimal strategy, it means that the contribution of non-CO_2 mitigation could be more limited if ambitious climate policy is delayed.

1. Introduction

It is widely recognized in climate policy research that worldwide mitigation of non-CO_2 greenhouse gases (GHGs) considerably reduces the overall costs of climate policy and extends the window of opportunity for aggressive cuts to global CO_2 emissions (Clarke et al., 2014; Hansen et al., 2000; Rao and Riahi, 2006; van Vuuren et al., 2006; Weyant et al., 2006). However, the exact role of non-CO_2 mitigation is unclear, as a result of uncertainty in baseline emissions, mitigation strategies, and mitigation potential and associated costs of a multitude of emission sources. This uncertainty also has implications for the optimal timing and reduction of CO_2.

While intrinsic uncertainty in long-term projections of non-CO_2 emissions is inevitable, it can be minimized by continued research on source specific emission trends and mitigation measures. Such work can function as a basis for the construction of region- and source-specific marginal abatement cost (MAC) curves, which are used in climate policy research and scenario development. Key inputs for the construction of the non-CO_2 MAC curves include estimates of emission reductions and costs of multiple measures combined, as well as estimates of technological progress and changes in implementation barriers over time.

Since they comprise such a broad knowledge base, non-CO_2 MAC curves are often used by integrated assessment models (IAMs) to determine emission reduction strategies and policy costs in comprehensive, long-term mitigation scenarios. Many IAMs, however, currently mainly rely on studies that are either relatively old (GECS, 2002; Graus et al., 2004; Lucas et al., 2007) or provide projections, however detailed, for the short term only (US-EPA, 2006, 2013), thus likely underestimate the potential for future technological progress. Therefore, there is a great need for detailed estimates of long-term, reduction potentials and costs based on recent insights.

This paper presents a new set of non-CO_2 MAC curves based on the most recent literature, and primarily meant to be used in models as a tool to develop and assess future climate policy scenarios. This study can be considered a follow-up to the work of Lucas et al. (2007) who summarized the construction of the non-CO_2 MAC curves 10 years ago. These MAC curves have been (and still are) extensively used by IAMs and in a wider climate policy context. The new set of MAC curves developed in this paper are an improvement to those of Lucas et al. in

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several ways: 1) they have been an updated with recent literature, where possible with a better coverage of high-cost mitigation options (up to 4000 \$/tC); 2) they have more consistent corrections for baseline emission reductions (e.g. from measures that have net zero cost or are associated with yield improvements); 3) they represent more consistent long-term potential across different global regions; 4) they better represent inertia in the implementation speed of non-CO_2 emission reduction.

The newly developed MAC curves cover more than 90% of the non-CO_2 GHG emissions. For each of the emission sources, the goal has been to use the most complete data source on mitigation options suitable for long-term projections. Furthermore, assumptions on long-term changes were added, such as potential overlap of measures, future technological learning, implementation barriers and limitations in implementation speed (inertia). For all the agricultural emission sources, we used a bottom-up approach (i.e. building MAC curves based on individual mitigation measures rather than making use of an external dataset), as consistent MAC data was lacking.

In order to assess the possible implications of the MAC assumptions in terms of plausible future non-CO_2 mitigation strategies and policy costs, the MAC curves have been implemented in the IMAGE 3.0 integrated assessment model (IAM) framework (Stehfest et al., 2014), and applied in the construction of ambitious, least-cost mitigation scenarios. The model provides a global, economy-wide climate policy context (e.g. economic developments, emission activities, policy ambitions, inertia in policy implementation and CO_2 mitigation options) that is used in conjunction with the new MAC curves.

In this paper, we present 1) a description of the datasets, additional literature and methodological steps in constructing the source specific, non-CO_2 MAC curves 2) an assessment of the MAC curves in the IMAGE 3.0 framework, including an analysis of medium and long-term policy costs and emission implications in an ambitious mitigation scenario, and 3) a sensitivity analysis of the implementation speed (or inertia) and timing of mitigation measures. The MAC curves are publicly available and can be found as a "Data-in-brief" file in the supplement.

2. Methods

This section describes the method used for constructing the new MAC curves. More specifically we discuss: 1) the coverage of global non-CO_2 emissions by the MAC curves described in this study 2) the construction of the MAC curves, and 3) the analytical steps taken to assess the MAC curves, in terms of mitigation potential, costs and implementation speed.

2.1. Emission coverage of the MAC curves

The MAC curves developed and described in this study have been made using the emission source categorization of the IMAGE 3.0 integrated assessment model framework (Stehfest et al., 2014). The non-CO_2 emission source categories in IMAGE represent all anthropogenic non-CO_2 GHGs (see Fig. 1 for the present day (2015) relative size of all sources, and section S1 in the supplement for the background data and the source-specific emissions in 2015 and 2100 in the no-climate policy baseline SSP2 (Van Vuuren et al., 2017)). The MAC curves provided in this study cover 91% of the present day non-CO_2 GHG emissions and are categorized using the same emission categories as used in Lucas et al. (2007). Several smaller emission sources not covered in the study (light-shaded in Fig. 1) are nitrous oxide (N_2O) and methane (CH_4) emissions from: 1) land clearing for agricultural extension (biomass burning and savannah burning), 2) combustion (traditional biomass use for heating and cooking and transportation fuels), 3) agricultural waste burning, and 4) industry emissions (mainly iron and steel production and the chemical sector). The relative share of emissions from these sources is expected to decline in a baseline scenario from 9% now to less than 4% of the total non-CO_2 emissions in 2100 (see S1). This percentage is further reduced in mitigation scenarios, where several sources are reduced indirectly as a result of CO_2 mitigation action (e.g. biomass burning and fuel combustion). Moreover, CH_4 emissions from combustion in transportation can likely be fully abated at little cost (Hussain et al., 2015; Russo et al., 2009).

2.2. Method for constructing the MAC curves

2.2.1. General method

MAC curves represent the combined reduction potential of all relevant mitigation measures at specific marginal costs for a specific emission source and country or region. In order to be relevant for long term climate policy projections, they should account for future changes in reduction potential and costs, due to 1) technological learning and 2) removal of implementation barriers.

The MAC curves developed in this study are based on a combination of existing datasets and an assessment of individual mitigation options described in literature (See Table 1 for the main characteristics of the MAC curves). In this section, we describe the construction steps of the MAC curves based on individual mitigation measures. For this study, this has been fully applied to the MAC curves of the agricultural sectors, for which no suitable MAC curve database was available. For the other MAC curves, where long-term assumptions were lacking in the databases, this general method was used to extend the MAC curves. This implied adding new mitigation measures and assumptions on future technological learning and removal of implementation barriers.

2.2.1.1. Reduction potentials. The reduction potential (RP) (in %) of a single mitigation measure in year *t* and region *r* is determined by:

$$RP_{(t,r)} = TA_{(r)} * RE * IP_{(t)} * OVcorr_{(t,r)} \tag{1}$$

With (all in %): TA: Technical applicability, or part of the baseline covered by the measure. Is often 100%, but smaller if the measure is not always suitable or targets only a sub process (e.g. reducing leakage in gas transportation, but not in extraction). Values can also differ per region. RE: Reduction efficiency, or relative reduction of targeted emissions compared to a baseline case, averaged over multiple studies. IP: Implementation potential, increases in time due to increased technology diffusion and implementation and the removal of barriers. OVcorr: Correction for overlap. The assumption is that the least costly measures are implemented first. If a subsequent measure is applied next to one or more measures already in place, it can have a diminished benefit[1] . Note that this correction increases in time (lower value) as IP increases.

The Maximum Reduction Potential (MRP) (in %) in year *t* and region *r* is the combined effect of all measures (i.e. the resulting output of all other input elements in (1) and (2)):

$$MRP_{(t,r)} = (RP_{1\ (t,r)} + RP_{2\ (t,r)} + RP_{3\ (t,r)} \ldots + RP_{x\ (t,r)}) * TP_{(t)} - Bcorr_{(t,r)} \tag{2}$$

with (all in %): TP: Technological progress. Increase of the reduction potential in time, as a result of new or improved technologies. Bcorr: Correction for emission reductions that already take place in the baseline scenario, in each region. The assumption is here that these reductions come from the least cost measures (i.e. that part of the low cost side of the MAC curve is excluded for further reductions in a mitigation scenario).

The method is schematically represented in Fig. 2 for two measures - A and B - that reduce emissions of the same source. B represents a more costly measure, and is therefore assumed to be introduced after A. The points A' and B' represent the theoretical reduction potential of the measures, when the measures' full reduction (RE) is applied to the

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[1] If measure y is aimed at reducing the same baseline emissions as measure x that is already implemented, the OVcorr of y = 1-RP_x.

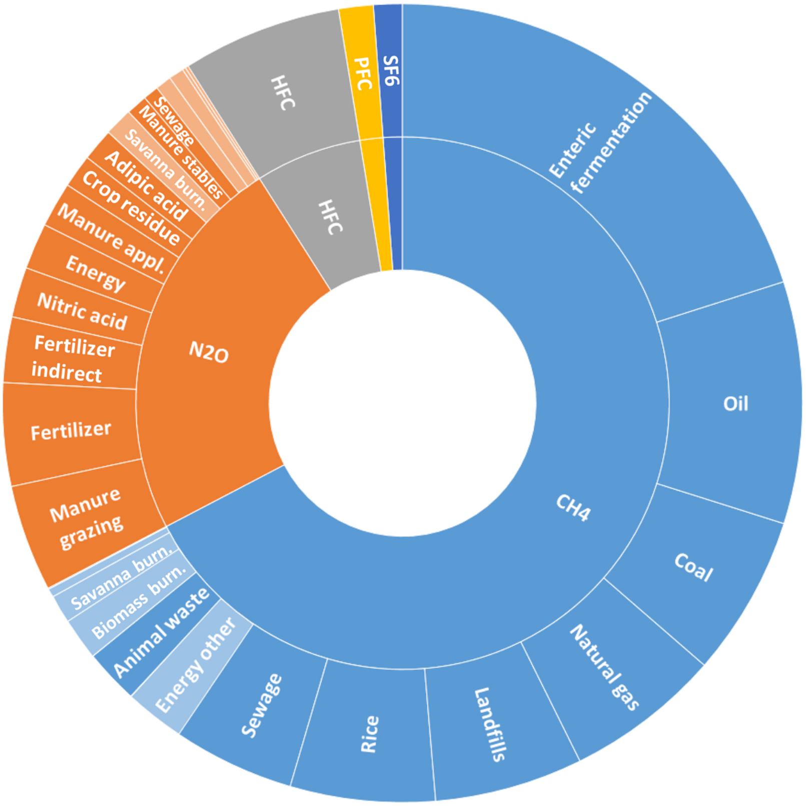

Fig. 1. Anthropogenic non-CO_2 GHG emissions by emission source in 2015, in share of total CO_2eq (based on AR4 100 yr Global Warming Potential (GWP). Source: IMAGE SSP2 (Stehfest et al., 2014; Van Vuuren et al., 2017) with calibrated CH_4 emissions from fossil energy sources based on GAINS (Höglund-Isaksson, 2017). No MAC curves have been developed for the light-shaded CH_4 and N_2O sources. See section S1 in the supplement for the absolute and relative sizes of the emission sources in 2015 and 2100 in SSP2 (main difference between years: relative share of HFC is 24% in 2100). Minor sources not shown in figure: Agricultural Waste Burning (N_2O, CH_4), Biological N-fixation (N_2O), Biomass Burning(N_2O), Industry (N_2O, CH_4).

relevant baseline emissions (TA). The points A and B represent the actual assumed reduction, which is lower than theoretically possible, because of implementation barriers (represented by IP < 100%) and, in the case of measure B, diminishing returns of the second measure (with OVcorr < 100%). The latter also leads to an increase of costs for B (ω), see description next section. Note further that A and B move closer to A' and B' in time due to an increasing IP. The two highlighted squares form the building blocks in the MAC curve (right). The last modification steps involve: 1) Technological progress (TP): "stretching" the MAC curve, which increases the MRP and decrease the marginal costs, and 2) Baseline correction (Bcorr): Lowering reduction potential of the MAC curve to make it compatible with a no climate policy baseline scenario, in case emission reductions already take place in the baseline case (e.g. from air quality measures or the use of fugitive CH_4 emissions as an energy source). In such a case, the assumption is that the emission reductions in the baseline result from the least-cost measures (making the MAC curve "shift towards the left").

2.2.1.2. Marginal costs. The assumption for the construction of the MAC curves is that the least costly measures are taken first. The best estimate of the costs of a specific measure was based on the average of cost estimates in literature and made regionally specific where data was available.

Marginal costs presented in literature need to be corrected for diminishing returns of measures, when multiple measures are implemented. The cost of a certain mitigation measure is based on the assumption that the measure can be fully applied to its emission source. When multiple measures are in place, the relative reduction per measure at a given cost decreases (or vice versa, the costs per reduced GHG increases). We corrected the cost of every subsequent (more expensive) measure, following:

$$\text{Cost new} = \text{Cost old} * 1/OVcorr \tag{3}$$

Note that ω in Fig. 2 represents Cost new – Cost old for measure B. One consequence of this approach is that more expensive measures that are implemented in a later stage (and have a relatively lower added reduction benefit) need a larger cost correction. Another result is that the marginal costs of individual measures are assumed to be higher when the implementation potential is higher, so towards the end of the century.

2.2.2. *Method by emission source*

Table 1 and section S9 in the supplement provide the main characteristics of the source-specific MAC curves, including the underlying datasets and included mitigation measures.

For Agricultural emission sources (*CH_4 from rice production, CH_4 from enteric fermentation in ruminants, CH_4 and N_2O from manure, N_2O from fertilizer*), we applied the bottom-up approach, building completely new MAC curves based on the most recent literature on mitigation measures using all of the MAC elements described in Section 2.2.1. See supplement for further details of this approach (S2), a list of all included and excluded measures, their costs and reduction efficiencies (S3) (which will also be discussed in a forthcoming paper (Nayak et al., 2018)) and the methodology to account for overlap and interaction between measures (S4).

The MAC curves for the fossil energy sources (*CH_4 from coal, oil and gas production*) were based on a dataset produced using the GAINS model (Höglund-Isaksson, 2012; 2017)(see S5 in the supplement). This dataset is consistent with energy supply and demand as in the IEA-WEO 2016 New Policies Scenario (IEA, 2016). The method of constructing these MACs is similar to the general method applied here. It has incorporated estimates from recent measurements of country-specific annual methane emissions, leading to a better explanation of historical discrepancies. The study assumed a linearly increasing implementation potential in time, leading to maximum implementation of the measures in 2020. Although the MAC curve dataset extends until the year 2100, it only includes the technical potential and costs of currently applied technologies, and can in that respect be considered relatively conservative (Höglund-Isaksson, 2012). Therefore, for the long term MAC curve, we included future technologies that are currently not in use, but

Table 1

Main characteristics non-CO_2 marginal abatement cost curves. Underlying datasets, included mitigation measures, emission factor affected by reduction, long-term mitigation assumptions, maximum reduction potentials (baseline independent, expressed in relative reductions compared to the source-specific, global average emission factors in 2015) and maximum reduction change / year (inertia).Abichou et al. (2016), Akiyama et al. (2010) Barcon et al. (2015), Basak (2015), Bates et al. (2009), Bell et al. (2010), Bylin et al. (2010), Dickie et al. (2014), Eagle et al. (2012), EC (2015), Eom et al. (2016), Eory et al. (2016), Feng et al. (2013), Frutos et al. (2017), Han et al. (2010), Harnisch et al. (2006), Henderson et al. (2015), Hinde et al. (2016), Hristov et al. (2013), Hui et al. (2010), Hulshof et al. (2012), IPCC/TEAP (2005), Jiao et al. (2006), Karakurt et al. (2012), Kinley et al. (2016), Launio et al. (2016), Lebrero et al. (2016), Lechtenböhmer and Dienst (2010), Li et al. (2014), Linquist et al. (2012), Lipsky (2014), Lopez et al. (2013), MacLeod et al. (2010), McKinsey (2010), Moran et al. (2008), Nalley et al. (2015), Nayak et al. (2015), Ndegwa et al. (2008), Nunotani et al. (2016), Park et al. (2008), Patel et al. (2016), Petersen et al. (2012), Ravikumar and Brandt (2017), Reid et al. (2014), Smith et al. (2008), Sun et al. (2017), Tariq et al. (2017), Thu et al. (2016), Torralbo et al. (2017), Towprayoon et al. (2005), Tyagi et al. (2010), Van Zijderveld et al. (2011), Wassman et al. (2000), Weiske and Michel (2007), Wu et al. (2017), Yang et al. (2012), Yu et al. (2004), Yue et al. (2005), Yusuf et al. (2012), Zhang et al. (2016) and Zhu et al. (2016).

	Dataset	Included mitigation measures	Additional assumptions	Emission factor metric	Maximum reduction potential 2050	Maximum reduction potential 2100	Inertia: Maximum reduction change / yr (# years max reduction) *
CH_4							
CH_4 - Coal production	GAINS (Höglund-Isaksson, 2012, 2017)	Pre-mine degasification, Oxidation of ventilation air methane (VAM)	In 2050: Oxidation of lean (up to 0.5%) VAM feasible, Abandoned mine CH_4 minimized In 2100: Post-mining emissions reduced by 50%	Emissions / Coal production	54%	79%	2.7% (20)
CH_4 - Oil production	GAINS (Höglund-Isaksson, 2012, 2017)	Recovery and utilization of vented gas, Reducing unintended leakage	In 2100: Small gas-to-liquid plants available for remote oil fields, monitoring of flares	Emissions / Oil production	80%	90%	5.3% (15)
CH_4 - Natural gas production	GAINS (Höglund-Isaksson, 2012, 2017)	Reduced leakage rates, Installation PE and PVC networks	In 2100: LDAR (infrared cameras) to promptly find and close leakages	Emissions / NG production	62%	80%	3.1% (20)
CH_4 - Landfills/Solid waste	(US-EPA, 2013)	Collection and flaring, LFG capture for energy use, Enhanced waste diversion (e.g., recycling, reuse).	2015-2100: Growth in reduction potential: 2% / 5 years, increased waste diversion and biological treatment.	Emissions / Capita	75%	90%	3.8% (20)
CH_4 - Sewage and wastewater	(US-EPA, 2013)	Anaerobic digestion and CH_4 collection, Wastewater treatment plants (WWTP) instead of latrines and disposal	2015-2100: Growth in reduction potential: 2% / 5 years	Emissions / Capita	62%	90%	3.1% (20)
CH_4 - Rice production	This study	Alternate flooding/drainage wetland rice, Direct wet seeding, Phosphogypsum and sulphate addition to inhibit methanogenesis, Composting rice straw compost	Technological progress: further reduction of remaining emissions: 10% in 2050, 20% in 2100	Emissions / Rice production	61%	77%	3.1% (20)
CH_4 - Enteric fermentation	This study	Genetic selection and breeding, Food supplements: nitrate and tannins, Grain processing, Improved health monitoring, Reduce herd size, Skipping the stocker phase	Technological progress: further reduction of remaining emissions: 10% in 2050, 20% in 2100	Emissions / Ruminants milk and meat production	41%	50%	4.3% (20)
CH_4 - Animal waste/manure	This study	Farm scale digesters, Decreased manure storage time, Improved manure storage covering, Improved housing systems and bedding, Manure acidification	Technological progress: further reduction of remaining emissions: 10% in 2050, 20% in 2100	Emissions / Livestock production	55%	71%	2.8% (20)
N_2O							
N_2O - Transport	GECS (2002), Lucas et al. (2007)	Low-N_2O catalytic converters for petrol cars	2015-2100: Growth in reduction potential: 2% / 5 years	Emissions / Light liquid fuel use in road transportation	85%	85%	4.3% (20)
N_2O - Adipic acid production	(US-EPA, 2013)	Thermal decomposition (potentially combined with catalyst)	2015-2100: Growth in reduction potential: 2% / 5 years	Emissions / Adipic acid production	100%	100%	10.0% (10)

(continued on next page)

Table 1 (*continued*)

N_2O - Nitric acid production	(US-EPA, 2013)	Catalytic decomposition, Thermal decomposition (potentially including reagent fuel)	2015-2100: Growth in reduction potential: 2% / 5 years	Emissions / Nitric acid production	90%	90%	9.0% (10)
N_2O - Fertilizer use	This study	Use of nitrification inhibitors, Optimizing fertilizer application, Spreader maintenance, Improved land manure application, Improved agronomy practices, Fertilizer free zone at field edges	Technological progress: further reduction of remaining emissions: 10% in 2050, 20% in 2100	Emissions / N-Fertilizer use	47%	64%	3.5% (10)
N_2O - Animal waste/Manure	This study	Reduced dietary protein, Decreased manure storage time, Improved manure storage covering, Improved housing systems and bedding	Technological progress: further reduction of remaining emissions: 10% in 2050, 20% in 2100	Emissions / Livestock production	47%	63%	2.4% (20)
N_2O - Domestic sewage	Lucas et al. (2007) and this study	N-removal at wastewater treatment plants, N-enriched wastewater as an alternative to fertilisers	2015-2100: Growth in reduction potential: 2% / 5 years	Emissions / Capita	50%	65%	2.5% (20)
F-gases							
HFCs - Refrigeration	Schwarz et al. (2011), this study	Substitution with zero GWP substances, Better sealed systems, Recovery after use		N.a. **	96%	96%	4.5% (20)
HFCs - Foams	Schwarz et al. (2011), this study	Substitution with zero GWP substances		N.a. **	100%	100%	4.5% (20)
HFCs - Production of HCFC-22 (HFC23 by-product)	(Lucas et al., 2007)	Thermal destruction		N.a. **	90%	98%	4.5% (20)
HFCs - Other	Schwarz et al. (2011), this study	Substitution with zero GWP substances, Better sealed systems, Recovery after use		N.a. **	97%	97%	4.5% (20)
PFCs - Aluminium production	(Lucas et al., 2007)	Point-Feed Prebake technology (PFPB)		N.a. **	80%	90%	4.0% (20)
PFCs - Semi-conductor production	(Ecofys, 2006)	Emission capture and (thermal) destruction		N.a. **	80%	99%	4.0% (20)
PFCs - Other sources PFCs	(Ecofys, 2006)	Substitution with zero GWP substances		N.a. **	80%	95%	4.0% (20)
SF_6 - Production of electrical equipment	(Lucas et al., 2007)	Improved recovery and recycling, Minimisation of leakage (detection and repair), Improved handling		N.a. **	80%	90%	4.0% (20)
SF_6- Use and decommissioning of elec. Eq.	(Lucas et al., 2007)	Improved recovery and recycling, Minimisation of leakage (detection and repair), Improved handling		N.a. **	80%	90%	4.0% (20)
SF_6 - Magnesium production	(Lucas et al., 2007)	Substitution with zero GWP substances		N.a. **	90%	90%	4.0% (20)
SF_6 - Other sources	(Lucas et al., 2007)	Improved recovery and recycling, Minimisation of leakage (detection and repair), Improved handling, Substitution with zero GWP substances		N.a. **	90%	100%	4.0% (20)

*In percentage points (i.e. percentage of the no climate policy baseline emissions). For the F-gases, one aggregated reduction potential per gas type is used to establish the maximum reduction change per year (for HFCs: 90%, for PFCs and SF6: 80%).
**F-gas reductions are defined in terms of reductions compared to a no-climate-policy baseline.

are likely candidates to considerably reduce future emissions (in terms of the general method in 2.2.1, we assumed an extended TA for coal production, added the RP of new technologies for oil).

For some sources, (*CH_4 from landfills/solid waste, CH_4 from sewage and wastewater, N_2O from adipic and nitric acid production, N_2O from transport, N_2O from Domestic sewage*), MACs curves were available, but mostly based on data up to 2030 (GECS, 2002; Lucas et al., 2007; US-EPA, 2013)). We have for this study, renewed the assumptions on technological progress (TP) beyond their final year, up to 2100, assumed to increase the reduction potential by 2% every 5 years, until the MRP was reached. The TP is in the lower part of the range found in the literature (Carrara and Marangoni, 2013). At CO_2eq prices between 500 $(2010)/tCeq and 4000 $(2010)/tCeq (exact values differ per source, depending on the cost estimate), the reduction potentials have been

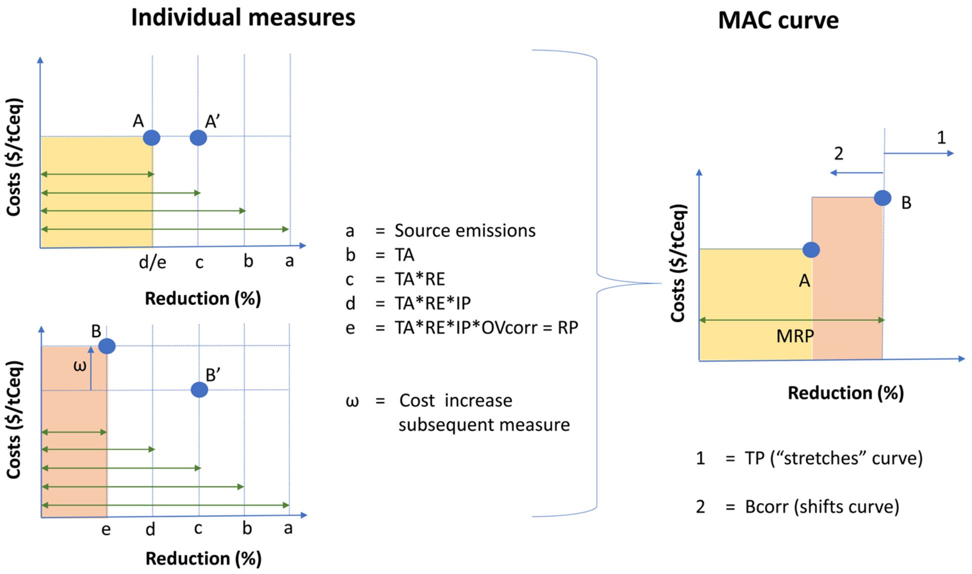

Fig. 2. General method for construction of the MAC curves. Schematic representation with two measures. Left graphs: differences between theoretical (A' and B') and actual (A and B) reduction potentials and costs, in relation to MAC components (*TA*: Technical applicability, *RE*: Reduction efficiency, IP: Implementation potential *OVcorr*: Correction for overlap between measures, only influences measure B, *RP*: Reduction potential). Right graph: MAC curve made up out of two measures (*TP*: Technological progress. *Bcorr*: Correction for emission reductions in the baseline scenario, *MRP*: Maximum reduction potential of measures combined).

linearly interpolated to the MRPs from literature, following the method applied by Lucas et al. (2007). For CH_4 from landfills/solid waste, CH_4 from sewage and wastewater and N_2O from transport, the future MRP could not be fully calculated based on individual measures due to incomplete data, and was estimated based on current best practices.

F-gas *(i.e. hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6))* emissions and emission reductions are endogenously calculated in a separate IMAGE module, as originally described in Ecofys (2006) and Lucas et al. (2007). For the update described here, where gas-specific data were available, the MAC curves were revised using the extensive study by Schwarz et al. (2011), thus relying more on measurements than extrapolation. This was possible for the largest F-gas sources (HFC foams, HFC refrigeration and HFC other) and generally led to higher reduction potentials. Removing an error in the old representation (which lowered the F-gas reductions to approximately 5% below MRP) also slightly affected the reduction potentials of PFCs and SF_6. In addition, HFC emissions have been calibrated up to the year 2012, following Velders et al. (2015), and based on detailed data reported by UN countries and recent observations of HFC atmospheric abundances. All F-gas updates described in this study have been included in the IMAGE SSP scenarios (Van Vuuren et al., 2017). Updates to the F-gas module were slightly less complex than described in the general method, as the mitigation measures are complementary (i.e. OVcorr = 100%).

2.2.3. *General characteristics of the MAC curves*

The MAC curves have been developed for the 26 world regions in the IMAGE 3.0 IAM framework (Stehfest et al., 2014). All MAC curves represent emission reductions resulting from measures that can be realized up to a GHG equivalent price of 4000 \$(2010)/tCeq (or 1091 \$(2010)/tCO_2eq, the maximum price that is applied in the IMAGE framework). Two sets of the MAC curves have been made publically available (see S8 in the supplement for description): 1) A baseline independent set (expressed in relative reductions compared to the source-specific, global average emission factors in 2015, and 2) A set that is consistent with the IMAGE SSP2 (Shared Socio-economic Pathway 2), a "middle-of-the-road" no-climate policy baseline scenario (Van Vuuren et al., 2017), by applying the factor *Bcorr*. For the F-gases, only the SSP2 based set is available, since for those sources no emission factors are used in the F-gas module (the emissions themselves generally equal the activity) and emissions are directly dependent on gross domestic product and population size. The F-gas MAC curves therefore represent relative reductions compared to a no-climate policy baseline (SSP2). Although large differences in emission factors exist between regions (e.g. much higher wastewater emissions in developing countries), it is likely that at very high carbon eq. prices, emission potentials converge toward the same (low) emission factor in different regions. Therefore, we assumed a convergence of regional reduction potentials at high carbon prices (i.e. relative reductions beyond what is currently realized regionally, cost the same for all regions), unless there was information about regional differences (e.g. physical differences in the CH_4 content of coal).

2.3. *Assessment mitigation potential, policy costs and inertia*

The MAC curves have been used as an input to IMAGE in conjunction with the socio-economic assumptions for SSP2 (Van Vuuren et al., 2017) with calibrated CH_4 emissions from fossil energy sources based on GAINS (Höglund-Isaksson, 2017). The assessment has been done with the FAIR module (Framework to Assess International Regimes for the differentiation of commitments) (Den Elzen et al., 2007) that calculates emission pathways up to the year 2100. The model has been used in two ways: 1) visualisation of the MACs by using prescribed carbon price profiles (shown in Fig. 3), and 2) a scenario exercise, where the MAC curves are used to determine cost-optimal mitigation strategies (shown in Section 4).

To visualize and summarize the net global mitigation potentials of the new MAC curves, they have been confronted with a range of stylized carbon price profiles (linear increase to the maximum price in 2030 and constant thereafter, see Fig. 3). Results are shown for 2050 and 2100, both for GHG specific and total non-CO_2 emissions. Reductions in these years are maximized for all carbon price levels, thus corresponding with the full regional MAC curve dataset, which is provided as a "Data in brief" document in the supplement. As a comparison, the same results were generated with the old set of MACs (Lucas et al., 2007).

The aim of the scenario exercise (Section 4) has been to understand plausible future non-CO_2 mitigation strategies and policy costs in a global, economy-wide climate policy context, given the current literature-based best estimate of future reduction potentials and costs (represented by the new MACs).For this assessment, the FAIR module generated a time-dependent carbon-price profile that led to cost-optimal timing of mitigation across the emission sources of all greenhouse gases (including CO_2). Cost-optimal here is the scenario with lowest overall implementation cost between now and 2100, when assuming a social discount rate of 5%. The role of non-CO_2 emission reduction in long-term mitigation scenarios has been analyzed by applying the new MAC curves in both a stringent (radiative forcing target of 2.6 W/m^2 in

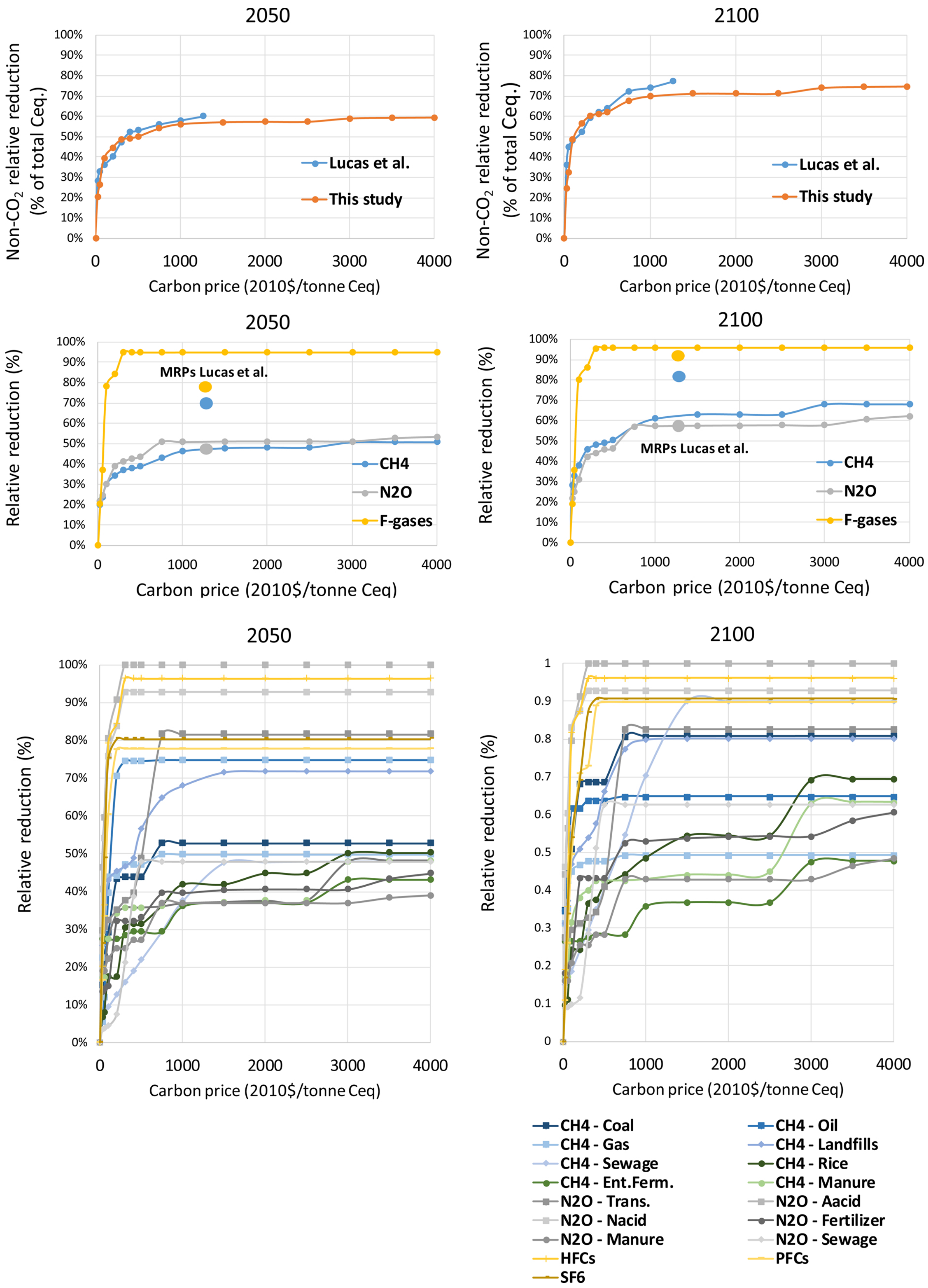

Fig. 3. Total global non-CO_2 mitigation potential in 2050 and 2100, all non-CO_2 MAC curves. Carbon prices on the y-axis refer to the maximum price of the stylized carbon price path (with a linear increase to the maximum price in 2030 and constant thereafter). Percentages represent relative reductions compared to present day emission factors. This study's results are compared to the old set of MACs (Lucas et al. (2007)). Upper two panels: Total relative non-CO_2 emission reductions (using AR4 100 yr Global Warming Potential and applying weighting based on the relative size of emission sources in SSP2) Middle two panels: GHG specific reduction potentials Lower two panels: Individual MAC curves (squared markers: energy emission sources, round markers: agriculture sources, diamond markets: waste, line markers: F-gases).

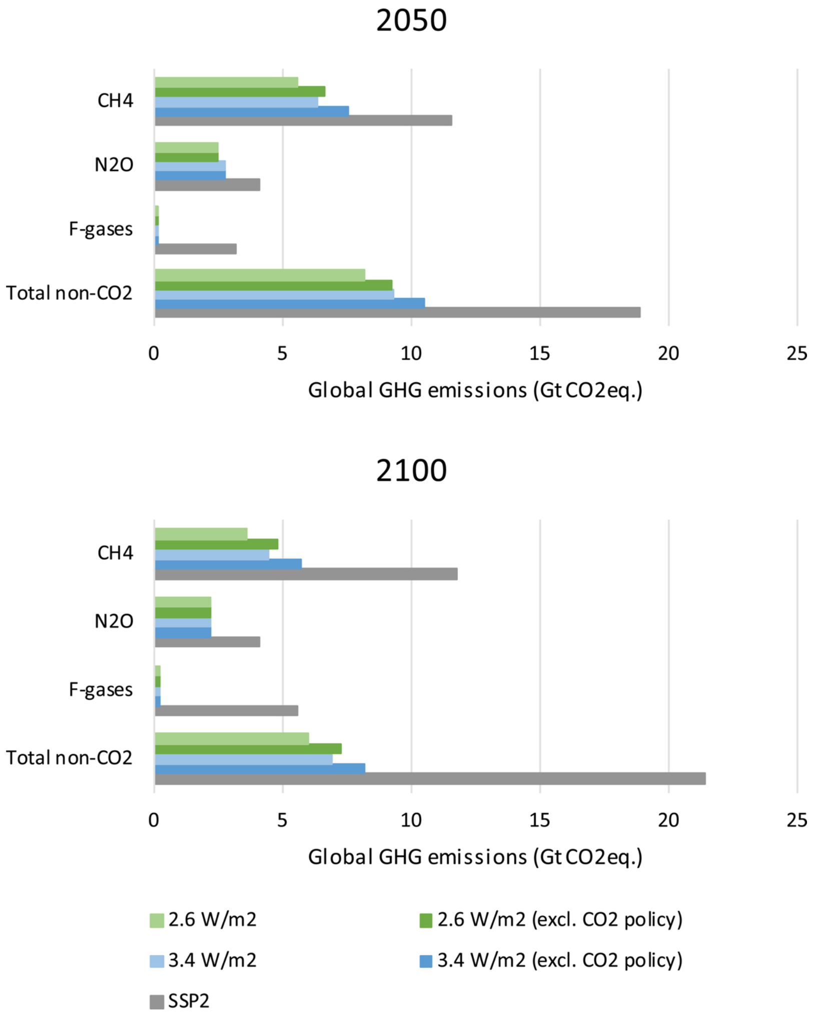

Fig. 4. Emissions in 2050 and 2100 for SSP2 at 2.6 W/m^2 and 3.4 W/m^2 climate targets. GHG emissions (gas specific and total, in Gt CO2eq, based on AR4 GWP100). As a benchmark is shown: 1) The SSP2 baseline 2) the 2.6 and 3.4 W/m^2 scenarios with non-CO$_2$ policy only. These two scenarios exclude the amount of CH$_4$ that is indirectly reduced from CO$_2$ mitigation, i.e. from decreased fossil fuel production.

2100) and moderate (3.4 W/m^2) climate policy scenario. The analysis covered policy costs, reduction potential per source, and the ratio between CO$_2$ and non-CO$_2$ mitigation. Policy costs here represent the direct implementation costs (which can be calculated as the area under the MAC curve(s)) and exclude secondary economic costs and benefits associated with direct expenditures.

2.3.1. Inertia in implementation speed of measures

In IMAGE, the yearly change in non-CO$_2$ reductions is restricted to prevent unrealistically fast implementation of reduction measures. This means that with a very high, sudden increase in the carbon price, the calculated emission reduction might be lower than the reduction level based on the MAC curve alone. This inertia in the implementation of measures is determined as follows. A maximum yearly increase in emission reduction compared to the previous year is determined (in percentage points), based on the minimum number of years in which the MRP estimated for 2050 can be achieved (more years equals stronger inertia, see last column in Table 1). As a default, it is assumed that the MRP of 2050 can be achieved in 20 years. We have deviated from the default for sources where 20 years was thought to be unrealistically long (for fertilizer application, adipic and nitric acid production and from oil production the minimum number of years was set to 10). Although it is very likely that some form of inertia will play a part in reality, the exact influence in practice is highly uncertain. To our knowledge, inertia in non-CO$_2$ mitigation has not been assessed in previous literature (unlike technological progress (Carrara and Marangoni, 2013; Lucas et al., 2007)), nor has it been implemented in other IAMs. Therefore, this study provides a sensitivity analysis to determine 1) the potential effect at different inertia levels (expressed in minimum number of years) on medium (2050) and long term (2100) reduction potentials, and 2) the inertia effect at different start years of mitigation.

3. Abatement potential

This section gives an overview of the updated non-CO$_2$ MAC curves. An extensive description of each of the emission sources, including the main characteristics of the updated MAC curves is provided in section S9 in the supplement. This also includes the underlying datasets, included measures, additional long-term assumptions and emission factor metric used to calculate emission reductions. See Table 1 for a summary of these results.

3.1. Assessment net mitigation potential and effect of update

Fig. 3 shows the global emission reductions of this study's MAC curves and those from Lucas et al. (2007), when confronting both sets with the stylized carbon tax scenarios. The new set of MAC curves represents comparable total non-CO$_2$ maximum reduction potentials (MRPs), notably at higher carbon prices (Note that the maximum price in Lucas et al. = 1000 \$(2000), which translates to 1266 \$(2010)). The overall MRPs in the new set are 59% in 2050 and 75% in 2100, compared to 60% and 77% in the old set, respectively. Although the aggregated GHG reduction potential is similar to Lucas et al., the gas specific MRPs are quite different. CH_4 reduction is projected to be much lower in the new set (in 2050, new: 51%, old: 67%, in 2100, new: 68%, old: 79%). Notably, projected MRPs are currently lower for enteric fermentation, rice, coal and natural gas production. N_2O reduction, however, is projected to be substantially higher. MRP, old vs new: in 2050: 44% vs 53%, in 2100: 52% vs 62%. (in 2050, new: 53%, old: 44%, in 2100, new: 62%, old: 52%), due to higher MRPs for fertilizer application, animal waste and domestic sewage. The MRPs for F-gases are higher in this study, mainly resulting from an erroneous representation of F-gas mitigation in an older version of IMAGE (in 2050, new: 95%, old: 74%, in 2100, new: 96%, old: 88%).

The main difference between the two sets are the projected policy costs, which are roughly twice as high in the new set at 4000 \$(2010)/tCeq in 2050 and three times as high in 2100 (not shown). This is the result of additional reduction measures that become cost-effective at higher carbon prices (between 1000 and 4000 \$(2010)/tCeq), notably from additional reduction potential in the agricultural sector. Due to an increase in costs when multiple measures are combined (from diminishing returns per measure), policy costs for these sources are relatively high. This effect is reinforced by a continuous, linear improvement of reduction potentials and technology diffusion for all major sources between 2050 and 2100.

4. Application of the MAC curves

4.1. Use in long-term mitigation scenarios

Fig. 4 shows the gas-specific and total non-CO_2 GHG emissions in the 2.6 W/m^2 and 3.4 W/m^2 scenarios in 2050 and 2100. As a comparison, the no-climate policy baseline SSP2 is provided. Also added are diagnostic versions of the two mitigation scenarios that exclude structural changes in the fossil fuel industry as a result of CO_2 mitigation. These scenarios indicate only the direct mitigation effect of non-CO_2 measures.

In the 2.6 W/m^2 scenario, the total non-CO_2 mitigation is projected to be 10.7 Gt CO_2eq in 2050 (57% of the total emissions) and 16.0 Gt CO_2eq (or 72%) in 2100. The differences with the 3.4 W/m^2 scenario are small, which has reductions of 51% and 68% in 2050 and 2100, respectively. In relative terms, the difference in CO_2 reduction between the two scenarios is larger (14% of the baseline CO_2 emissions compared to 4% for non-CO_2, not shown), due to the more costly CO_2 measures that take effect at higher carbon prices. A large share of the maximum non-CO_2 reduction potential is already reached at low carbon prices (e.g. 66% of the MRP at 100 \$(2010)/tCeq). Because of the large similarities between the two scenarios in terms of non-CO_2 emissions, this section will further focus on the 2.6 W/m^2 scenario.

CH_4 emission reduction is 6.0 and 8.2 Gt CO_2eq or 52% and 70% in 2050 and 2100, respectively. Note that this reduction includes mitigation of CH_4 by lowered fossil fuel production, indicated by the difference with the CO_2 policy excluding diagnostic scenario (in 2100: 1.3 Gt CO_2eq or 9% points). F-gases are almost completely mitigated in both years (3.0 Gt CO_2eq (or 95%) in 2050 and 5.3 Gt CO_2eq (or 96%) in 2100), indicating their large reduction potential at relatively low cost. N_2O mitigation remains relatively stable at 1.7 Gt CO_2eq (or 40%) in 2050 and 1.9 Gt CO_2eq (or 46%) in 2100.

The remaining non-CO_2 emissions in 2100 in the 2.6 W/m^2 scenario predominantly come from agricultural sources (82% of the total non-CO_2) emissions, which is in line with projections based on older MAC curves (Gernaat et al., 2015; Harmsen et al., 2018). The largest emission sources are CH_4 from enteric fermentation (33% of total non-CO_2) emissions followed by N_2O from fertilizer application (24%).

Table 2 provides a more detailed overview of the emission source-specific emission reductions and policy costs (i.e. direct implementation costs). It illustrates the relative importance of source-specific mitigation in a multi-GHG climate strategy, including CO_2 mitigation (see "Share in total GHG reduction", percentages equal absolute reductions divided by total GHG reduction). Similarly, this is shown for the policy costs ("Share in total policy costs"). Measures are more cost-effective than average if the share in reduction is larger than the share in policy costs, i.e. for values in the last two columns that are smaller than one. This is clearly the case for most non-CO_2 sources (exception: CH_4 from sewage), particularly in 2100 as the share of relatively expensive CO_2 measures increases towards the end of the century. Then, non-CO_2 mitigation measures are projected to be 50% less costly on average than average GHG prices. Fig. 5 presents a graphical representation of the policy cost per reduced GHG for each of the sources (x-axis), as well as a comparison of the sources on the basis of their share in the total GHG reduction (y-axis). Mitigation of HFCs and CH_4 from fossil fuel production can be considered very attractive, since both sources are projected to have the largest reduction potential in 2050 and 2100, at relatively low costs. Agriculture sources and landfills have a relatively large share in the total policy costs due to a combination of a medium reduction potential and medium costs per reduced CO_2-eq. CH_4 from sewage is one of the most expensive sources to reduce, as this would generally require large infrastructure investments to realize strong mitigation.

Next to its attractiveness from a cost-efficiency standpoint, non-CO_2 mitigation also relaxes the level of ambition required for short-term CO_2 mitigation. In section S6 in the supplement this is indicated by the remaining carbon budget for a 2.6 W/m^2 target when using this study's MAC curves in a cost-optimal mitigation scenario. Based on this first order estimate (note that the exact value heavily depends on the climate sensitivity), the carbon budget for the 2015–2100 period is projected to be 1070 GtCO_2. In the analysis, the level of non-CO_2 mitigation was varied and its effect on the carbon budget measured. As an extreme example, if no direct non-CO_2 GHG mitigation would take place (while taking into account non-CO_2 emissions indirectly reduced by CO_2 mitigation), the carbon budget would be almost half of that value (580 GtCO_2), which indicates the relevance of non-CO_2 mitigation. More realistically, for every 10% change in non-CO_2 mitigation in the 2.6 W/m^2 case, the global carbon budget changes by roughly 50 GtCO_2 (e.g. a carbon budget of 814 GtCO_2 if mitigation would be reduced by half). As a further diagnostic test, hypothetical cases have been analysed where one of the GHGs (CH_4, N_2O, F-gases) was not mitigated. This showed that mitigation (compared to no mitigation) of CH_4 and F-gases lead to the largest changes in the carbon budget (45% and 42% of the total change by all GHGs, respectively) followed by N_2O (13%).

4.2. Inertia sensitivity analysis

Fig. 6 shows the results of the sensitivity analysis (see section 2.3). The impact of inertia is illustrated by the total non-CO_2 reduction in 2050. The left panel shows the reduction at different levels of inertia (with less years equaling faster implementation/less inertia). For this analysis, it is assumed that mitigation starts in 2020 and that the maximum carbon price is reached in 2030. The right panel indicates the reduction at different start years of mitigation, but at equal inertia assumptions (20 years needed for maximum reduction). The closer this start year is to 2050, the more reduction can be limited by inertia effects.

Inertia has a limited effect on emission reduction in 2050. Only if inertia is high, i.e. implementation is slow (30 years), reduction is projected to be 7% lower than when implementation is fast (10 years) and inertia plays no role. Note that inertia will likely not limit the reduction potential in 2100 (See further analyses of inertia in the 2.6 W/m^2 case, S7 in the supplement).

The limiting role of inertia can, however, be substantial if climate action is delayed. Fig. 6 shows that a start year of mitigation in 2040

Table 2
Emission source-specific reductions and policy costs for the 2.6 W/m^2 scenario. Absolute reductions in Gt CO_2eq are based on the AR4 100 yr GWP.

	Absolute reduction (Gt CO_2 eq.)		Share in total GHG reduction (incl CO_2)		Policy costs (billion 2010$/yr)		Share in total policy costs (incl. CO_2)		Cost/reduction ratio **	
Year	*2050*	*2100*	*2050*	*2100*	*2050*	*2100*	*2050*	*2100*	*2050*	*2100*
CH_4 total *	**6.0 (4.9)**	**8.2 (6.9)**	**11.0% (9.0%)**	**8.5% (7.2%)**	**222**	**338**	**7.2%**	**4.1%**	**0.6**	**0.5**
CH_4 - Coal production *	1.1 (0.6)	2.1 (1.7)	2.0% (1.0%)	2.2% (1.8%)	18	44	0.6%	0.5%	0.3	0.2
CH4 - Oil production *	1.2 (1.0)	1.1 (0.8)	2.1% (1.9%)	1.1% (0.8%)	34	8	1.1%	0.09%	0.5	0.1
CH_4 - Natural gas production *	1.0 (0.6)	1.1 (0.5)	1.9% (1.1%)	1.2% (0.5%)	9	5	0.3%	0.07%	0.2	0.1
CH_4 - Landfills/Solid waste	0.69	0.62	1.3%	0.6%	40	36	1.3%	0.4%	1.0	0.7
CH_4 - Sewage and wastewater	0.34	0.76	0.6%	0.8%	39	119	1.3%	1.4%	2.1	1.8
CH_4 - Rice production	0.37	0.59	0.7%	0.6%	28	41	0.9%	0.5%	1.3	0.8
CH_4 - Enteric fermentation	1.20	1.72	2.2%	1.8%	51	78	1.7%	0.9%	0.8	0.5
CH_4 - Animal waste/manure	0.13	0.21	0.2%	0.2%	3	7	0.1%	0.1%	0.4	0.4
N_2O total	**1.67**	**1.91**	**3.1%**	**2.0%**	**72**	**104**	**2.3%**	**1.3%**	**0.8**	**0.6**
N_2O – Transport	0.08	0.09	0.1%	0.1%	6	8	0.2%	0.1%	1.4	1.0
N_2O - Adipic acid production	0.24	0.18	0.4%	0.2%	4	3	0.1%	0.04%	0.3	0.2
N_2O - Nitric acid production	0.36	0.36	0.7%	0.4%	6	4	0.2%	0.1%	0.3	0.1
N_2O - Fertilizer use	0.45	0.63	0.8%	0.7%	23	38	0.8%	0.5%	0.9	0.7
N_2O - Animal waste/Manure	0.49	0.59	0.9%	0.6%	29	46	0.9%	0.6%	1.0	0.9
N_2O - Domestic sewage	0.05	0.06	0.1%	0.1%	4	5	0.1%	0.1%	1.4	0.9
F-gases total	**3.01**	**5.34**	**5.5%**	**5.6%**	**63**	**114**	**2.0%**	**1.4%**	**0.4**	**0.2**
HFCs	2.75	5.02	5.0%	5.2%	59	104	1.9%	1.3%	0.4	0.2
PFCs	0.10	0.08	0.2%	0.1%	2	3	0.1%	0.03%	0.3	0.4
SF6	0.16	0.24	0.3%	0.3%	2	7	0.1%	0.1%	0.2	0.4
Total non-CO_2 *	**10.7 (9.6)**	**15.4 (14.2)**	**20% (18%)**	**16% (15%)**	**357**	**556**	**12%**	**7%**	**0.6**	**0.4**

[*] Values between brackets represent reductions if no CO_2 mitigation policy would take place. These policies indirectly reduce CH_4 emissions due to a reduction of fossil fuel production activities.

[**] Calculated as share in total GHG reduction costs / share in total GHG reduction. A value of less than one represents reduction costs (per tonne of CO_2eq) that are lower than average, which is the case for most non-CO_2 categories.

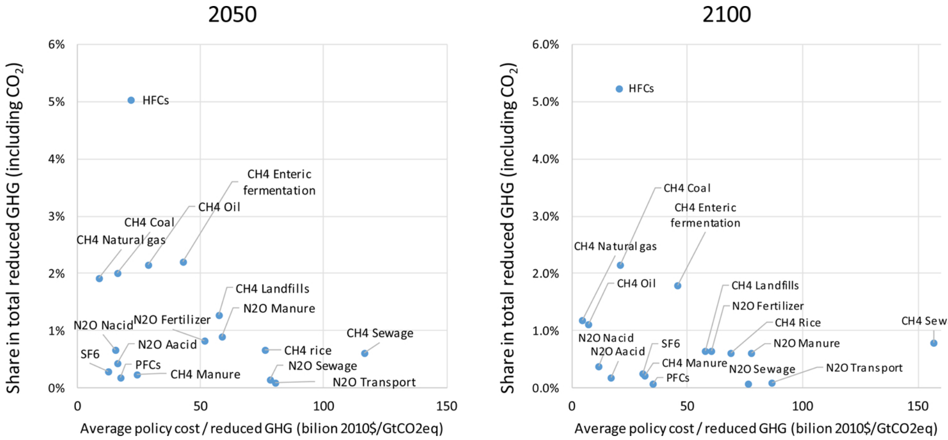

Fig. 5. Policy cost per reduced GHG vs. amount of reduced emissions - 2.6 W/m2 scenario.

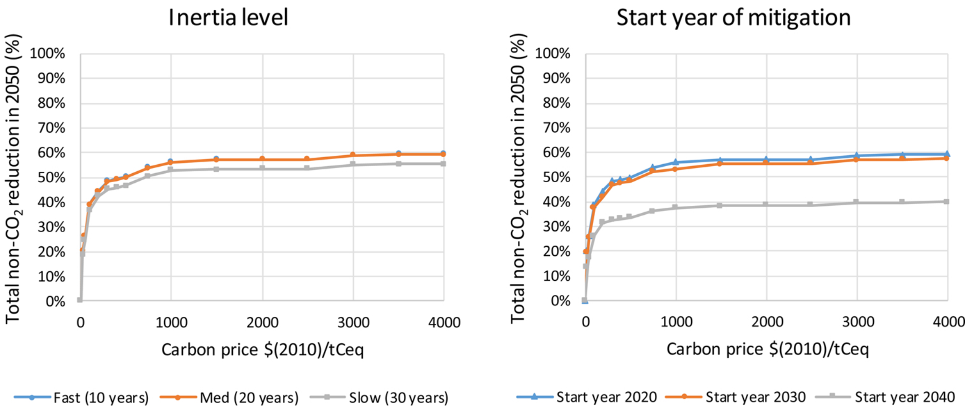

Fig. 6. Sensitivity analysis of inertia non-CO_2 mitigation. The total non-CO_2 reduction in 2050 is shown for three inertia levels (less years equals less inertia), and three start years of mitigation. Carbon prices refer to the maximum price of the stylized carbon price path (with a linear increase to the maximum price ten years after the start year).

(i.e. baseline emissions before that), ten years before the target year, leads to 33% lower reduction in 2050 compared to the case with a sufficiently early start year (2020). This could play a role if ambition to mitigate is raised near the target year, but also if climate strategies favor late mitigation. In a study with the IMAGE model, Van den Berg et al. (2015) showed that the use of an alternative climate metric that promotes late CH_4 mitigation can result in higher CH_4 emissions resulting from inertia. Note further that, although non-CO_2 emissions in 2100 in a stringent mitigation scenario are not affected by inertia, short-term inertia can affect the long term climate. For long-lived forcers (N_2O, PFCs, SF_6), higher, inertia-induced short-term emissions leads to a larger atmospheric burden, making longer-term climate targets more difficult to reach.

5. Discussion

Although MAC curves are used as a valuable tool in climate policy research, they have limitations that need to be addressed. Kesicki and Ekins (2012) identified several of these, which this study has aimed to minimize as follows:

- *MAC curves often represent a static snapshot* of one period of time, usually one year. This is obviated in this study by adding assumptions on intertemporal changes (e.g. technological learning, increasing implementation potential), which, however uncertain, help in capturing some potential long-term dynamics (note that this does not include a dynamic interaction with the full economy)
- *MAC curves can be inconsistent with a baseline scenario, by double counting of emission reduction.* The formulation of the baseline independent MAC curves and their implementation in IMAGE prevent double counting of reductions.
- *Underlying assumptions are often not laid out transparently.* These have been articulated in this paper as much as possible.
- *They fail to take account of the dynamic character of decarbonizing the economy. In addition, non-financial (e.g. environmental and health) costs are excluded.* Both these aspects can to some degree be addressed by the combined use of the MAC curves and an integrated assessment model (IAM), such as IMAGE. IAMs represent economic interactions, account for policy implications in a wider economic context (e.g. timing of mitigation and path dependency) and can assess a large range of environmental impacts.

Related to the latter point, Vogt-Schilb et al. (2014, 2018) pointed out that the shape of a future MAC curve (i.e. the future technology mix with associated reduction potentials and costs) is based on assumptions on investment choices earlier in time. They propose a representation of mitigation that accounts for this path-dependency. Theoretically, an alternative way to do this for non-CO_2 mitigation would be to explicitly model individual measures/technologies dynamically, as is often done for CO_2 mitigation. However, the required detailed knowledge for such a representation of all measures is found to be lacking in literature. Alternatively, the MAC curve approach in this study represents a "least uncertain" approximation of the future reduction potential and costs of one specified pre-determined set of mitigation measures, namely the set leading to the highest found MRPs. This required a range of assumptions that do cover dynamic processes (e.g. technological progress/ diffusion, inertia), which are uncertain, but are expected to occur in reality.

It is also likely that path-dependency issues are smaller for non-CO_2 mitigation (Vogt-Schilb used CO_2 as an example), as most measures are end-of-pipe solutions or do not require large-scale infrastructural investments, unlike most CO_2 mitigation measures.

In contrast to the short- to medium term perspectives of the non-CO_2 MAC curves developed by the GAINS model group and the US-EPA (Höglund-Isaksson, 2012; Purohit and Höglund-Isaksson, 2017; US-EPA, 2013; Winiwarter et al., 2018), the long-term perspective of this study allows for making bolder assumptions about effects on emission reduction potentials from technological learning and removal of implementation barriers. The former studies describe the present day technical reduction potential in much more detail (and are therefore also used as the basis of our work), but largely refrain from making assumptions on future developments if this cannot be supported by large and/or multiple case studies. For long-term climate policy projections it is however necessary to consider that very likely at least some technology improvements will occur, and implementation barriers will be lowered, particularly at very high carbon prices (or very stringent climate policy). Determining the long-term reduction potentials and costs of a large range of mitigation measures is intrinsically uncertain, and will remain an ongoing process. Cost data for most measures is very sparse, and estimating long-term changes in abatement costs is speculative. Therefore, this study's main conclusions relate to reduction and implementation potentials of existing or newly developed measures, which are based on an increasingly large body of literature, be it to some extent on experimental work.

The MAC curves in this study represent only the technological mitigation potential. Behavioral change shifts could also play a major role in reducing emissions (e.g. (Bajželj et al., 2014)), but are not included in this study, since they affect activity levels, rather than emission intensities. Particularly for livestock emissions this is very relevant, e.g. enteric fermentation emissions alone are estimated to represent more than half of all remaining methane emissions in a 2 ° mitigation case in 2100 (Harmsen et al., 2018).

The MAC curves also do not include indirect effects from non-CO_2 mitigation, such as: 1) structural economic changes resulting from high non-CO_2 prices: lower fossil fuel, livestock and GHG-intensive crop demand, and 2) indirect emission changes: CO_2 sequestration resulting from agricultural measures, or increased soil N_2O emissions from rice CH_4 mitigation. Similarly, CO_2 mitigation indirectly affecting CH_4

emissions by lowering fossil fuel production has a potentially large effect on CH_4 emissions. When applying these MAC curves in models, representing such effects requires additional analytical steps. In IMAGE, the latter effects are included, but non-CO_2 price-related structural economic changes are not accounted for, and need to be further analyzed, ideally using computable general equilibrium (CGE) models.

6. Conclusions

This study presents a new comprehensive set of MAC curves of all major non-CO_2 emission sources, based on the most recent literature. With a focus on the long-term (up to 2100), the estimated reduction potentials and costs come with large uncertainties and need to be used with care. However, by accounting for all relevant dynamical processes (e.g. technological progress, technology diffusion and interaction between measures), the MAC curves are considered more suitable for longer term climate policy research and scenario development than short-term focused datasets.

Compared to preceding work, new insights lead to a higher projected maximum reduction potential (MRP) of N_2O, a lower MRP of CH_4 and a comparable total non-CO_2 MRP, but at higher costs. The total non-CO_2 MRP in 2100 is 75%, compared to 77% with the old set from the preceding MAC curve analysis (Lucas et al., 2007). Policy costs are projected to be up to three times higher in the new set, since new measures are taken into account that are more costly, mainly in the agricultural sector. The CH_4 MRP is projected to be at 68% (compared to 79% in the old set), the N_2O MRP at 62% (compared to 52% in the old set).

When applying the new MAC curves in a strong mitigation (2.6 W/m^2) scenario, the total non-CO_2 mitigation compared to a no-climate policy baseline case (SSP2) is projected to be 10.7 Gt CO_2eq in 2050 (57% of the total emissions) and 16.0 Gt CO_2eq (or 72%) in 2100. CH_4 emission reduction (including a decrease in fossil fuel production) is projected to be 70% in 2100. F-gases are almost completely mitigated (by 96%) and N_2O mitigation is more limited at 46%. The abatement of agricultural emissions forms the major bottleneck in non-CO_2 mitigation, with 82% of the remaining non-CO_2 emissions in the strong mitigation case in 2100, predominantly from enteric fermentation and fertilizer application. Emission reductions beyond the technical potential described in this study could come from human dietary changes to reduce global livestock activities.

The attractiveness of non-CO_2 mitigation varies strongly by emission source. Mitigation of HFCs and CH_4 from fossil fuel sources can be considered very attractive, due to a large, but relatively low-cost reduction potential. Conversely, reduction of CH_4 from wastewater is projected to be relatively costly, due to large infrastructure investments, which can however be attractive from a health benefit standpoint.

With a 2.6 W/m^2 climate target, and cost-optimal GHG mitigation, the carbon budget is estimated at 1070 Gt CO_2 for the 2015–2100 period. Reducing the level of overall non-CO_2 mitigation by 10% decreases the carbon budget by roughly 50 GtCO_2. The mitigation of CH_4 and F-gases account for the largest share in changes in the carbon budget (45% and 42%, respectively), followed by N_2O (13%).

Inertia in the implementation speed of mitigation measures can limit the non-CO_2 reduction potential if climate action is delayed. Although it is highly uncertain how fast non-CO_2 mitigation can be fully scaled up, it is likely that a late start of mitigation (close to the target year), can lead to a much lower potential (here: one third lower if the first mitigation effort starts 10 years before the target year).

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2019.05.013.

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