

# Long-term marginal abatement cost curves of non-CO<sub>2</sub> greenhouse gases

Mathijs J.H.M. Harmsen<sup>1,2</sup>, Detlef P. van Vuuren<sup>1,2</sup>, Dali R. Nayak<sup>3</sup>, Andries F. Hof<sup>1,2</sup>, Lena Höglund-Isaksson<sup>4</sup>, Paul L. Lucas<sup>1</sup>, Jens B. Nielsen<sup>1</sup>, Pete Smith<sup>3</sup>, Elke Stehfest<sup>1</sup>

<sup>1</sup> PBL Netherlands Environmental Assessment Agency, Bezuidenhoutseweg 30, NL-2594 AV, The Hague, the Netherlands. Email corresponding author: [Mathijs.harmsen@pbl.nl](mailto:Mathijs.harmsen@pbl.nl)

<sup>2</sup> Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, NL-3584, CS Utrecht, The Netherlands

<sup>3</sup> Institute of Biological and Environmental Sciences, School of Biological Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen AB24 3UU, Scotland, UK

<sup>4</sup> Air Quality and Greenhouse Gases Program, International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria

## Abstract

This study presents a new comprehensive set of long-term Marginal Abatement Cost (MAC) curves of all major non-CO<sub>2</sub> 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<sub>2</sub>O) and a lower MRP of methane (CH<sub>4</sub>). The combined MRP for all non-CO<sub>2</sub> 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<sup>2</sup> scenario, the total non-CO<sub>2</sub> mitigation is projected to be 10.9 Mt CO<sub>2</sub>equivalents in 2050 (i.e. 58% reduction compared to baseline emissions) and 15.6 Mt CO<sub>2</sub>equivalents in 2100 (i.e. a 71% reduction). In applying the new MAC curves, we account for inertia in the implementation speed of mitigation measures. Although this does not strongly impact results in an optimal strategy, it means that the contribution of non-CO<sub>2</sub> mitigation could be more limited if ambitious climate policy is delayed.

## Keywords

Non-CO<sub>2</sub>; mitigation; MAC curves; climate policy

## Highlights

- Long-term non-CO<sub>2</sub> MAC curves developed based on most recent literature
- Including all major non-CO<sub>2</sub> emission sources and mitigation measures for 26 world regions
- Maximum reduction potential of nitrous oxide estimated higher, of methane lower
- Overall non-CO<sub>2</sub> mitigation estimated at 58% in 2050 and 71% in 2100
- Delayed climate action can lower mitigation potentials

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## 1. Introduction

It is widely recognized in climate policy research that worldwide mitigation of non-CO<sub>2</sub> greenhouse gases (GHGs) considerably reduces the overall costs of climate policy and extends the window of opportunity for aggressive cuts to global CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>.

While intrinsic uncertainty in long-term projections of non-CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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 several ways: 1) they have been 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<sub>2</sub> emission reduction.

The newly developed MAC curves cover more than 90% of the non-CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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](#).

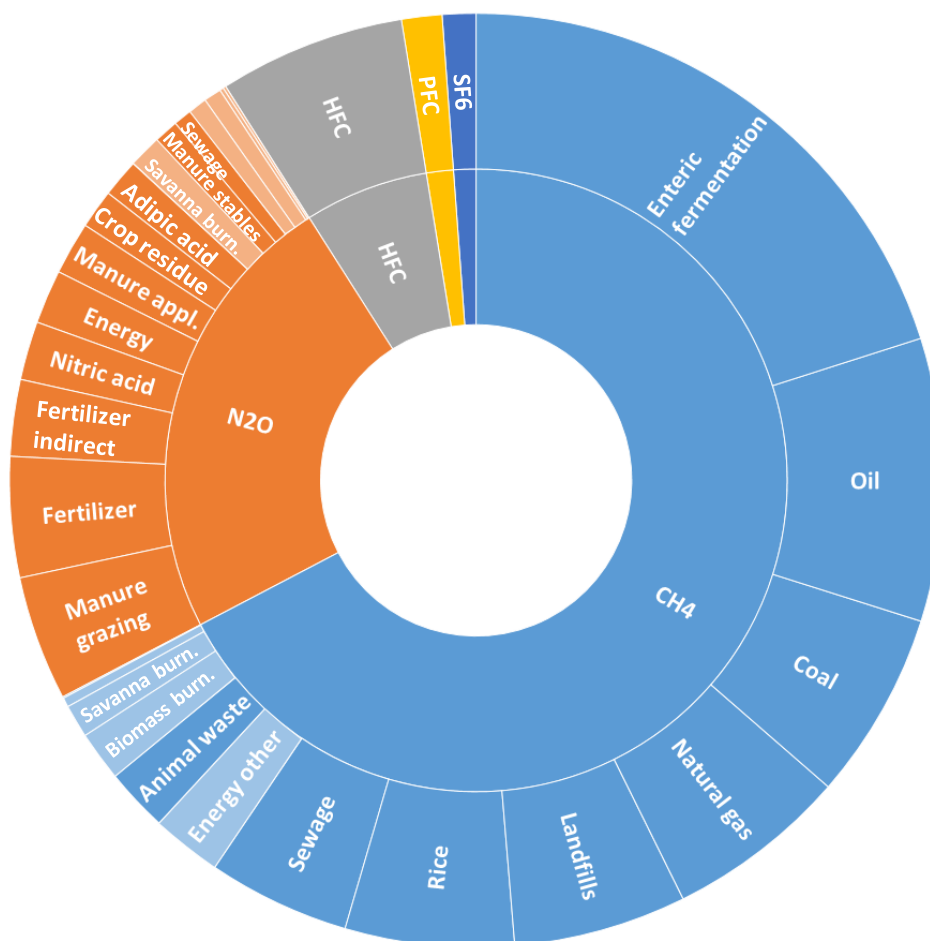
## 2. Methods

This section describes the method used for constructing the new MAC curves. More specifically we discuss: 1) the coverage of global non-CO<sub>2</sub> 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<sub>2</sub> emission source categories in IMAGE represent all anthropogenic non-CO<sub>2</sub> GHGs (see Figure 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<sub>2</sub> 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 Figure 1) are nitrous oxide (N<sub>2</sub>O) and methane (CH<sub>4</sub>) 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<sub>2</sub> emissions in 2100 (see S1). This percentage is further reduced in mitigation scenarios, where several sources are reduced indirectly as a result of CO<sub>2</sub> mitigation action (e.g. biomass burning and fuel combustion). Moreover, CH<sub>4</sub> emissions from combustion in transportation can likely be fully abated at little cost (Hussain et al., 2015; Russo et al., 2009).

**Figure 1: Anthropogenic non-CO<sub>2</sub> GHG emissions by emission source in 2015**, in share of total CO<sub>2</sub>eq (based on AR4 100 yr Global Warming Potential (GWP)). Source: IMAGE SSP2 (Stehfest et al., 2014; Van Vuuren et al., 2017) with calibrated CH<sub>4</sub> emissions from fossil energy sources based on GAINS (Höglund-Isaksson, 2017). No MAC curves have been developed for the light-shaded CH<sub>4</sub> and N<sub>2</sub>O 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<sub>2</sub>O, CH<sub>4</sub>), Biological N-fixation (N<sub>2</sub>O), Biomass Burning(N<sub>2</sub>O), Industry (N<sub>2</sub>O, CH<sub>4</sub>).



## 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.

## Reduction potentials

The reduction potential ( $RP$ ) (in %) of a single mitigation measure in year  $t$  and region  $r$  is determined by:

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

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<sup>1</sup>. 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)):

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

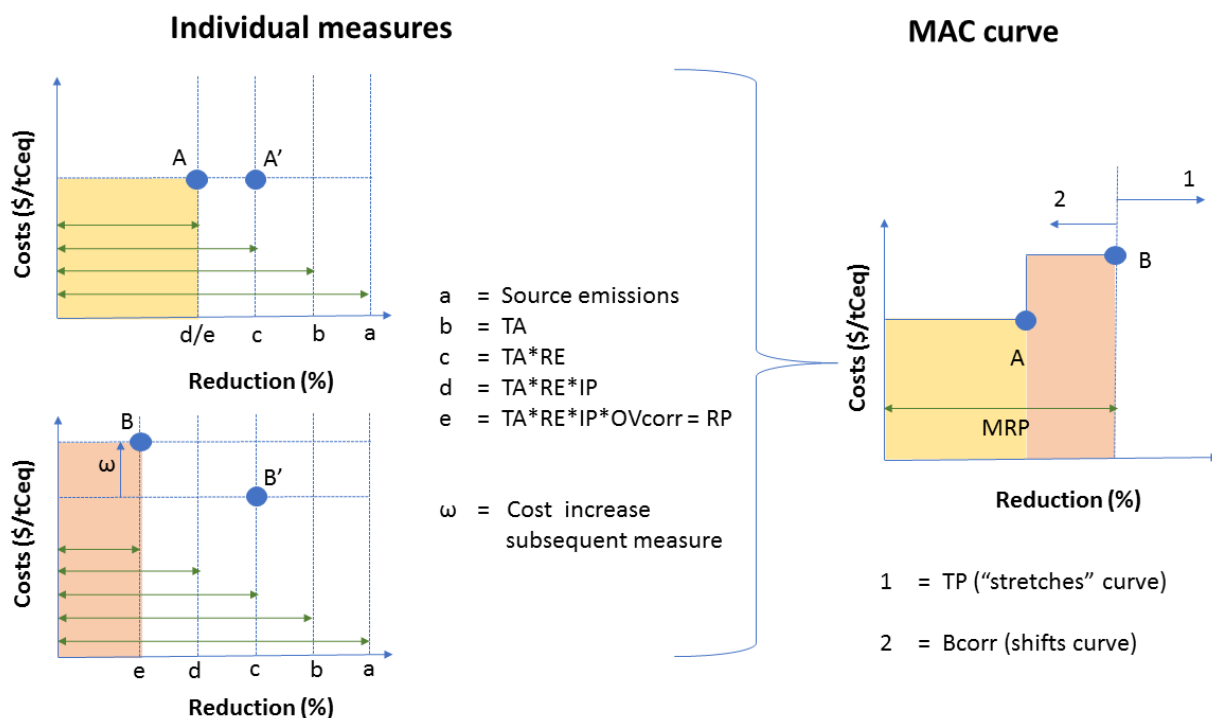
with (all in %):  $TP$ : Technological progress. Increase of the reduction potential in time, as a result of new or improved technologies.  $Bcorr$ : Correction for emission reductions that already take place in the baseline scenario, in each region. The assumption is here that these reductions come 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 Figure 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 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 ( $\omega$ ), 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

<sup>1</sup> If measure y is aimed at reducing the same baseline emissions as measure x that is already implemented, the  $OVcorr$  of y =  $1 - RP_x$ .

the use of fugitive CH<sub>4</sub> 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”).

**Figure 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).



### 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:

$$\text{Cost new} = \text{Cost old} * 1/OVcorr \quad (3)$$

Note that ω in Figure 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 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 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<sub>6</sub>. 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)/tCe<sub>q</sub> (or 1091 \$(2010)/tCO<sub>2</sub>eq, 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<sub>4</sub> 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<sub>4</sub> 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 Figure 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 Figure 3). Results are shown for 2050 and 2100, both for GHG specific and total non-CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>). 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<sub>2</sub> 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<sup>2</sup> in 2100) and moderate (3.4 W/m<sup>2</sup>) climate policy scenario. The analysis covered policy costs, reduction potential per source, and the ratio between CO<sub>2</sub> and non-CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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.

**Table 1: Main characteristics non-CO<sub>2</sub> 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).

	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) *
<b>CH<sub>4</sub></b>							
CH <sub>4</sub> - 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 <sub>4</sub> minimized In 2100: Post-mining emissions reduced by 50%	Emissions / Coal production	54%	79%	2.7% (20)
CH <sub>4</sub> - 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 <sub>4</sub> - 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 <sub>4</sub> - 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 <sub>4</sub> - Sewage and wastewater	(US-EPA, 2013)	Anaerobic digestion and CH <sub>4</sub> 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 <sub>4</sub> - 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 <sub>4</sub> - 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 <sub>4</sub> - 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)
<b>N<sub>2</sub>O</b>							

<b>N<sub>2</sub>O - Transport</b>	GECS (2002), Lucas et al. (2007)	Low-N <sub>2</sub> O 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)
<b>N<sub>2</sub>O - Adipic acid production</b>	(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)
<b>N<sub>2</sub>O - Nitric acid production</b>	(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)
<b>N<sub>2</sub>O - Fertilizer use</b>	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)
<b>N<sub>2</sub>O - Animal waste/Manure</b>	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)
<b>N<sub>2</sub>O - Domestic sewage</b>	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)
<b>F-gases</b>							
<b>HFCs - Refrigeration</b>	Schwarz et al. (2011), this study	Substitution with zero GWP substances, Better sealed systems, Recovery after use		N.a. **	96%	96%	4.5% (20)
<b>HFCs - Foams</b>	Schwarz et al. (2011), this study	Substitution with zero GWP substances		N.a. **	100%	100%	4.5% (20)
<b>HFCs - Production of HCFC-22 (HFC23 by-product)</b>	(Lucas et al., 2007)	Thermal destruction		N.a. **	90%	98%	4.5% (20)
<b>HFCs - Other</b>	Schwarz et al. (2011), this study	Substitution with zero GWP substances, Better sealed systems, Recovery after use		N.a. **	97%	97%	4.5% (20)
<b>PFCs - Aluminium production</b>	(Lucas et al., 2007)	Point-Feed Prebake technology (PFPB)		N.a. **	80%	90%	4.0% (20)
<b>PFCs - Semiconductor production</b>	(Ecofys, 2006)	Emission capture and (thermal) destruction		N.a. **	80%	99%	4.0% (20)
<b>PFCs - Other sources PFCs</b>	(Ecofys, 2006)	Substitution with zero GWP substances		N.a. **	80%	95%	4.0% (20)
<b>SF<sub>6</sub> - Production of electrical equipment</b>	(Lucas et al., 2007)	Improved recovery and recycling, Minimisation of leakage (detection and repair), Improved handling		N.a. **	80%	90%	4.0% (20)
<b>SF<sub>6</sub> - Use and decommissioning of elec. Eq.</b>	(Lucas et al., 2007)	Improved recovery and recycling, Minimisation of leakage (detection and repair), Improved handling		N.a. **	80%	90%	4.0% (20)
<b>SF<sub>6</sub> - Magnesium production</b>	(Lucas et al., 2007)	Substitution with zero GWP substances		N.a. **	90%	90%	4.0% (20)
<b>SF<sub>6</sub> - Other sources</b>	(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 SF<sub>6</sub>: 80%)

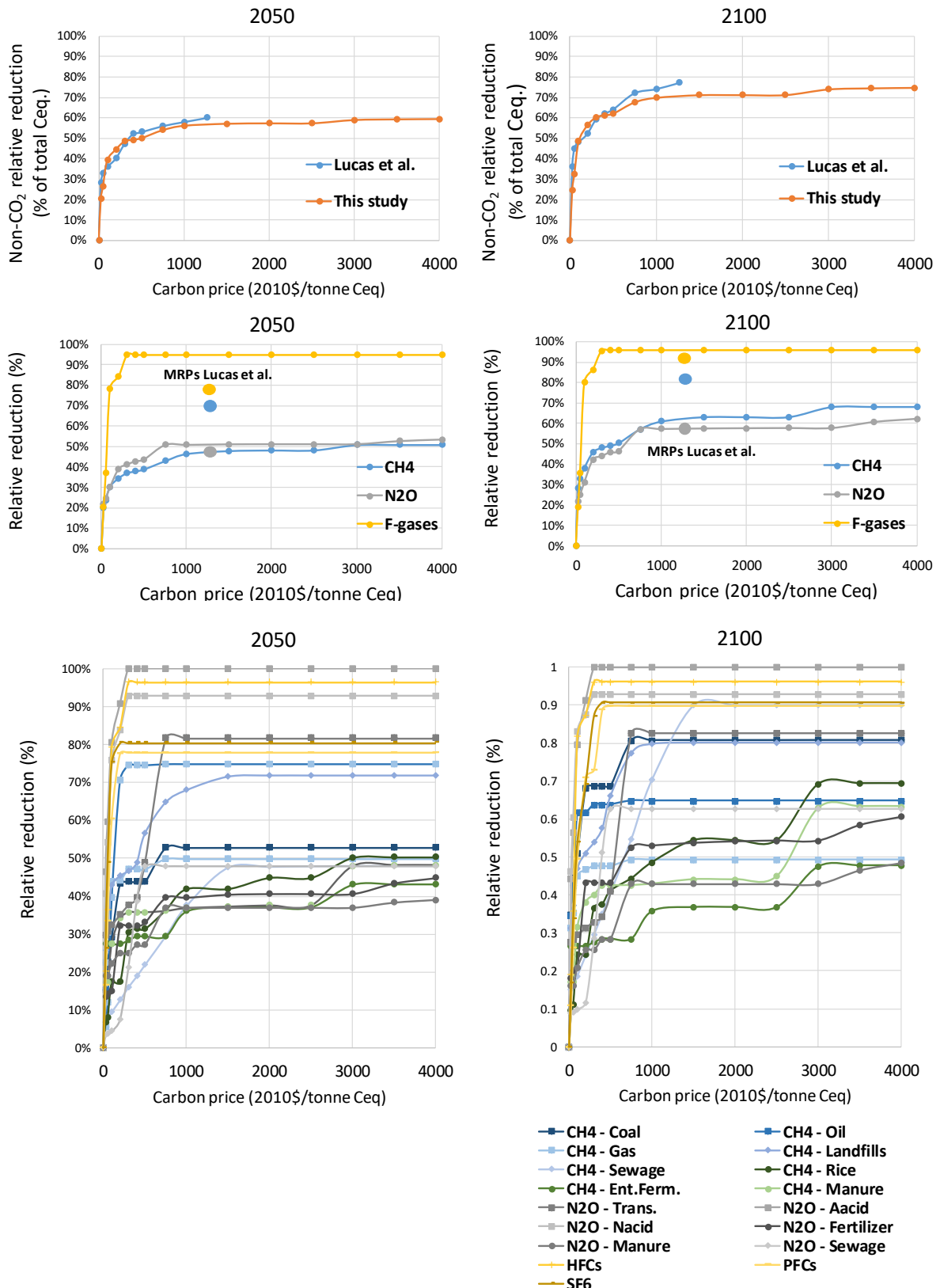
\*\* F-gas reductions are defined in terms of reductions compared to a no-climate-policy baseline

### 3.1 Assessment net mitigation potential and effect of update

Figure 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<sub>2</sub> 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<sub>4</sub> 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<sub>2</sub>O 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.

**Figure 3 –Total global non-CO<sub>2</sub> mitigation potential in 2050 and 2100, all non-CO<sub>2</sub> 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<sub>2</sub> 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 markers: waste, line markers: F-gases)



## 4. Application of the MAC curves

### 4.1 Use in long-term mitigation scenarios

Figure 4 shows the gas-specific and total non-CO<sub>2</sub> GHG emissions in the 2.6 W/m<sup>2</sup> and 3.4 W/m<sup>2</sup> 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<sub>2</sub> mitigation. These scenarios indicate only the direct mitigation effect of non-CO<sub>2</sub> measures.

In the 2.6 W/m<sup>2</sup> scenario, the total non-CO<sub>2</sub> mitigation is projected to be 10.7 Gt CO<sub>2</sub>eq in 2050 (57% of the total emissions) and 16.0 Gt CO<sub>2</sub>eq (or 72%) in 2100. The differences with the 3.4 W/m<sup>2</sup> scenario are small, which has reductions of 51% and 68% in 2050 and 2100, respectively. In relative terms, the difference in CO<sub>2</sub> reduction between the two scenarios is larger (14% of the baseline CO<sub>2</sub> emissions compared to 4% for non-CO<sub>2</sub>, not shown), due to the more costly CO<sub>2</sub> measures that take effect at higher carbon prices. A large share of the maximum non-CO<sub>2</sub> 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<sub>2</sub> emissions, this section will further focus on the 2.6 W/m<sup>2</sup> scenario.

CH<sub>4</sub> emission reduction is 6.0 and 8.2 Gt CO<sub>2</sub>eq or 52% and 70% in 2050 and 2100, respectively. Note that this reduction includes mitigation of CH<sub>4</sub> by lowered fossil fuel production, indicated by the difference with the CO<sub>2</sub> policy excluding diagnostic scenario (in 2100: 1.3 Gt CO<sub>2</sub>eq or 9% points). F-gases are almost completely mitigated in both years (3.0 Gt CO<sub>2</sub>eq (or 95%) in 2050 and 5.3 Gt CO<sub>2</sub>eq (or 96%) in 2100), indicating their large reduction potential at relatively low cost. N<sub>2</sub>O mitigation remains relatively stable at 1.7 Gt CO<sub>2</sub>eq (or 40%) in 2050 and 1.9 Gt CO<sub>2</sub>eq (or 46%) in 2100.

The remaining non-CO<sub>2</sub> emissions in 2100 in the 2.6 W/m<sup>2</sup> scenario predominantly come from agricultural sources (82% of the total non-CO<sub>2</sub>) emissions, which is in line with projections based on older MAC curves (Gernaat et al., 2015; Harmsen et al., 2019). The largest emission sources are CH<sub>4</sub> from enteric fermentation (33% of total non-CO<sub>2</sub>) emissions followed by N<sub>2</sub>O from fertilizer application (24%).



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

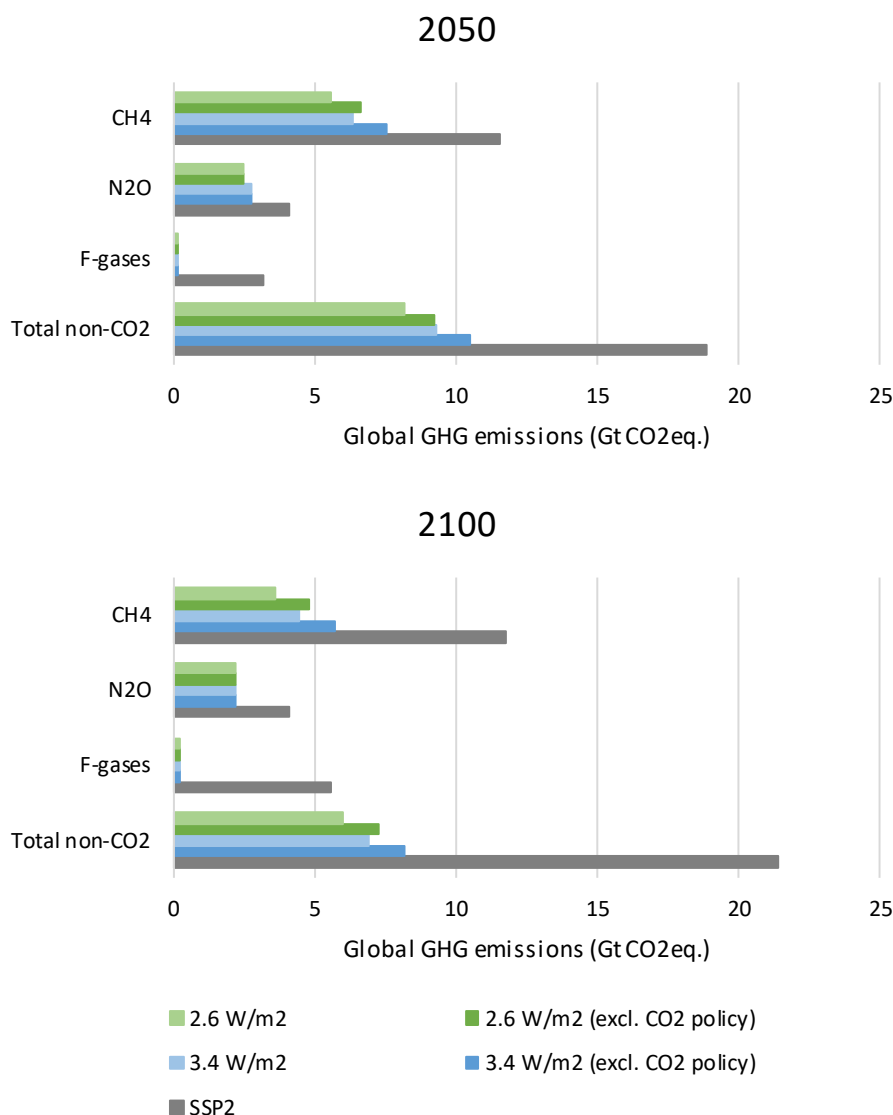


Table 2 provides a more detailed overview of the emission source-specific emission reductions and policy costs (i.e. direct implementation costs). It illustrates the relative importance of source-specific mitigation in a multi-GHG climate strategy, including CO<sub>2</sub> mitigation (see “Share in total 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<sub>2</sub> sources (exception: CH<sub>4</sub> from sewage), particularly in 2100 as the share of relatively expensive CO<sub>2</sub> measures increases towards the end of the century. Then, non-CO<sub>2</sub> mitigation measures are projected to be 50% less costly on average than average GHG prices. Figure 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<sub>4</sub> 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<sub>2</sub>-eq. CH<sub>4</sub> from sewage is one of the most expensive sources to reduce, as this would generally require large infrastructure investments to realize strong mitigation.

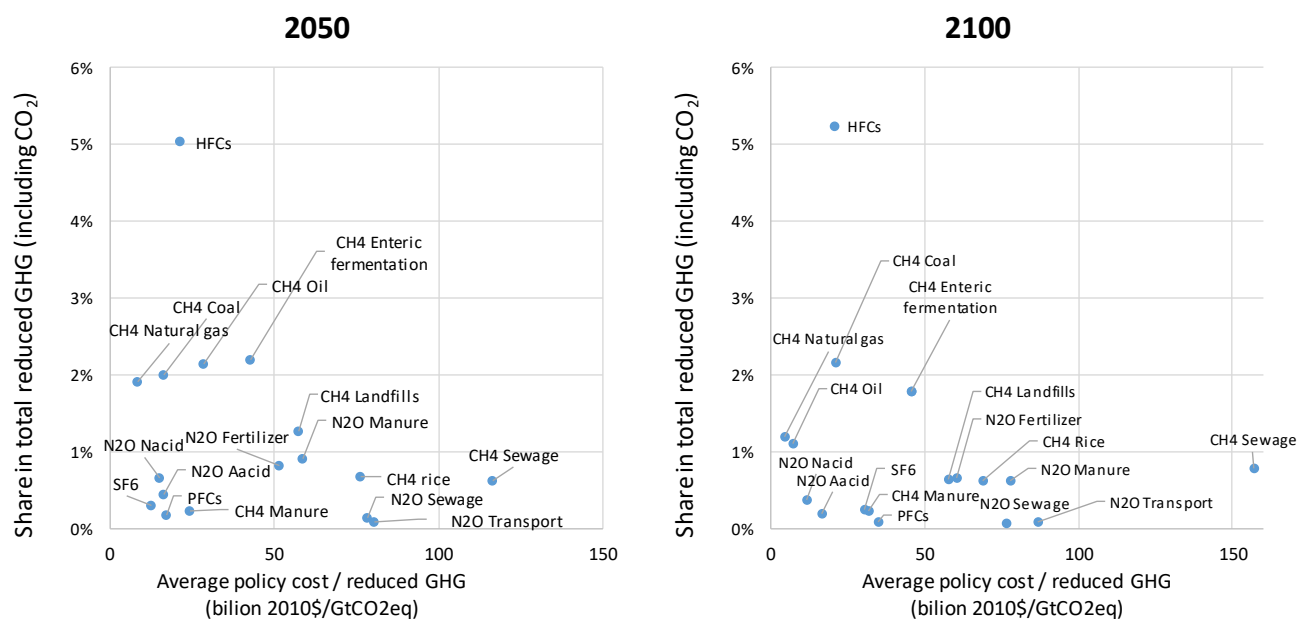
**Table 2: Emission source-specific reductions and policy costs for the 2.6 W/m<sup>2</sup> scenario.** Absolute reductions in Gt CO<sub>2</sub>eq are based on the AR4 100 yr GWP.

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

\* Values between brackets represent reductions if no CO<sub>2</sub> mitigation policy would take place. These policies indirectly reduce CH<sub>4</sub> 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<sub>2</sub>eq) that are lower than average, which is the case for most non-CO<sub>2</sub> categories

Figure 5: Policy cost per reduced GHG vs. amount of reduced emissions - 2.6 W/m<sup>2</sup> scenario



Next to its attractiveness from a cost-efficiency standpoint, non-CO<sub>2</sub> mitigation also relaxes the level of ambition required for short-term CO<sub>2</sub> mitigation. In section S6 in the [supplement](#) this is indicated by the remaining carbon budget for a 2.6 W/m<sup>2</sup> 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<sub>2</sub>. In the analysis, the level of non-CO<sub>2</sub> mitigation was varied and its effect on the carbon budget measured. As an extreme example, if no direct non-CO<sub>2</sub> GHG mitigation would take place (while taking into account non-CO<sub>2</sub> emissions indirectly reduced by CO<sub>2</sub> mitigation), the carbon budget would be almost half of that value (580 GtCO<sub>2</sub>), which indicates the relevance of non-CO<sub>2</sub> mitigation. More realistically, for every 10% change in non-CO<sub>2</sub> mitigation in the 2.6 W/m<sup>2</sup> case, the global carbon budget changes by roughly 50 GtCO<sub>2</sub> (e.g. a carbon budget of 814 GtCO<sub>2</sub> if mitigation would be reduced by half). As a further diagnostic test, hypothetical cases have been analysed where one of the GHGs (CH<sub>4</sub>, N<sub>2</sub>O, F-gases) was not mitigated. This showed that mitigation (compared to no mitigation) of CH<sub>4</sub> 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<sub>2</sub>O (13%).

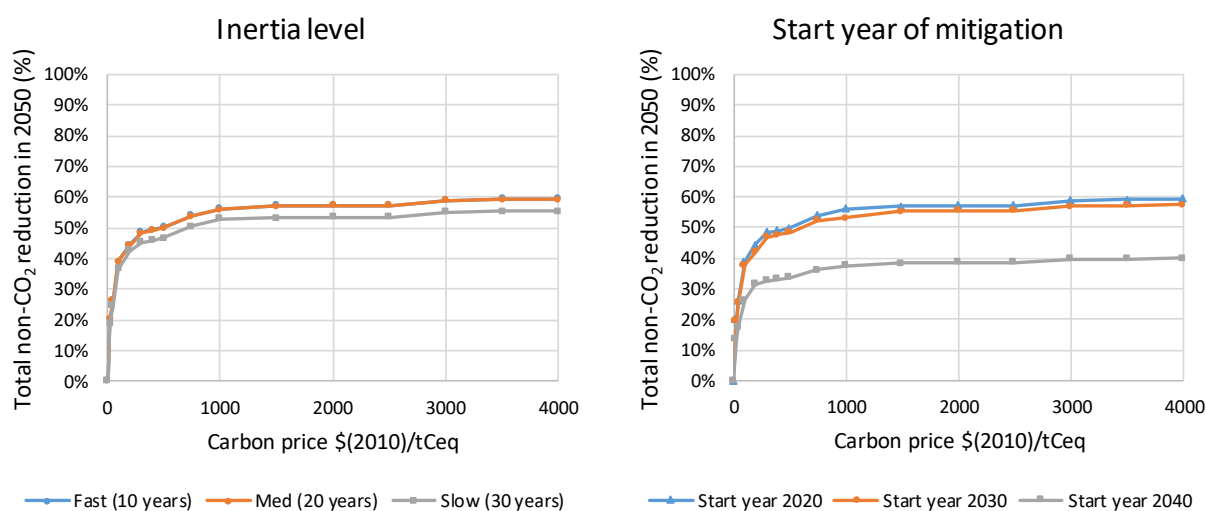
## 4.2 Inertia sensitivity analysis

Figure 6 shows the results of the sensitivity analysis (see section 2.3). The impact of inertia is illustrated by the total non-CO<sub>2</sub> 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<sup>2</sup> case, S7 in the [supplement](#)).

The limiting role of inertia can, however, be substantial if climate action is delayed. Figure 6 shows that a start year of mitigation in 2040 (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<sub>4</sub> mitigation can result in higher CH<sub>4</sub> emissions resulting from inertia. Note further that, although non-CO<sub>2</sub> 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<sub>2</sub>O, PFCs, SF<sub>6</sub>), higher, inertia-induced short-term emissions leads to a larger atmospheric burden, making longer-term climate targets more difficult to reach.

**Figure 6: Sensitivity analysis of inertia non-CO<sub>2</sub> mitigation.** The total non-CO<sub>2</sub> 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).



## 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<sub>2</sub> mitigation would be to explicitly model individual measures/technologies dynamically, as is often done for CO<sub>2</sub> 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<sub>2</sub> mitigation (Vogt-Schilb used CO<sub>2</sub> as an example), as most measures are end-of-pipe solutions or do not require large-scale infrastructural investments, unlike most CO<sub>2</sub> mitigation measures.

In contrast to the short- to medium term perspectives of the non-CO<sub>2</sub> 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 degree mitigation case in 2100 (Harmsen et al., 2019).

The MAC curves also do not include indirect effects from non-CO<sub>2</sub> mitigation, such as: 1) structural economic changes resulting from high non-CO<sub>2</sub> prices: lower fossil fuel, livestock and GHG-intensive crop demand, and 2) indirect emission changes: CO<sub>2</sub> sequestration resulting from agricultural measures, or increased soil N<sub>2</sub>O emissions from rice CH<sub>4</sub> mitigation. Similarly, CO<sub>2</sub> mitigation indirectly affecting CH<sub>4</sub> emissions by lowering fossil fuel production has a potentially large effect on CH<sub>4</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>O, a lower MRP of CH<sub>4</sub> and a comparable total non-CO<sub>2</sub> MRP, but at higher costs.** The total non-CO<sub>2</sub> 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<sub>4</sub> MRP is projected to be at 68% (compared to 79% in the old set), the N<sub>2</sub>O MRP at 62% (compared to 52% in the old set).

**When applying the new MAC curves in a strong mitigation (2.6 W/m<sup>2</sup>) scenario, the total non-CO<sub>2</sub> mitigation compared to a no-climate policy baseline case (SSP2) is projected to be 10.7 Gt CO<sub>2</sub>eq in 2050 (57% of the total emissions) and 16.0 Gt CO<sub>2</sub>eq (or 72%) in 2100.** CH<sub>4</sub> 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<sub>2</sub>O mitigation is more limited at 46%. The abatement of agricultural emissions forms the major bottleneck in non-CO<sub>2</sub> mitigation, with 82% of the remaining

non-CO<sub>2</sub> 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<sub>2</sub> mitigation varies strongly by emission source.** Mitigation of HFCs and CH<sub>4</sub> from fossil fuel sources can be considered very attractive, due to a large, but relatively low-cost reduction potential. Conversely, reduction of CH<sub>4</sub> from wastewater is projected to be relatively costly, due to large infrastructure investments, which can however be attractive from a health benefit standpoint.

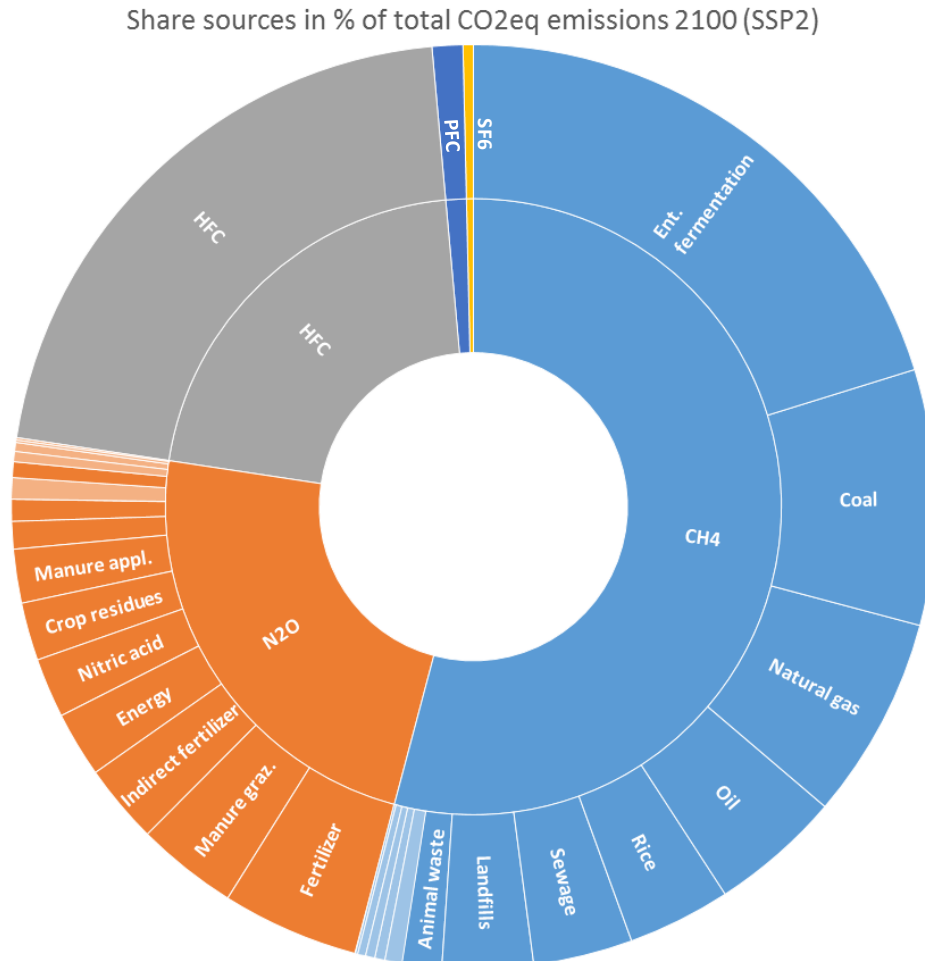
**With a 2.6 W/m<sup>2</sup> climate target, and cost-optimal GHG mitigation, the carbon budget is estimated at 1070 Gt CO<sub>2</sub> for the 2015-2100 period.** Reducing the level of overall non-CO<sub>2</sub> mitigation by 10% decreases the carbon budget by roughly 50 GtCO<sub>2</sub>. The mitigation of CH<sub>4</sub> and F-gases account for the largest share in changes in the carbon budget (45% and 42%, respectively), followed by N<sub>2</sub>O (13%).

**Inertia in the implementation speed of mitigation measures can limit the non-CO<sub>2</sub> reduction potential if climate action is delayed.** Although it is highly uncertain how fast non-CO<sub>2</sub> 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).

## Supplementary Material

### S1. Non-CO<sub>2</sub> emissions in the IMAGE SSP2

**Figure S.1: Anthropogenic non-CO<sub>2</sub> GHG emissions, share of total CO<sub>2</sub>eq in 2100**, in share of total CO<sub>2</sub>eq (based on AR4 100 yr Global Warming Potential (GWP) in the IMAGE SSP2 scenario (Stehfest et al., 2014; Van Vuuren et al., 2017) with calibrated CH<sub>4</sub> emissions from fossil energy sources based on GAINS (Höglund-Isaksson, 2017). No MAC curves have been developed for the light-shaded CH<sub>4</sub> and N<sub>2</sub>O sources. Main differences between years: relative share of HFC increases, relative share of sources without a MAC curve decreases, see also table S1.





**Table S1: Anthropogenic non-CO2 GHG emissions, share of total CO2eq in 2015 and 2100** in the IMAGE SSP2 scenario (Stehfest et al., 2014; Van Vuuren et al., 2017) with calibrated CH4 emissions from fossil energy sources based on GAINS (Höglund-Isaksson, 2017). Data is provided in absolute terms i.e. total CO2eq (based on AR4 100 yr Global Warming Potential (GWP)) and relative terms, i.e. share of total CO2eq. Grey-shaded cells indicate sources without a MAC curve.

GHG	Source	2015		2100	
		Emissions (Mt CO2eq/yr)	% of total non-CO2	Emissions (Mt CO2eq/yr)	% of total non-CO2
CH4	Enteric fermentation	2745	20%	3727	17%
CH4	Oil	1339	10%	1113	5%
CH4	Coal	891	7%	2168	10%
CH4	Natural gas	860	6%	1724	8%
CH4	Landfills	819	6%	772	4%
CH4	Rice	800	6%	876	4%
CH4	Sewage	674	5%	843	4%
CH4	Energy other	332	2%	142	1%
CH4	Animal waste	300	2%	338	2%
CH4	Biomass burning	233	2%	54	0%
CH4	Savannah burning	158	1%	68	0%
CH4	Agricultural waste burning	46	0%	51	0%
CH4	Industry	7	0%	22	0%
<b>CH4 Total</b>		<b>9203</b>	<b>67%</b>	<b>11900</b>	<b>55%</b>
N2O	Manure grazing	591	4%	653	3%
N2O	Fertilizer	570	4%	883	4%
N2O	Indirect fertilizer	362	3%	513	2%
N2O	Nitric acid	277	2%	385	2%
N2O	Energy	255	2%	422	2%
N2O	Manure application	250	2%	347	2%
N2O	Crop residues	184	1%	374	2%
N2O	Adipic acid	180	1%	178	1%
N2O	Savannah burning	157	1%	68	0%
N2O	Manure stables	116	1%	142	1%
N2O	Domestic sewage	88	1%	103	0%
N2O	Biological N-fixation	87	1%	135	1%
N2O	Biomass burning	83	1%	19	0%
N2O	Chemicals	19	0%	53	0%
N2O	Agricultural waste burning.	14	0%	15	0%
<b>N2O Total</b>		<b>3234</b>	<b>24%</b>	<b>4291</b>	<b>20%</b>
HFC	HFC	882	6%	5222	24%
PFC	PFC	191	1%	89	0%
SF6	SF6	159	1%	265	1%
<b>Total</b>		<b>13670</b>	<b>100%</b>	<b>21767</b>	<b>100%</b>
<b>Total % covered by MAC curve:</b>		<b>91%</b>		<b>96%</b>	

## S2. Bottom-up methodology agricultural MAC curves

### Reduction potential

The new agricultural MAC curves for CH<sub>4</sub> and N<sub>2</sub>O emissions are constructed using sets of mitigation measures found in literature. These sets are the combinations with the highest estimated maximum reduction potential, determined using the following equation:

$$RP = RE * TA * OVcorr_{(t)} * IP_{(t)}$$
$$MRP_{(t)} = (RP_{1(t)} + RP_{2(t)} + RP_{3(t)} \dots + RP_{x(t)}) * TP_{(t)} - Bcorr_{(t)} \quad (2)$$

With:

<i>MRP</i>	=	<i>Maximum Reduction Potential of all measures combined</i>
<i>RP</i>	=	<i>Reduction Potential of one measure</i>
<i>RE</i>	=	<i>Reduction Efficiency, relative reduction of targeted emissions compared to baseline</i>
<i>TA</i>	=	<i>Technical Applicability, or part of the baseline covered by the measure</i>
<i>OVcorr</i>	=	<i>Correction for overlap</i>
<i>IP</i>	=	<i>Implementation potential, dependent on barriers in future years</i>

The estimated *RE* for a specific measure is the average of all the *RE* values for this measure found in literature. Maximum and minimum *RE* values can be used to construct MAC curves with higher and lower range estimates, but was not be used here.

The *TA* is in many cases 100%, when a measure can be applied to all emission sources. However, in some, measures are not applicable worldwide, for instance where the measures are already in place or cannot be combined with an emission source (e.g. drainage in the case of upland (irrigated) rice, excessive flooding that would prohibit drainage for rice, or optimizing fertilizer application when all fertilizer is effectively used). *TA* estimates have mainly been based on Graus et al. (2004) and modified where deemed needed based on available literature.

In the case of mutually excluding measures (e.g. mid-season drainage and alternate flooding / drainage), the measures with the lowest reduction potential were excluded. In the case of partial overlap, with a diminished benefit of the second measure (e.g. different food supplements that reduce enteric fermentation), a correction factor, *OVcorr*, was applied to the reduction potential of the second measure to account for the reduced effectiveness. This correction factor compensates for two effects:

- 1) Diminishing reduction effect when measures are placed in series (e.g. manure storage covering and digesters to reduce animal waste emissions). For this effect, we used the following calculation. If measure *y* is aimed at reducing the same baseline emissions as measure *x* that is already implemented, the *OVcorr* of *y* = 1-RP<sub>x</sub>.
- 2) Interaction / overlap between measures that are implemented in parallel (e.g. multiple food supplements that are used to reduce the same emissions). For this correction, we made a distinction between high, medium, low and no interaction. It was assumed that with high overlap, the second measure had 20% of the original reduction efficiency. With

medium overlap this was assumed to be 50%, and with low overlap 70%. See [supplement S4](#) for an overview of the assumed interaction between measures.

The implementation potential of the agricultural measures is based on (Graus et al., 2004). This value is expected to increase in time due to increased technology diffusion and implementation. Assumed values are 10% in 2020, 70% in 2050 and 100% in 2100 for Rice CH<sub>4</sub> and Fertilizer N<sub>2</sub>O emissions. For livestock measures, the implementation potential is assumed to be slightly higher, particularly in the short term; 20% in 2020, 90% in 2050 for enteric fermentation, 20% in 2020, 50% in 2050, 70% in 2100 for animal waste.

### Technology improvements

It can be expected that the future *MRP* values are actually higher than the *MRP* values derived from the MACs, with all the abatement measures from this assessment fully included. This is the case for two reasons: 1) Some existing technologies might not have been included in this assessment, which could have added to the reduction potential 2) Future technology improvements and currently non-existing future technologies can potentially do the same in the future. It can be expected that the second argument is stronger in the far future. Therefore, we assume that in 2050, after implementing all measures included in the MAC the remaining emissions can be reduced 10% more. For 2100, we assume that the remaining emissions can be reduced 20% more than what is expected based only on the MAC. So:

$$\begin{aligned}MRP_{2050} &= 1 - (1 - MRP_{MAC}) * 90\% \\MRP_{2100} &= 1 - (1 - MRP_{MAC}) * 80\%\end{aligned}$$

Between 2050 and 2100, the *MRP* values are linearly interpolated to arrive at a *MRP* for each year. It is assumed that the additional technology improvements occur at very high GHG prices: at or above 3000 \$/tC or 818 \$/tCO<sub>2</sub>. In the IMAGE model, this *MaxPrice* is introduced as the carbon price at which the maximum reduction takes place. In earlier model versions this price was set much lower: 1000 \$/tC for most agricultural sources (Lucas et al., 2007). This update therefore leads to an added emission reduction benefit at higher carbon prices.

### Marginal costs

The assumption for the construction of the MAC curves is that the least costly measures are taken first. Only a selection of the studies included estimates of marginal costs of reduction measures. As with the reduction efficiency, the best estimate of the marginal costs of a specific measure was based on the average of cost estimates in literature. The available cost data was converted to 2005 \$ / tCO<sub>2</sub>eq (as 2005 dollars are used as the cost metric in the IMAGE model), and made regionally specific where data was available.

The assumption for the construction of the MAC curves is that the least costly measures are taken first. The best estimate of the marginal 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 decreases, while the implementation costs may remain

the same. Assuming that that least cost measures are implemented first, we corrected the cost of every subsequent (more expensive) measure, following:

$$\text{Cost new}_x = \text{Cost old}_x * 1/OVcorr_x \quad (3)$$

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.

### S3. Included and excluded mitigation measures in agriculture MAC curves

#### MAC curve for Rice CH<sub>4</sub>

	Technical Applicability	Reduction efficiency	Correction for overlap			Abatement potential *		
			2020	2050	2100	2020	2050	Max 2100 /
Direct seeding	75%	20%	100%	100%	100%	3%	11%	15%
Replace urea with ammonium sulphate	75%	24%	97%	90%	85%	3%	11%	15%
Straw compost	50%	48%	94%	78%	70%	4%	13%	17%
Alternate flooding / drainage	40%	57%	89%	65%	53%	4%	10%	12%
Addition of phosphogypsum	75%	39%	85%	55%	41%	5%	11%	12%
Maximum reduction potential						20%	57%	71%

\* Excluding technological progress and correction for baseline emission reductions

Implementation potential 2020	20%
Implementation potential 2050	70%
Max Abatement Potential (2100)	100%

The mitigation measures that have been used to construct the MAC curve are the following (taking into account overlap between measures and aiming for the highest MRP) :

1. Alternate flooding/ drainage: this measure reduces anaerobic conditions. **Varying costs, depending on the region, average cost-effectiveness 148 \$/tCO<sub>2</sub>eq** (Nalley et al., 2015; Thu et al., 2016) **average CH<sub>4</sub> reduction efficiency 57%** (Feng et al., 2013; Graus et al., 2004; Jiao et al., 2006; Nalley et al., 2015; Nayak et al., 2015; Tariq et al., 2017; Thu et al., 2016; Towprayoon et al., 2005; Tyagi et al., 2010; Wassman et al., 2000; Yang et al., 2012; Yu et al., 2004; Yue et al., 2005)
2. Direct wet seeding: replaces transplanting; exact CH<sub>4</sub>-reducing mechanism unclear. **Varying costs, depending on the region, average cost-effectiveness 0–63 \$/tCO<sub>2</sub>eq** (Graus et al., 2004), **average CH<sub>4</sub> reduction efficiency 20%** (Graus et al., 2004; Wassman et al., 2000)
3. Phosphogypsum: addition of this by-product (3t/ha) releases sulphate, which inhibits methanogenesis. **High cost, average cost-effectiveness 61–385 \$/tCO<sub>2</sub>eq** (Graus et al., 2004) **average CH<sub>4</sub> reduction efficiency 39%** (Graus et al., 2004; Linnquist et al., 2012; Wassman et al., 2000)
4. Replace urea with ammonium sulphate (AS): replaces commonly used urea; sulphate inhibits methanogenesis. **Very low cost, average cost-effectiveness 1–15 \$/tCO<sub>2</sub>eq** (Graus et al., 2004) **CH<sub>4</sub> reduction potential 22%** (Graus et al., 2004; Wassman et al., 2000)
5. Rice straw compost: substitutes for fresh rice straw; lowers organic matter. **Medium high cost, average cost-effectiveness 28–142 \$/tCO<sub>2</sub>eq** (Graus et al., 2004; Launio et al., 2016), **average CH<sub>4</sub> reduction efficiency: 48%**

The following measures have been excluded from the MAC curve (due to overlap with the measures above and/or lower reduction potentials):

1. Midseason drainage and no organic matter: reduces anaerobic conditions; lowers organic matter source. **Low cost, average CH<sub>4</sub> reduction efficiency 77%**
2. Conservation tillage: changing from conventional to conservation tillage or reduced tillage in rice based cropping system. **Reduced cost as compared to conventional tillage, average CH<sub>4</sub> reduction efficiency 22%.**

- Enhance efficiency fertilizer which includes nitrification inhibitors, slow release fertilizers: decreases both CH<sub>4</sub> and N<sub>2</sub>O emission. **Increased cost, average CH<sub>4</sub> reduction efficiency 18%, average N<sub>2</sub>O reduction efficiency 27%.**
- Off season straw application: shifting straw amendment from in- season to off-season, reduces CH<sub>4</sub> emission by reducing availability of DOC (dissolved organic carbon) and thus methanogenesis. **No change in cost, average CH<sub>4</sub> reduction efficiency 17%**
- Straw mulching: Ditch or strip mulching of straw instead of evenly incorporating reduces CH<sub>4</sub> emission with exposure of fresh straw to more light and more CH<sub>4</sub> oxidation. **No change or low cost , average CH<sub>4</sub> reduction efficiency 11% to 32%.**

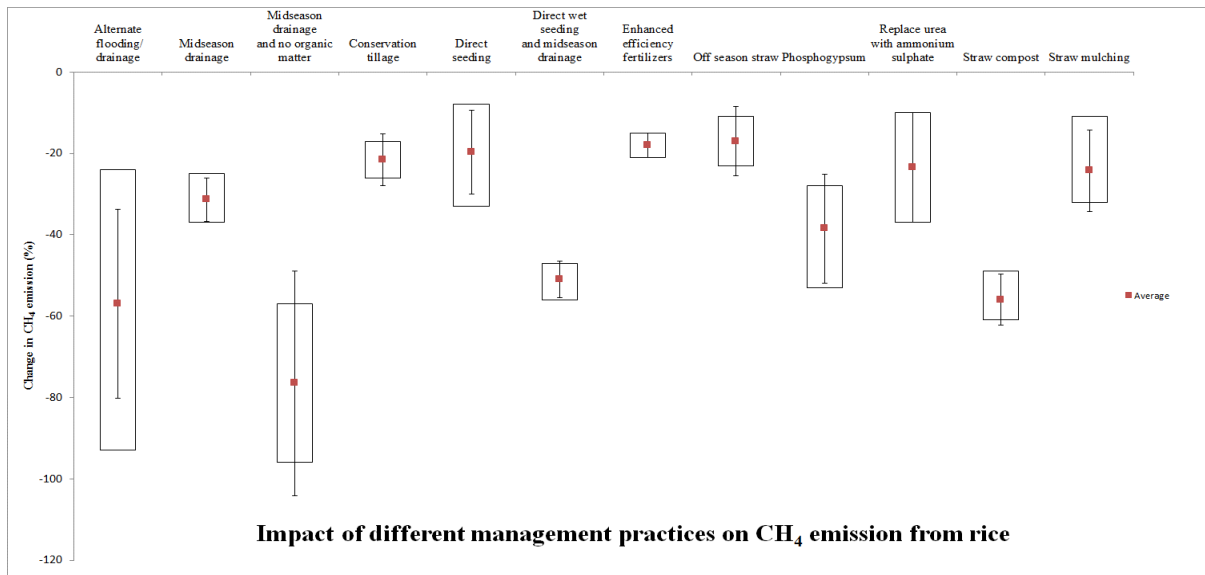


Figure S3.1. Reduction potential of different rice CH<sub>4</sub> mitigation measures.

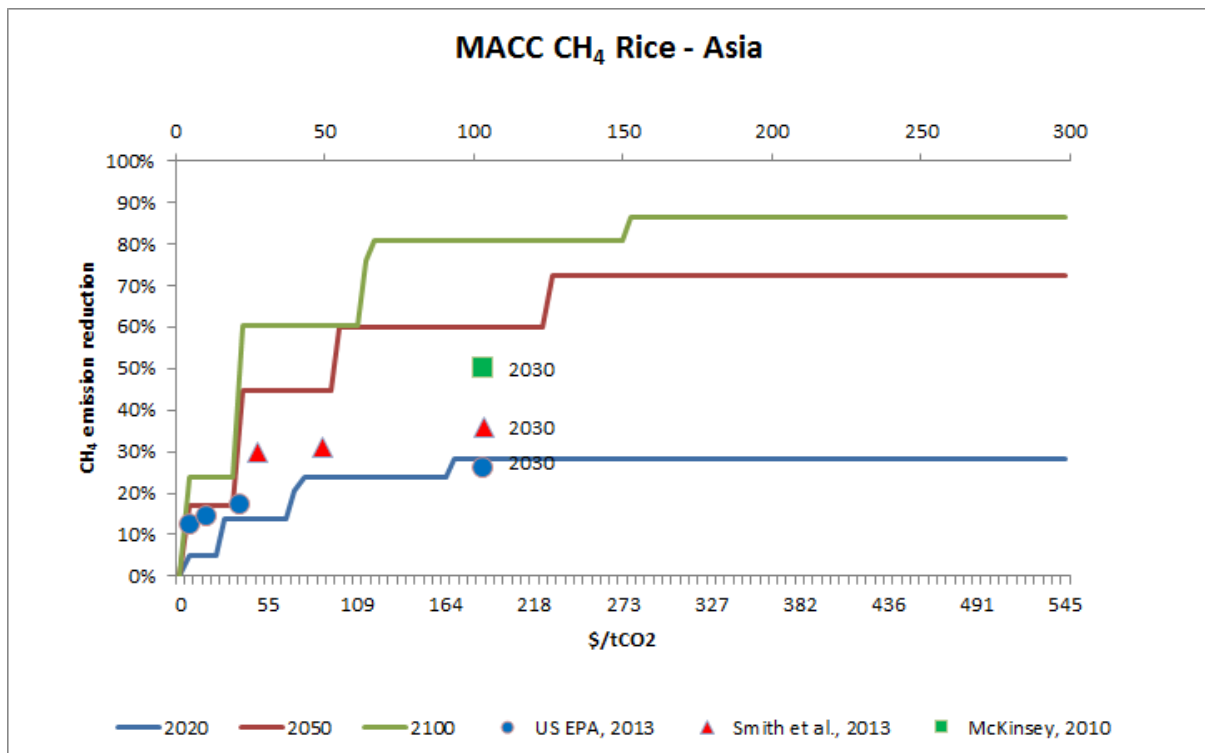


Figure S3.2. Updated MAC curve for rice for Korea, China and South East Asia

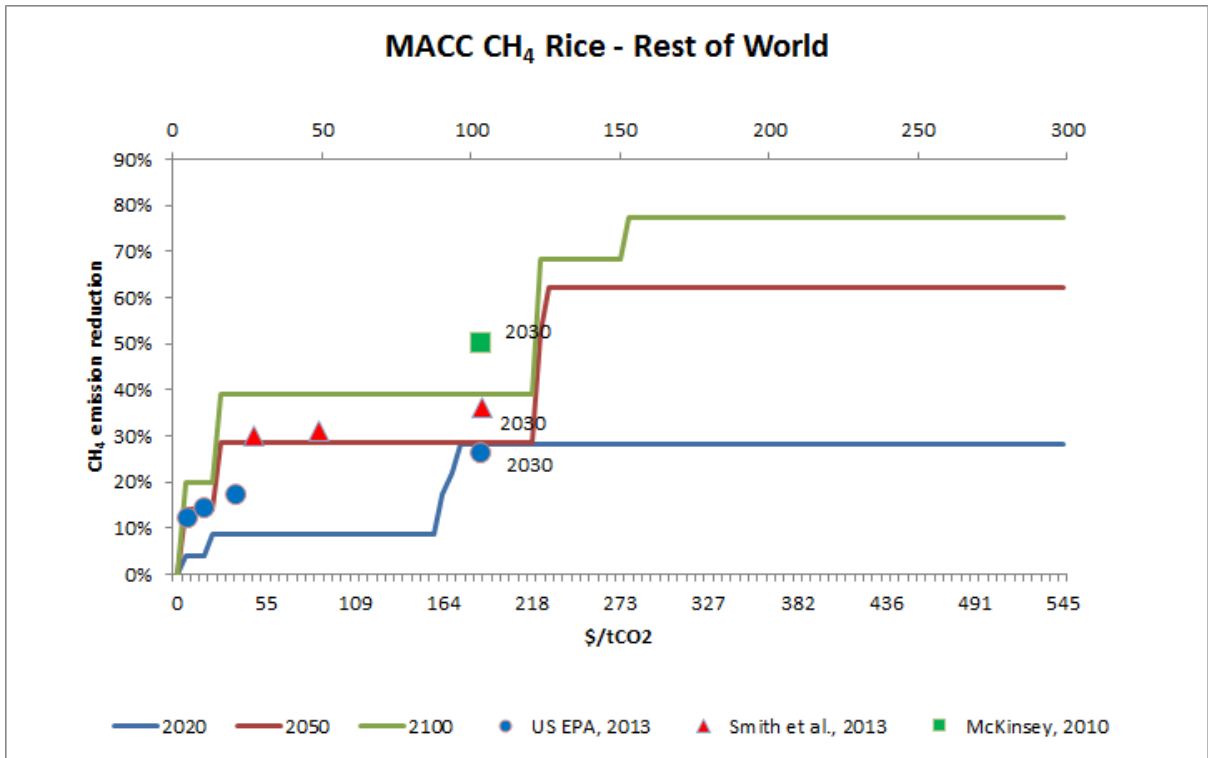


Figure S3.3. Updated MAC curve for rice for Rest of the world i.e. excluding Korea, China and South East Asia

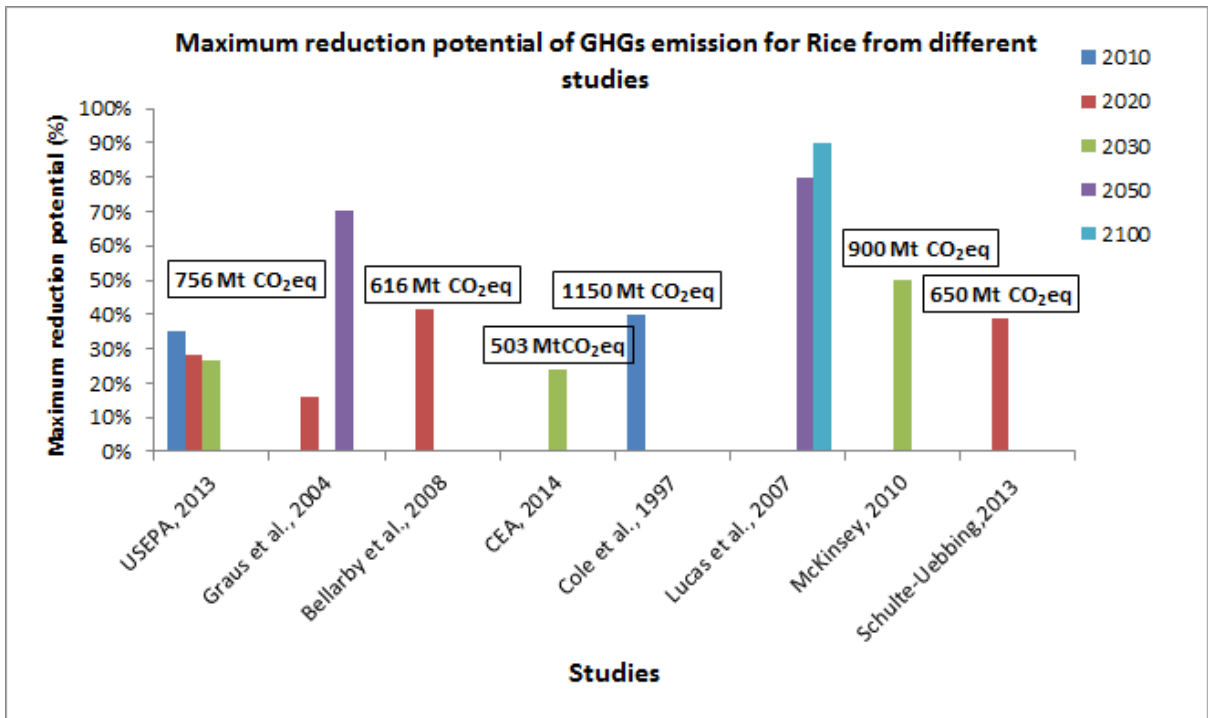


Figure S3.4. Maximum reduction potential (%) of GHGs emission from rice collated from literature. Values in the square boxes are baseline emissions for different future years.

## MAC curve for Enteric Fermentation CH<sub>4</sub>

	Technical Applicability	Reduction efficiency	Correction for overlap			Abatement potential *		
			2020	2050	2100	2020	2050	Max 2100
<b>Genetic selection</b>	75%	21%	75%	75%	75%	2%	11%	12%
<b>Improved health monitoring</b>	75%	15%	49%	45%	44%	1%	5%	5%
<b>Tannins</b>	75%	20%	19%	17%	17%	1%	2%	2%
<b>Grain processing</b>	75%	20%	19%	17%	16%	1%	2%	2%
<b>Nitrate</b>	70%	26%	95%	80%	78%	3%	13%	14%
<b>Extend productive life</b>	75%	10%	32%	24%	22%	0%	2%	2%
<b>Max reduction potential</b>						<b>4%</b>	<b>28%</b>	<b>38%</b>

\* Excluding technological progress and correction for baseline emission reductions

Implementation potential 2020	20%
Implementation potential 2050	90%
Max Abatement Potential (2100)	100%

The mitigation measures that have been used to construct the MAC curve are the following (taking into account overlap between measures and aiming for the highest MRP):

1. Nitrate: Addition of electron receptors such as nitrate may reduce CH<sub>4</sub> emission by 30 to 50% and increase productivity. **Low to moderate cost, average cost-effectiveness 107 \$/tCO<sub>2</sub>eq** (Eory et al., 2016; Henderson et al., 2015) **average CH<sub>4</sub> reduction efficiency 40%** (Dickie et al., 2014; Hulshof et al., 2012; Van Zijderveld et al., 2011).
2. Tannins: Plant extracts such as tannins or saponins are very effective in reducing rumen CH<sub>4</sub> emission. **Low cost, average cost-effectiveness 15 \$/tCO<sub>2</sub>eq** (McKinsey, 2010), **average CH<sub>4</sub> reduction efficiency 14%** (Hristov et al., 2013; Nayak et al., 2015)
3. Grain processing: Improving starch digestibility of grain through mechanical processing such as steam flaking instead of dry rolling may reduce CH<sub>4</sub> emission by 10%. This also improves productivity. **Low to moderate cost, average cost-effectiveness 50 \$/tCO<sub>2</sub>eq** (No data, medium cost estimate), **average CH<sub>4</sub> reduction efficiency 10%** (Hristov et al., 2013).
4. Genetic selection and breeding. Selection of low CH<sub>4</sub> generation and higher feed efficiency per unit of milk produced **Small to medium economic benefit, negative cost, average cost-effectiveness 0 \$/tCO<sub>2</sub>eq**. (Graus et al., 2004)(measure: higher milk production) **average CH<sub>4</sub> reduction efficiency 21%** (Bell et al., 2010)
5. Improved health monitoring and illness prevention or Prevention. Controlling or eradicating endemic livestock diseases. **Small to medium economic benefit, negative cost, average cost-effectiveness 0 \$/tCO<sub>2</sub>eq** (Eory et al., 2016; McKinsey, 2010) **average CH<sub>4</sub> reduction efficiency 15%** (Eory et al., 2016).

The following measures have been excluded from the MAC curve (due to overlap with the measures above and/or lower reduction potentials):

1. Antibiotics: Addition of antibiotics or ionophores such as Monensin to diet may reduce CH<sub>4</sub> emission by <10%. Monensin is banned in Europe but it is normally used in beef production



system in North America. Ionophores improve feed efficiency. **Moderate cost, average CH<sub>4</sub> reduction efficiency 15%.**

2. Improved feeding practices: Includes replacing roughage with concentrate, improving forages/inclusion of legumes and feeding extra dietary oil. **Low to moderate cost, average CH<sub>4</sub> reduction efficiency 9%.**
3. Precision feeding: Accurate prediction of animal requirements and accurate feed analyses go hand-in-hand with minimizing feed waste, maximizing production, and minimizing GHG emissions per unit of animal product. **Moderate to high cost, average CH<sub>4</sub> reduction efficiency 20%.**
4. Longer term management changes and animal breeding: Increasing productivity through breeding and better management practices spreads the energy cost of maintenance across a greater feed intake, often reducing methane output per kilogram of animal product. **Moderate cost, average CH<sub>4</sub> reduction efficiency 3%.**
5. Enhance milk production by use of metabolic modifier: bovine somatotropin. Non-Dairy production **Very low cost, average CH<sub>4</sub> reduction efficiency 3%**
6. Increase the body weight of cattle at time of slaughter. **Very high cost, average CH<sub>4</sub> reduction efficiency 5%**
7. Intensive grazing: change the feeding to include grazing in pasture rather than all processed feed mixture. **Very low cost, average CH<sub>4</sub> reduction efficiency 13%**
8. Increasing level of feed intake to change volatile fatty acid (VFA) in rumen to generate more propionate with improved genetics. **Very low cost, average CH<sub>4</sub> reduction efficiency 9%**
9. Increased Conversion Efficiency - High Fat Diet: Addition of fats to diet meets energy requirements and increases propionate in rumen. **Very low cost, average CH<sub>4</sub> reduction efficiency 5%**
10. Increased Conversion Efficiency: Include more non-structural carbohydrates in concentrate; leads to lower rumen pH. **Very low cost, average CH<sub>4</sub> reduction efficiency 10%**
11. Increased Conversion Efficiency - Replace roughage with concentrates: Replacement of roughage that contains high portions of structural carbohydrates with concentrates to improve propionate generation in rumen **Very low cost, average CH<sub>4</sub> reduction efficiency 8%**
12. Increased rumen efficiency: Addition of propionate precursors in daily supplements. **Medium high cost, average CH<sub>4</sub> reduction efficiency 15%**

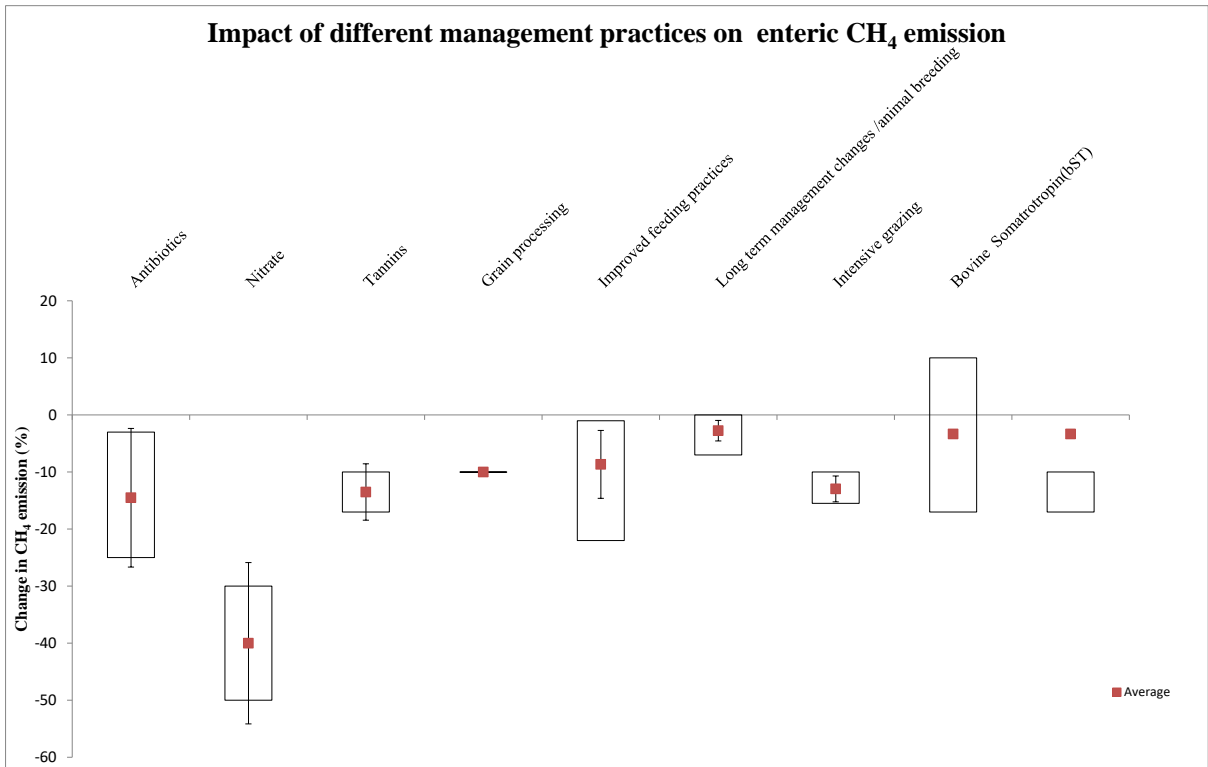


Figure S3.5. Reduction potential of different CH<sub>4</sub> mitigation measures for enteric fermentation.

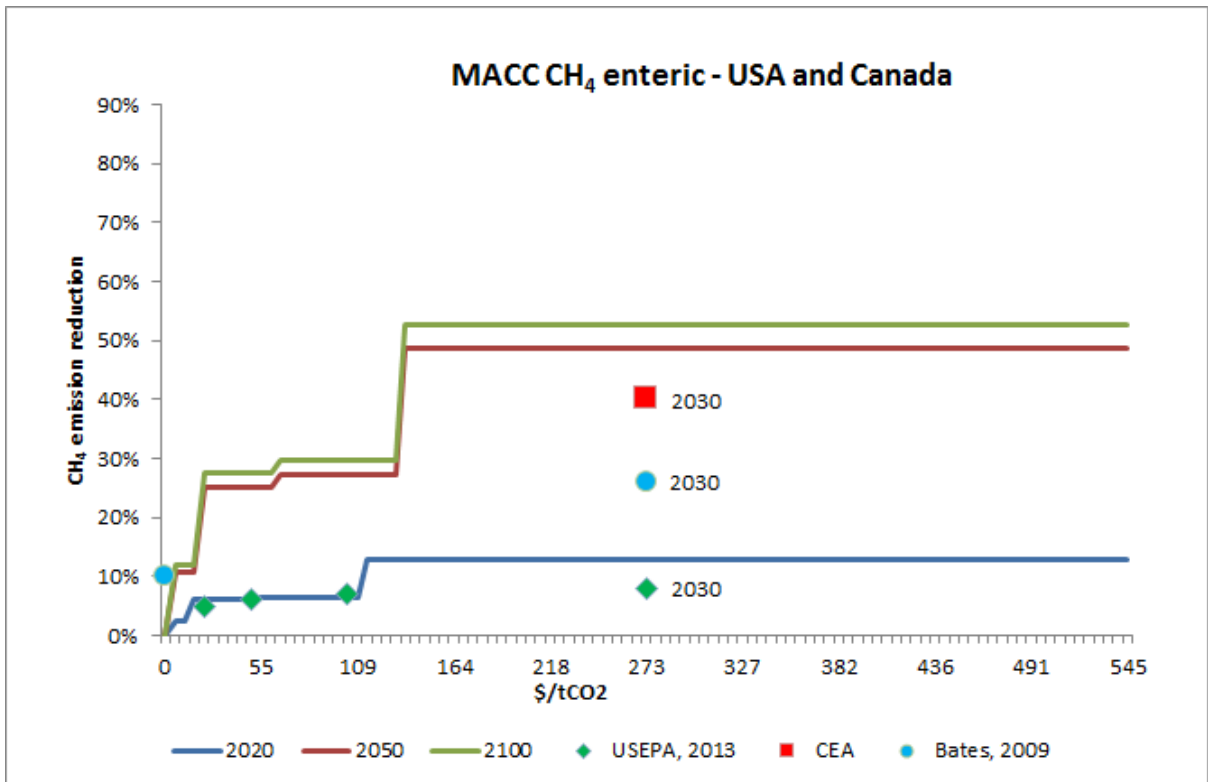


Figure S3.6. MAC curve for enteric fermentation for Canada and USA

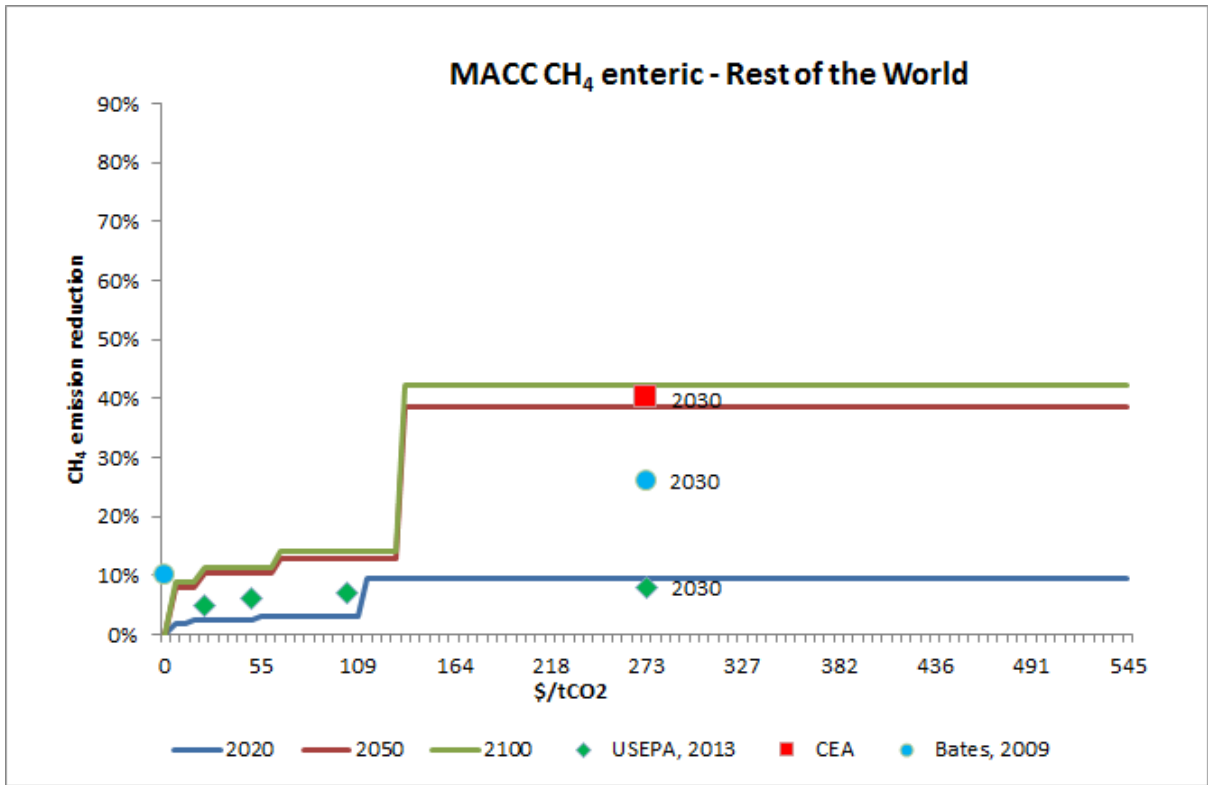


Figure S3.7. MAC curve for enteric fermentation for all other regions than Canada and USA

## MAC curve for Animal waste CH<sub>4</sub>

	Technical Applicability	Reduction efficiency	Correction for overlap			Abatement potential *		
			2020	2050	2100	2020	2050	Max 2100 /
Decrease manure storage time	90%	35%	100%	100%	100%	6%	16%	22%
Manure storage covering	50%	30%	47%	42%	39%	1%	3%	4%
Digester	90%	75%	92%	81%	74%	12%	27%	35%
Manure acidification	50%	77%	16%	11%	8%	1%	2%	2%
Housing and bedding	50%	35%	20%	13%	9%	1%	1%	1%
<b>Max reduction potential</b>						22%	49%	64%

\* Excluding technological progress and correction for baseline emission reductions

Implementation potential 2020	20%
Implementation potential 2050	50%
Max Abatement Potential (2100)	70%

The mitigation measures that have been used to construct the MAC curve are the following (taking into account overlap between measures and aiming for the highest MRP):

1. Digesters: Application of anaerobic digester for either small-scale farm systems, or centralized plants in intensive agricultural areas. The biogas generated from anaerobic digestion is used to produce heat or both heat and electricity. **Medium high cost, average cost-effectiveness 0–52 \$/tCO<sub>2</sub>eq** (Graus et al., 2004) **average CH<sub>4</sub> reduction efficiency 75% (warm climates), 50% (cool climates)**
2. Decreased manure storage time: Reduced storage time through frequent land application to avoid the anaerobic conditions that create CH<sub>4</sub>; can also reduce N<sub>2</sub>O emissions depending on application timing. **Low to medium cost, average cost-effectiveness 30 \$/tCO<sub>2</sub>eq** (No data, estimated value used), **average CH<sub>4</sub> reduction efficiency 35%**
3. Manure storage covering: Covering manure storages with permeable or impermeable covers is an effective mitigation practice. However with an impermeable cover the CH<sub>4</sub> captured under the cover is burned using a flare system or engine-generator to produce electricity; otherwise the captured CH<sub>4</sub> would build pressure inside the storage creating an explosion hazard and/or escape through leaks and cover ruptures. **Low cost, average cost-effectiveness 70 \$/tCO<sub>2</sub>eq** (Weiske and Michel, 2007) **average CH<sub>4</sub> reduction efficiency 30%**
4. Housing systems and bedding: Concrete slatted floors with drainage/flush systems result in fewer emissions than solid floors with hay or other bedding may reduce both CH<sub>4</sub> and N<sub>2</sub>O emission. **Medium cost, average cost-effectiveness 149 \$/tCO<sub>2</sub>eq** (Weiske and Michel, 2007) **average CH<sub>4</sub> reduction efficiency 35%** (Dickie et al., 2014)
5. Manure acidification: Manure acidification decreases NH<sub>3</sub> volatilization by 14 to 100%. Ammonia volatilization is directly proportional to the proportion of NH<sub>3</sub>-N in the total ammoniacal nitrogen (TAN) in manure. At constant temperature, the dissociation constant (K<sub>d</sub>), which is a function of medium pH, determines the equilibrium between ammonium and NH<sub>3</sub> in aqueous systems. Lower manure pH results in lower proportion of NH<sub>3</sub> and, therefore, decreased potential of NH<sub>3</sub> volatilization. **Average cost-effectiveness 83 \$/tCO<sub>2</sub>eq** (Eory et al., 2016) **average CH<sub>4</sub> reduction efficiency 77%** (Hristov et al., 2013; Ndegwa et al., 2008; Petersen et al., 2012)

The following measures have been excluded from the MAC curve (due to overlap with the measures above and/or lower reduction potentials):

1. Manure composting: Composting of animal manure causes significant N and CO<sub>2</sub> losses, but the benefits of reducing odour and CH<sub>4</sub> emissions, compared with anaerobically-stored manure, make it a recommended GHG mitigating option. Nitrogen losses, predominantly as NH<sub>3</sub> but also as N<sub>2</sub>O, however, are large. **Moderate cost, average CH<sub>4</sub> reduction efficiency > 30%.**
2. Animal Husbandry: Improved health monitoring and illness prevention or Prevention, control and eradication of diseases: Controlling or eradicating endemic livestock diseases represents an opportunity to reduce emission intensity of livestock products without compromising productivity. Identification and prioritization of region specific target diseases, estimating their abatement potential and cost would be important to assess contribution of this mitigation measure to reduce GHG emission from global livestock sector. **Small to medium economic benefit, average CH<sub>4</sub> reduction efficiency 15%.**
3. Animal Husbandry: Improved productive life: Extending productive lifetime of animals can decrease total GHG emissions per total product over the animal's lifetime and is already classified as a best practice (Joint report by GRA and SAI). Different approaches include improved conception rates, earlier time of first reproduction and increasing reproductive lifetime, and adjusting overall lifetime to minimise overall GHG emissions per unit of product (which implies increasing longevity for dairy cows, but also reducing time to slaughter for beef cattle through higher growth rates). **Small economic benefit, average CH<sub>4</sub> reduction efficiency 10%.**
4. Animal Husbandry: Improving animal productivity and reducing herd size: In most part of the world, the single most effective GHG mitigation strategy is to increase animal productivity while reducing the herd size aiming the same amount of edible product output. The two major constrains for increasing animal productivity is the genetic potential of the animals and availability of quality feed. The genetic production potential of an animal can be achieved through planned cross breeding or selection within breeds and proper nutrition. **average CH<sub>4</sub> reduction efficiency ≥30%**

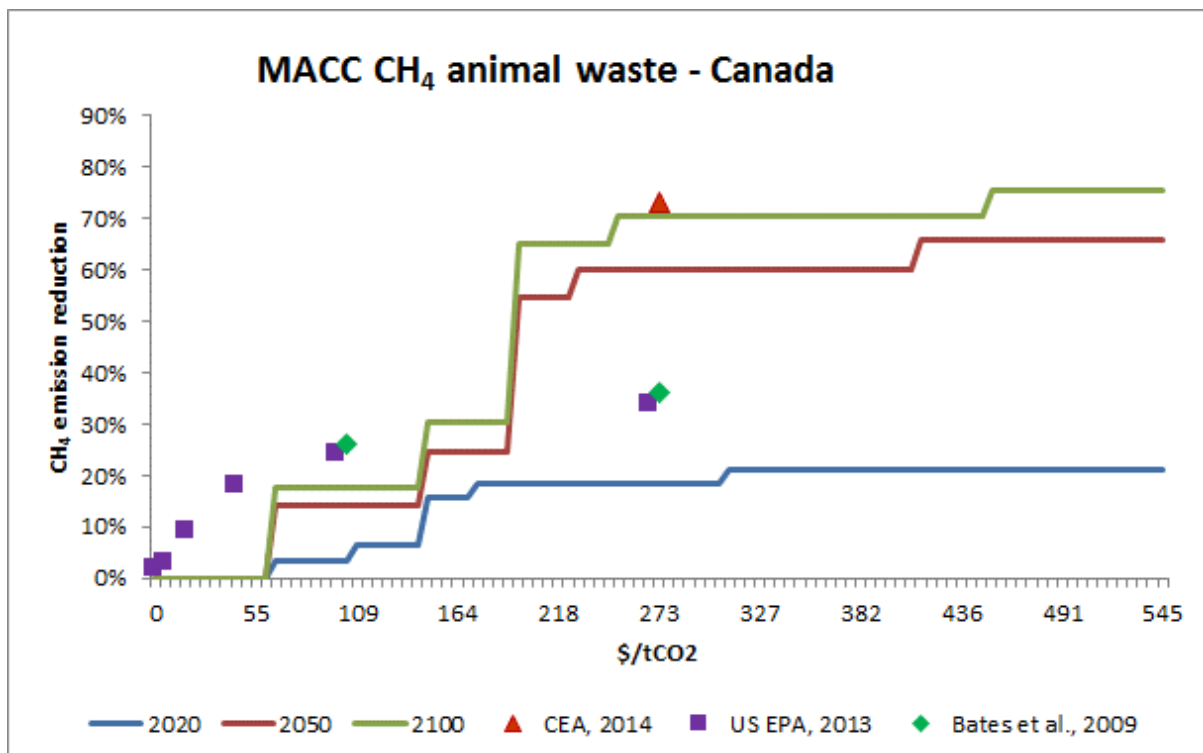


Figure S3.8. MAC curve for animal waste CH<sub>4</sub> in Canada

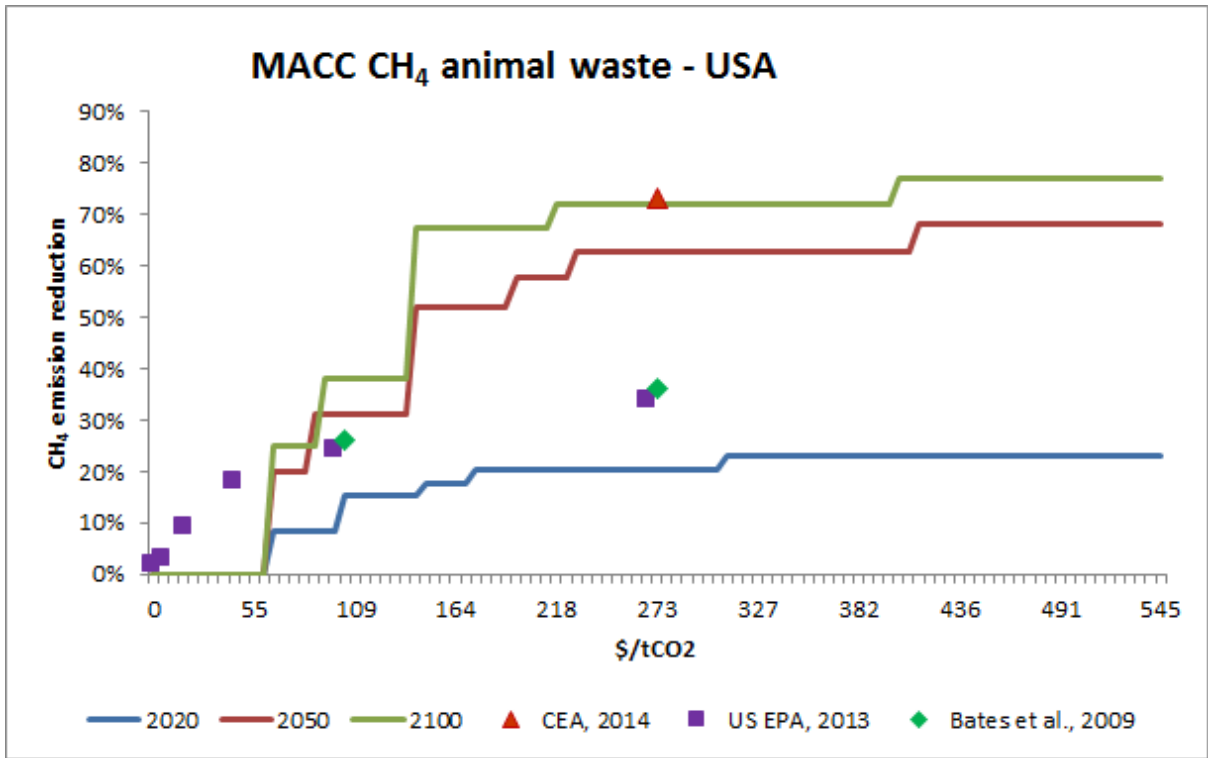


Figure S3.9. MAC curve for animal waste CH<sub>4</sub> in USA

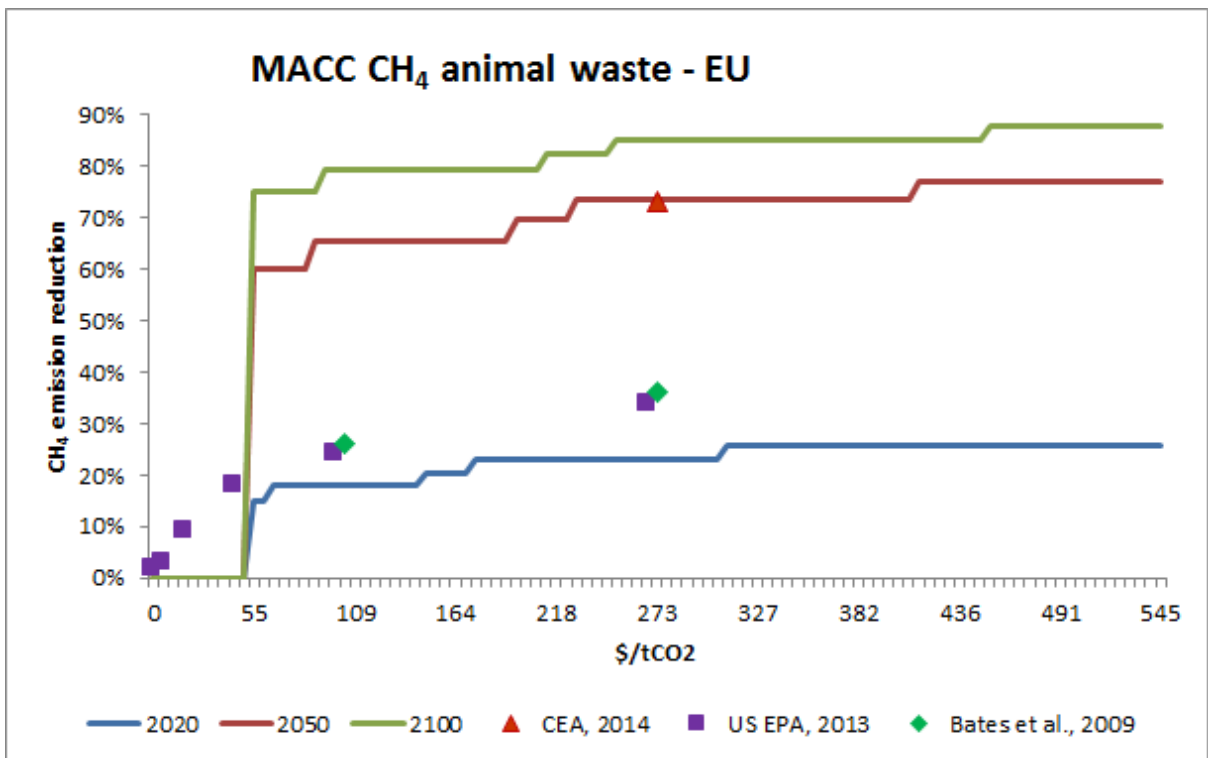


Figure S3.10. MAC curve for animal waste CH<sub>4</sub> in Eastern Europe

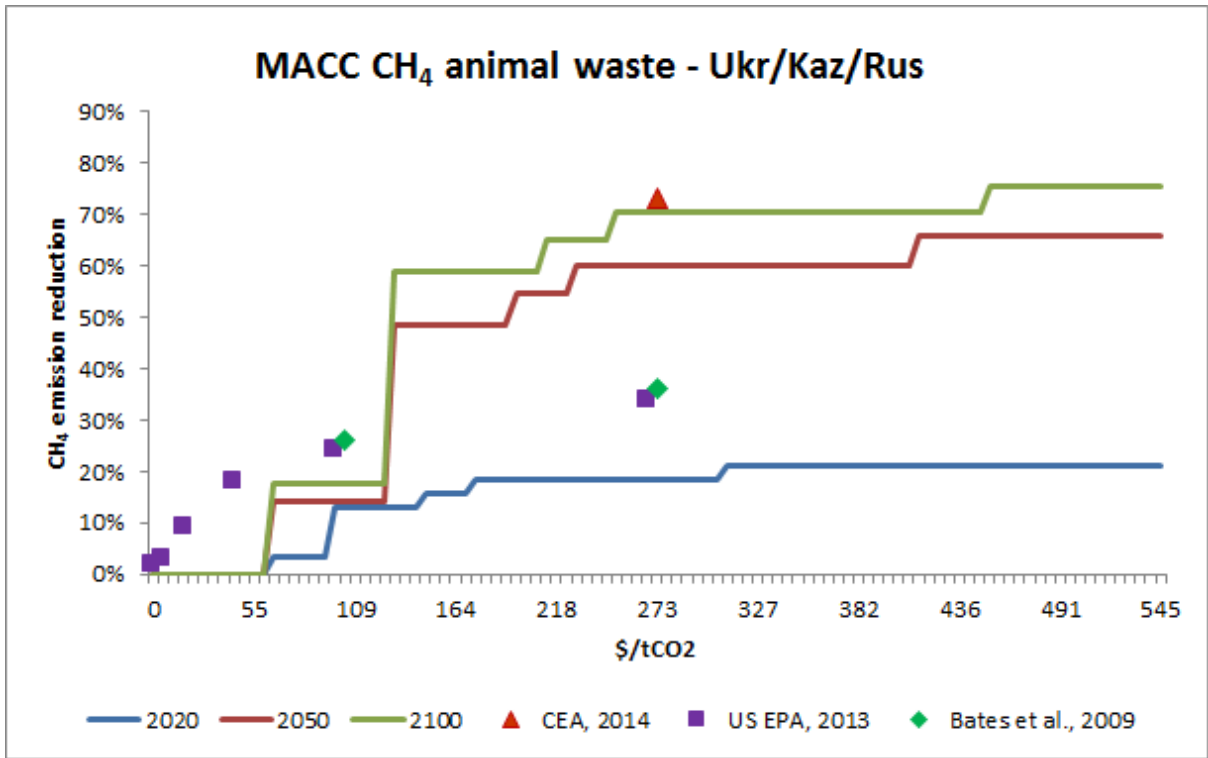


Figure S3.11. MAC curve for animal waste CH<sub>4</sub> in Ukraine, Kazakhstan and Russia

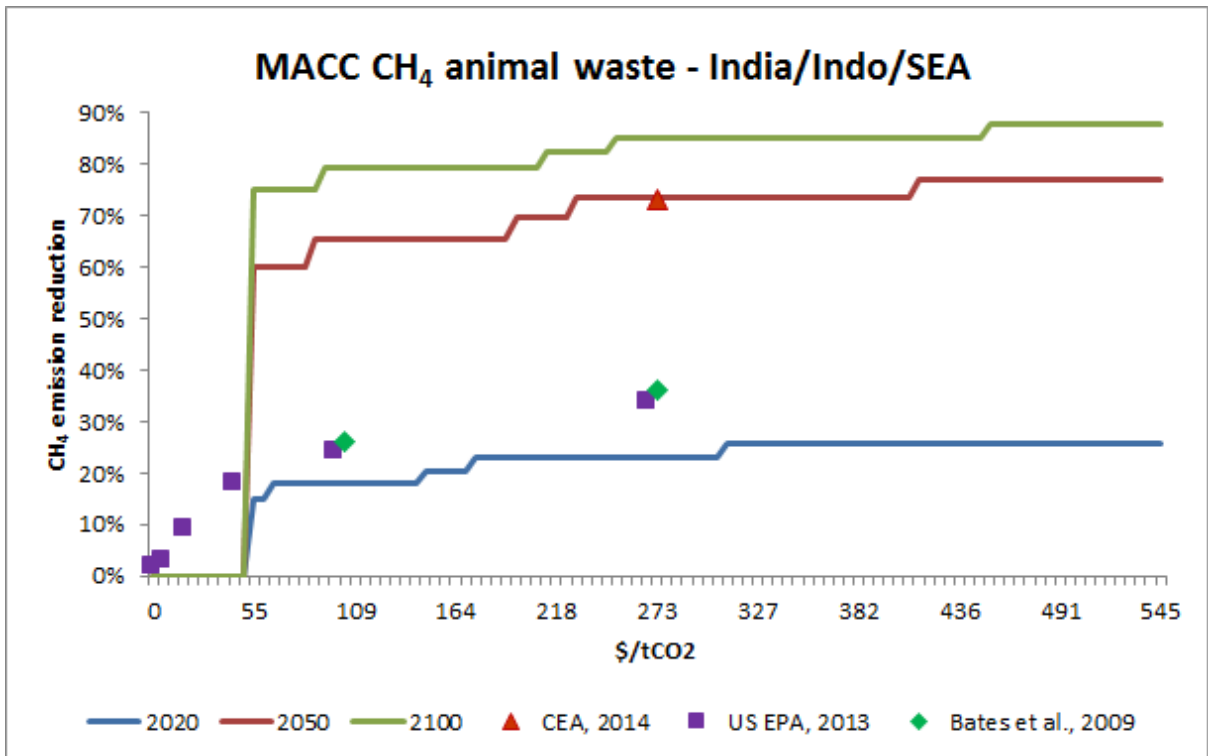


Figure S3.12. MAC curve for animal waste CH<sub>4</sub> in India, Indonesia and South East Asia

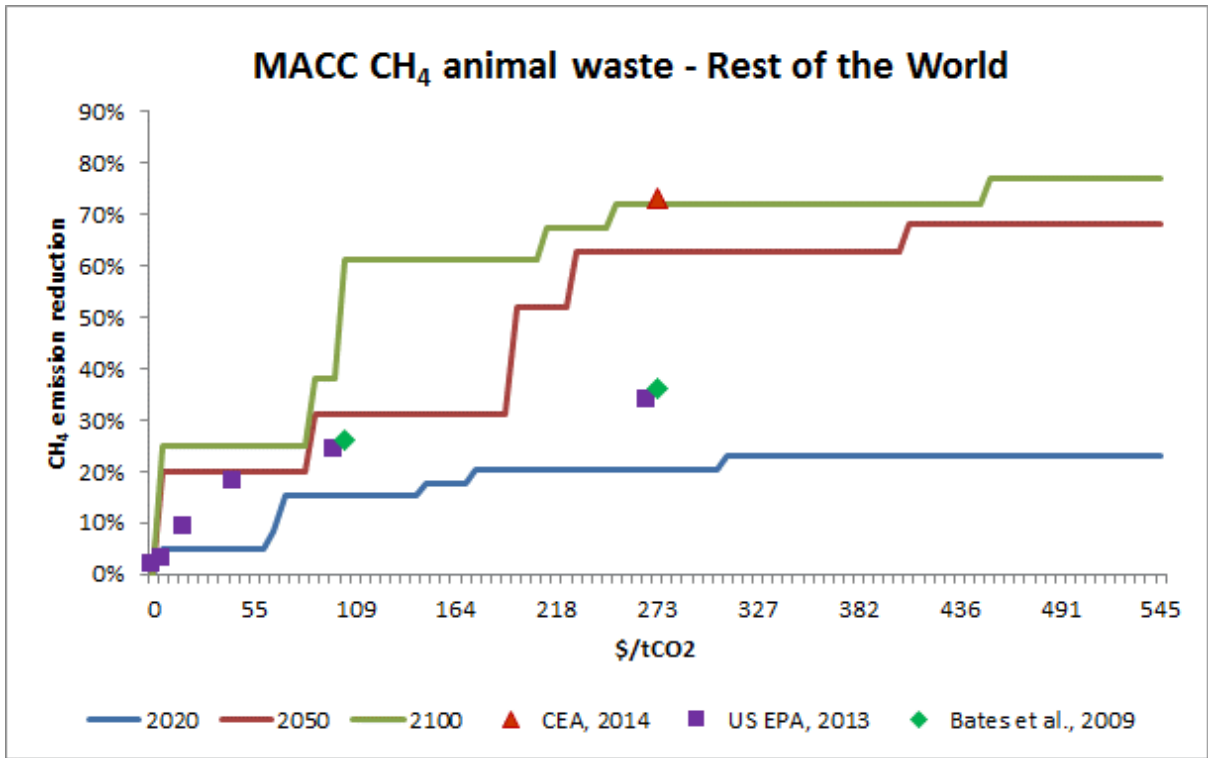


Figure S3.13. MAC curve for animal waste CH<sub>4</sub> in the rest of the world



## MAC curve for Fertilizer N<sub>2</sub>O

	Technical Applicability	Reduction efficiency	Correction for overlap			Abatement potential *		
			2020	2050	2100	2020	2050	Max 2100 /
Improved land manure application	45%	14%	70%	70%	70%	0%	3%	4%
Spreader maintenance	100%	22%	50%	48%	48%	1%	7%	11%
Improved agronomy practices	45%	20%	34%	31%	30%	0%	2%	3%
Sub-optimal fertilizer applications	45%	26%	69%	61%	58%	1%	5%	7%
Nitrification inhibitors	100%	38%	97%	82%	76%	4%	22%	29%
Fertilizer free zone	100%	4%	94%	61%	47%	0%	2%	2%
<b>Max reduction potential</b>						<b>7%</b>	<b>41%</b>	<b>55%</b>

\* Excluding technological progress and correction for baseline emission reductions

Implementation potential 2020	10%
Implementation potential 2050	70%
Max Abatement Potential (2100)	100%

The mitigation measures that have been used to construct the MAC curve are the following (taking into account overlap between measures and aiming for the highest MRP):

1. Use of nitrification inhibitors: Nitrification inhibitors such as DCD, Nimin reduces N<sub>2</sub>O emission by slowing the conversion of ammonium to nitrate. **Cost increases by 9% to 10% as compared to only inorganic fertilizer, average cost-effectiveness 32–177 \$/tCO<sub>2</sub>eq** (Basak, 2015; Eory et al., 2016), **average N<sub>2</sub>O reduction efficiency 38%**. (Akiyama et al., 2010; Bates et al., 2009; Dickie et al., 2014; Moran et al., 2008; Torralbo et al., 2017; US-EPA, 2013; Wu et al., 2017; Zhu et al., 2016)
2. Sub-optimal fertilizer applications, winter wheat: reduce N-based fertilizer by 50 kg/ha. **Medium high cost, average cost-effectiveness -17 – 851 \$/tCO<sub>2</sub>eq** (Graus et al., 2004) **average N<sub>2</sub>O reduction efficiency 26%**
3. Spreader maintenance: more uniform spreading to increase efficiency; avoid over-application and under-application. **Reduced cost, average cost-effectiveness -59 – -1 \$/tCO<sub>2</sub>eq** (Graus et al., 2004) **reduction potential estimate: 22%** (Graus et al., 2004)
4. Improved land manure application: Options such as reducing inorganic N application with allowance for manure/residual N, improved timing of slurry and manure application, separating slurry/manure applications from fertiliser applications by several days, applying manure to dry rather than wet areas, applying solid rather than liquid manure could be included to this category. **Mostly reduced cost, average cost-effectiveness -78 \$/tCO<sub>2</sub>eq** (Bates et al., 2009; MacLeod et al., 2010; Moran et al., 2008) **average N<sub>2</sub>O reduction efficiency 14%** (Dickie et al., 2014; Eagle et al., 2012; Moran et al., 2008)
5. Improved agronomy practices. Adopting systems less reliant on inputs (nutrient, pesticides), plant varieties with improved N-use efficiency, use of rotations with legume crops, use of catch or cover crops reduces N<sub>2</sub>O emission. **Low cost, average cost-effectiveness 4 \$/tCO<sub>2</sub>eq** (Eory et al., 2016; Smith et al., 2008), **average N<sub>2</sub>O reduction efficiency 20%** (Moran et al., 2008)

- Fertilizer free zone: avoiding fertilizer loss by leaving fertilizer free zones at field edges. **Very high cost, average cost-effectiveness 103 –1036 \$/tCO<sub>2</sub>eq** (Graus et al., 2004) **average N<sub>2</sub>O reduction efficiency 4%** (Graus et al., 2004)

The following measures have been excluded from the MAC curve (due to overlap with the measures above and/or lower reduction potentials):

- Controlled release fertilizer: Slow or controlled release fertilizers could increase recovery of N and minimize N losses to environment. **Increased cost, average N<sub>2</sub>O reduction efficiency 23%**
- Optimizing timing of N application: Synchronous timing of N application or split application of N according to crop demand may reduce N loss, including N<sub>2</sub>O emission. **Increased cost, average N<sub>2</sub>O reduction efficiency 7%**
- Improved placement of N: Deep placement of N as compared to shallow placement particularly in reduced or no tillage system could decrease N<sub>2</sub>O emission by 26%. In the US, improved N fertilizer placement was achieved through banding. **Increased cost with requirement of specialized equipment and increased labour, average N<sub>2</sub>O reduction efficiency 13%**

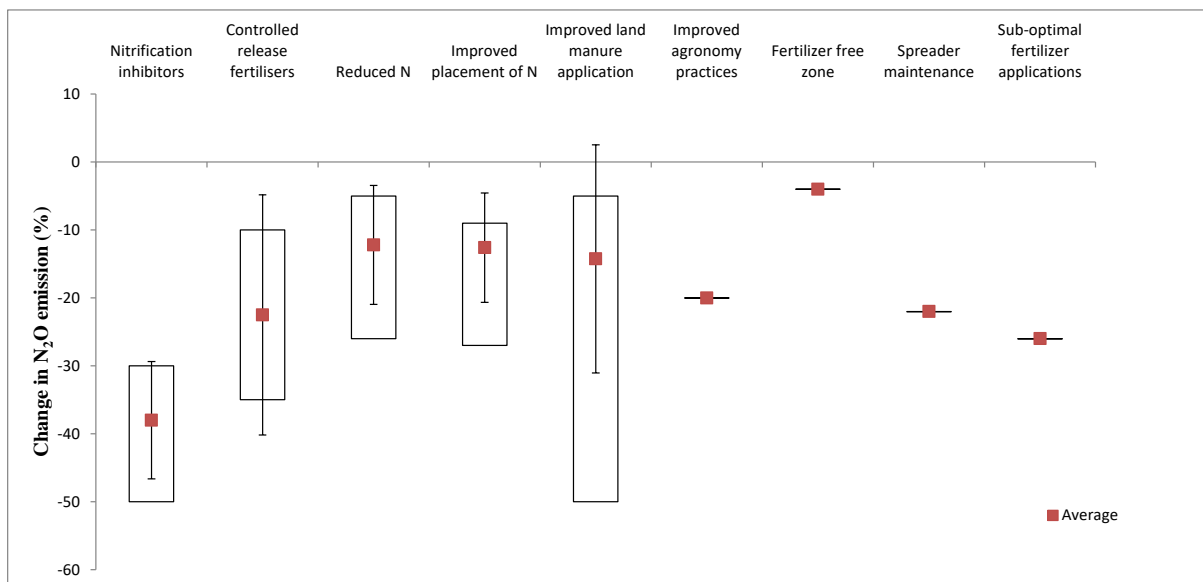


Figure S3.15. Reduction potential of different N<sub>2</sub>O fertilizer mitigation measures.

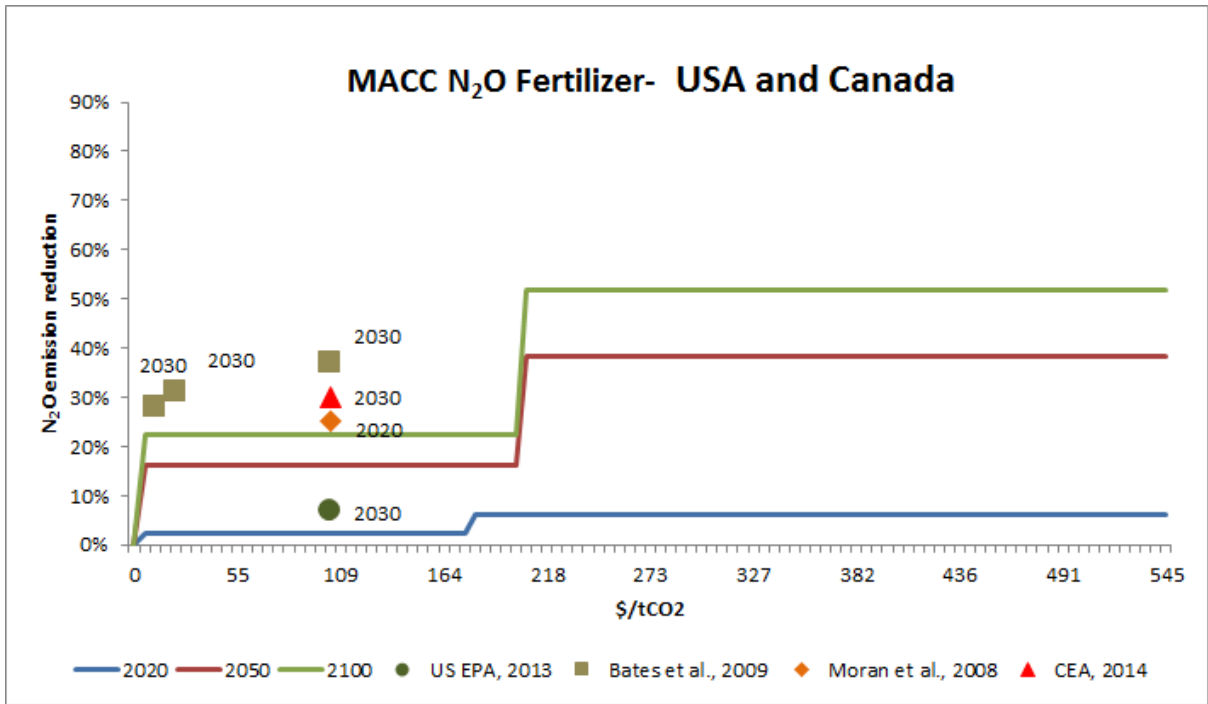


Figure S3.16. MAC curve for fertilizer N<sub>2</sub>O for Canada/USA

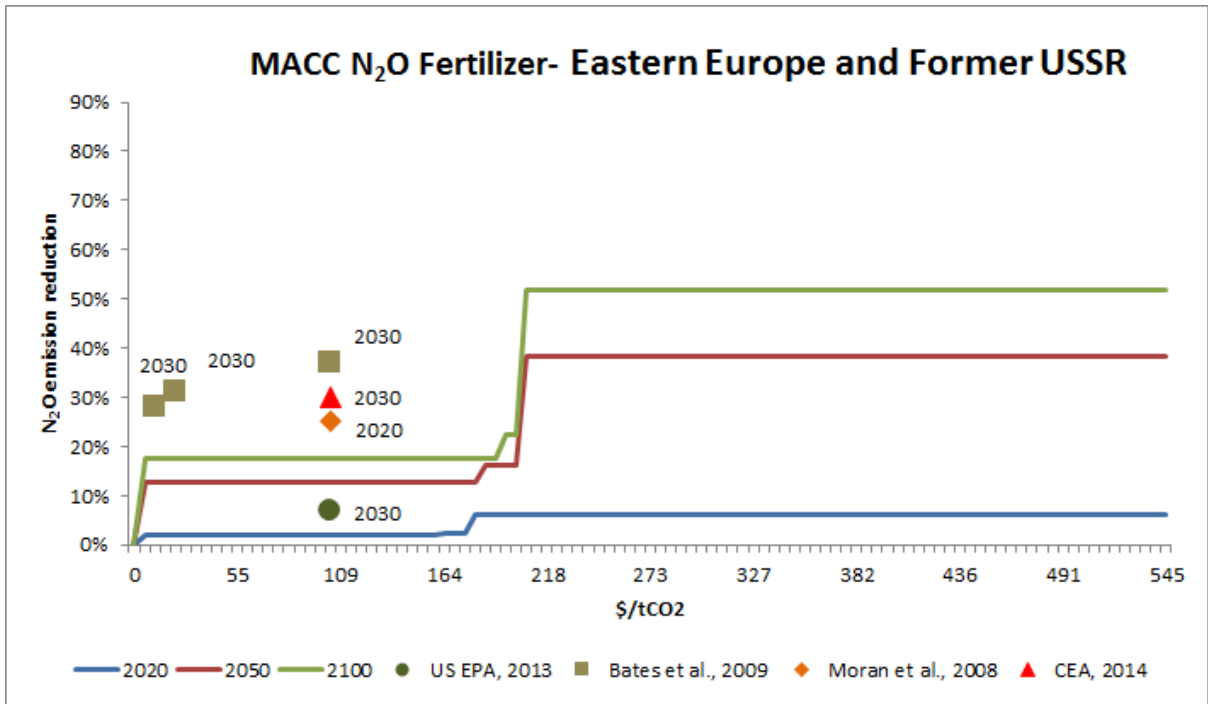


Figure S3.17. MAC curve for fertilizer N<sub>2</sub>O for Eastern Europe and former USSR

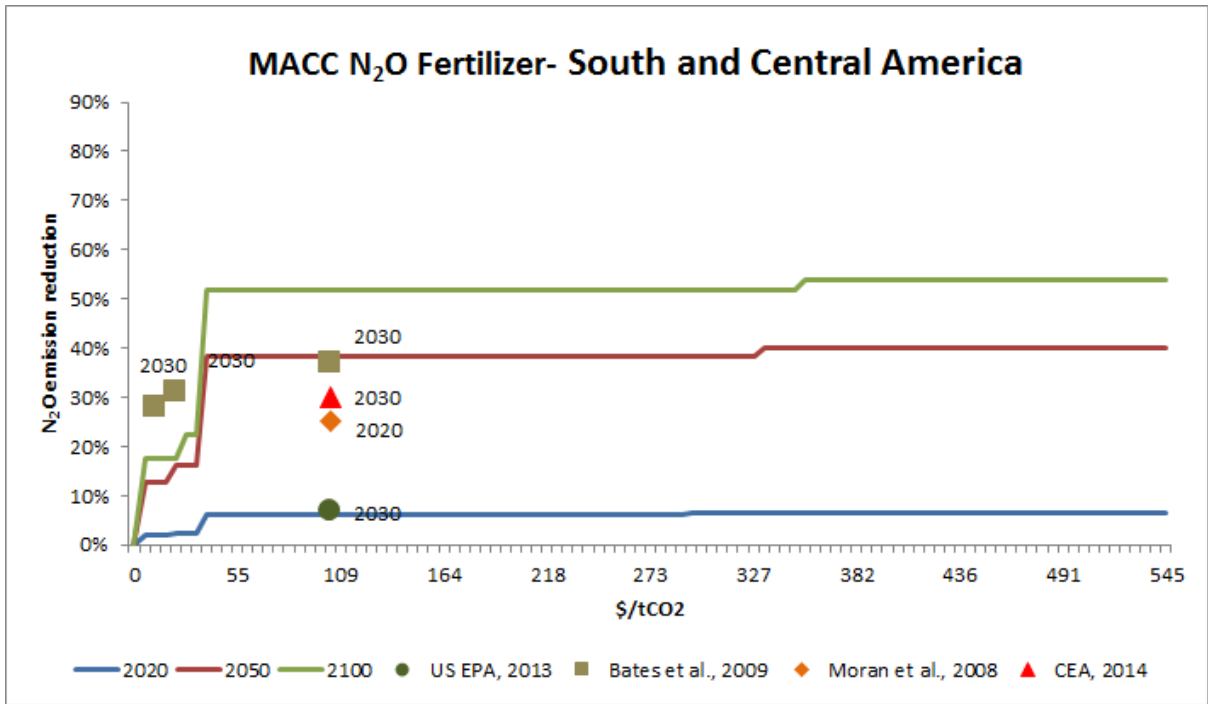


Figure S3.18. MAC curve for fertilizer N<sub>2</sub>O for South America and Central America

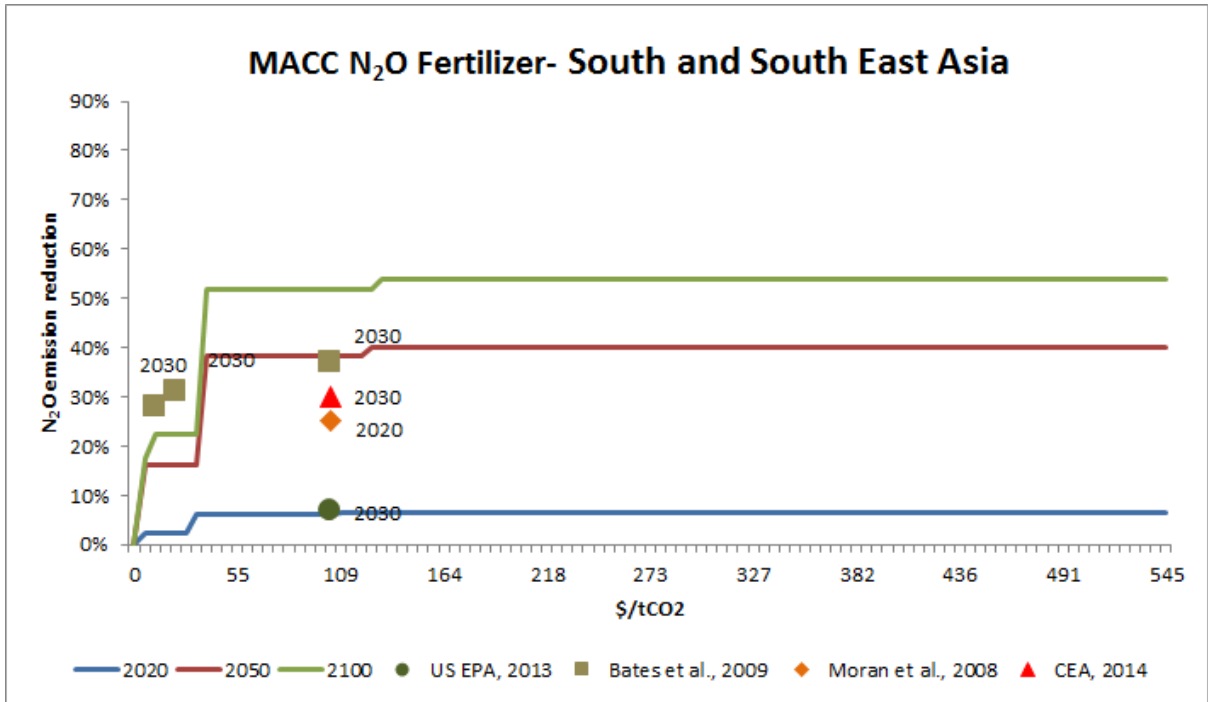


Figure S3.19. MAC curve for fertilizer N<sub>2</sub>O for South Asia and South East Asia

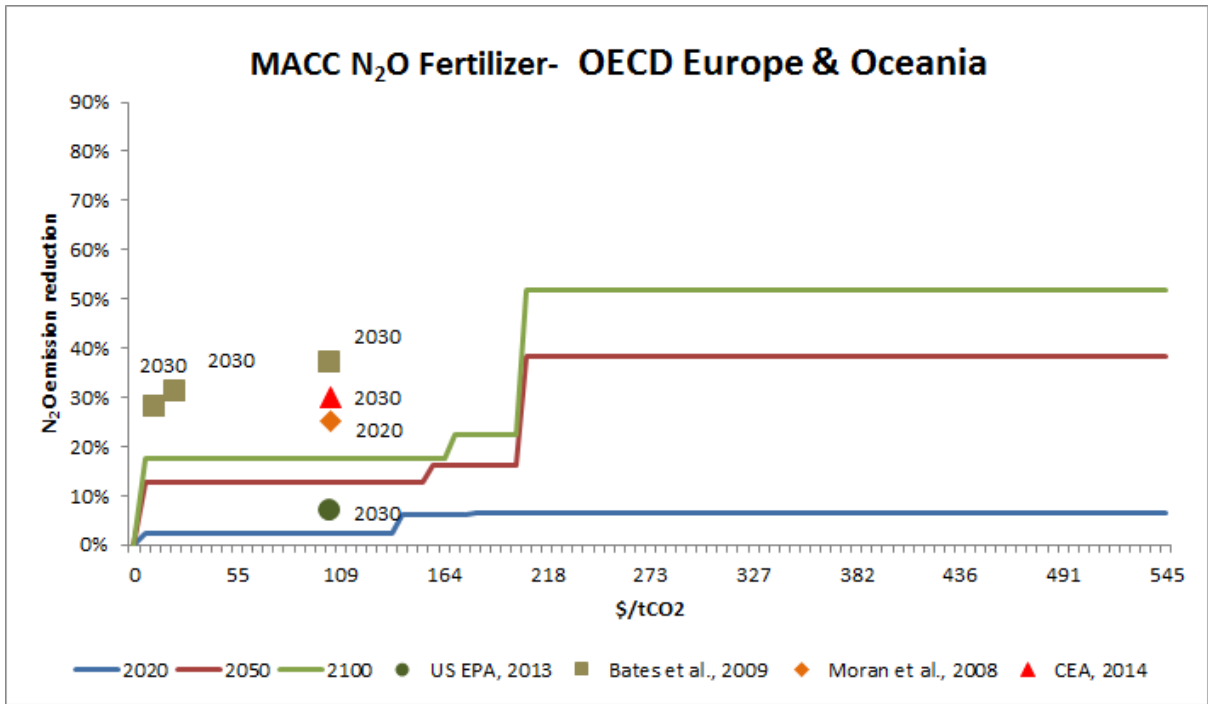


Figure S3.20. MAC curve for fertilizer N<sub>2</sub>O for Europe & Oceania

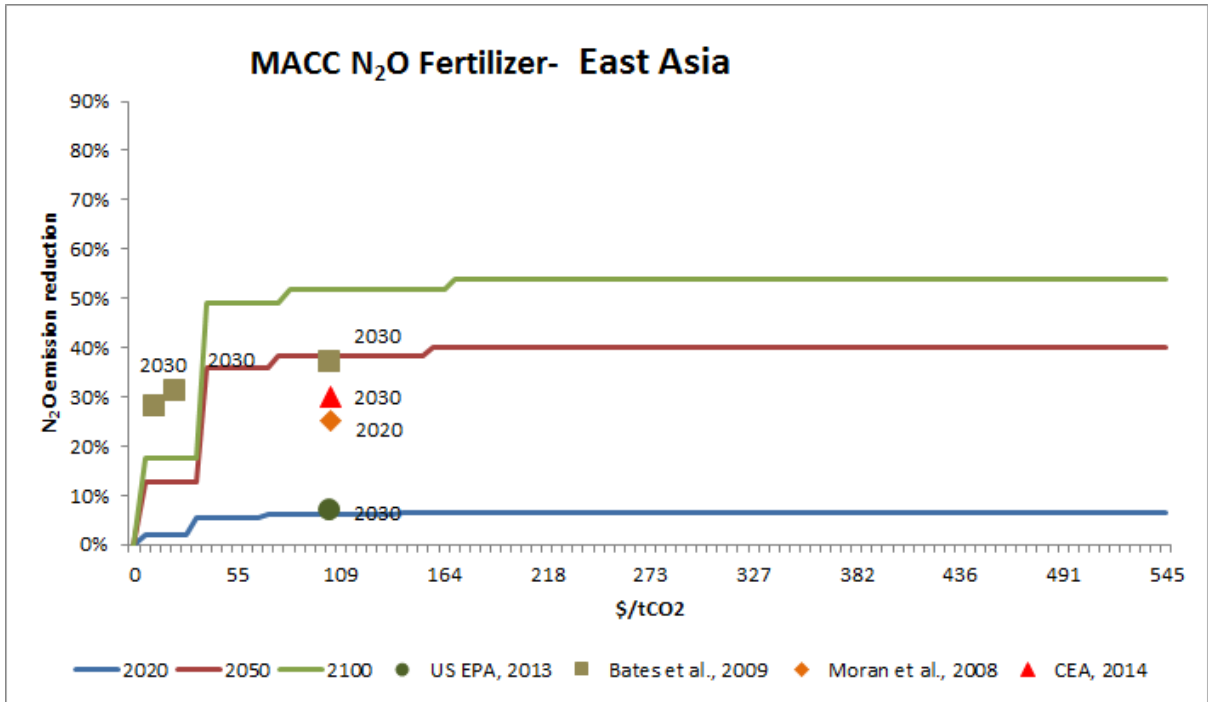


Figure S3.21. MAC curve for fertilizer N<sub>2</sub>O for East Asia

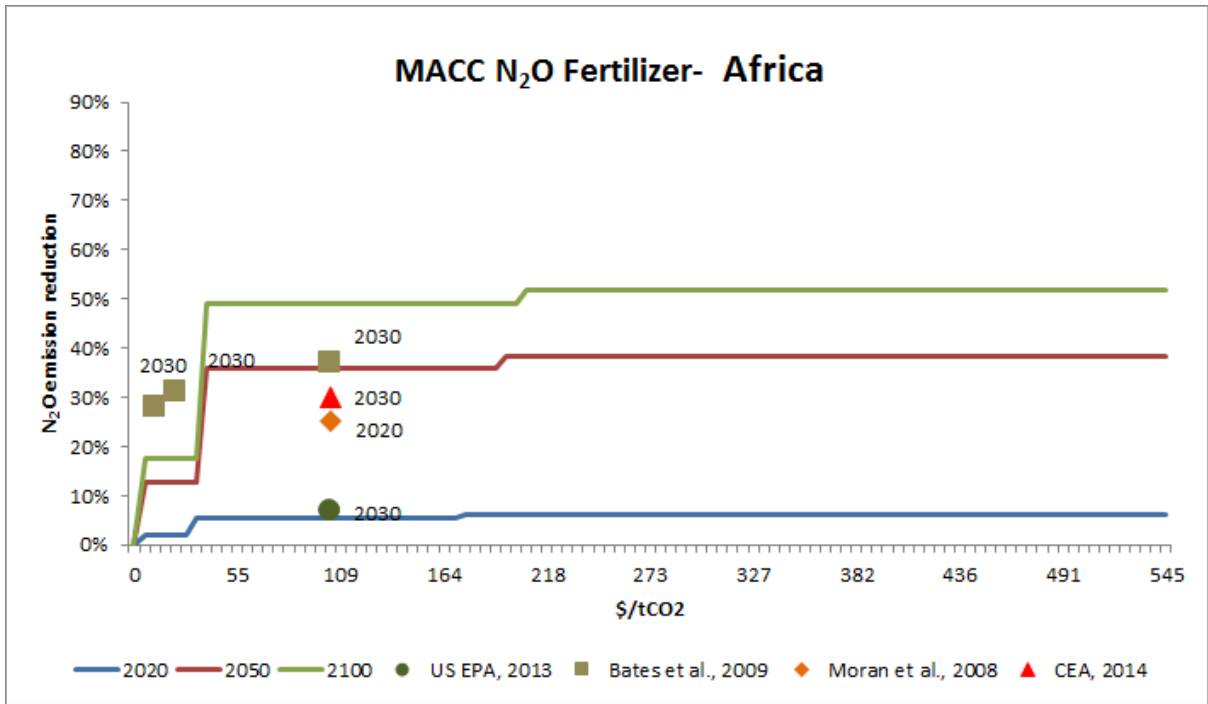


Figure S3.22. MAC curve for fertilizer N<sub>2</sub>O for Africa

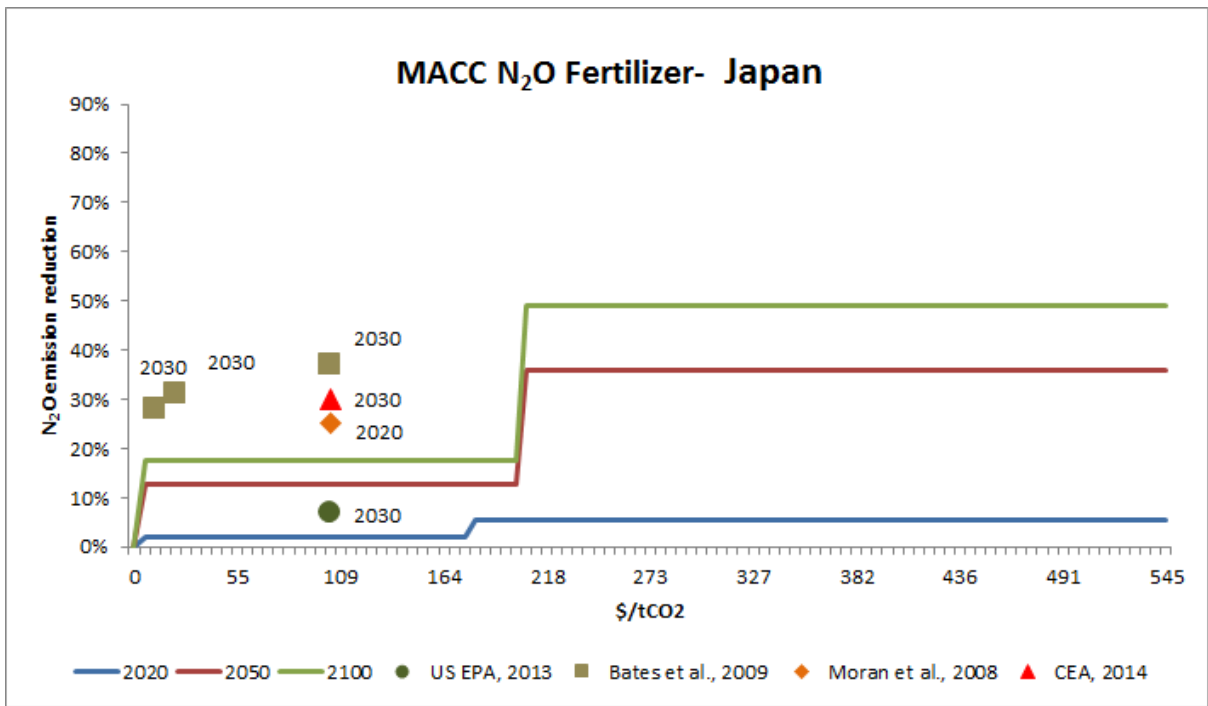
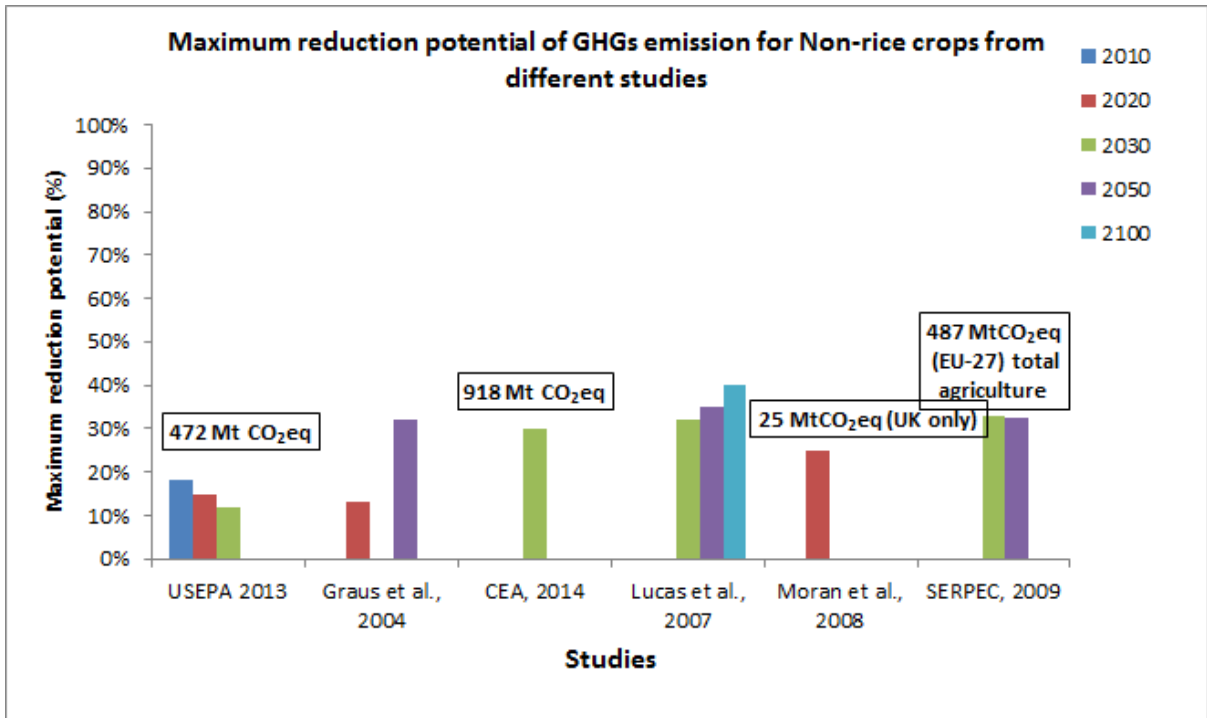


Figure S3.23. MAC curve for fertilizer N<sub>2</sub>O for Japan



**Figure S3.24** Maximum reduction potential (%) of Fertilizer/soil GHG emission from non-rice crops collated from literature. Values in the square boxes are baseline emissions for different future years. For CEA, (2014), baseline emission includes emissions from synthetic fertilizers, crop residues and manure applied to soil. Baseline emissions and mitigation potential for SERPEC(2009) include both emissions and mitigation from crops and livestock for the year 2005.

## MAC curve for Animal waste N<sub>2</sub>O

	Technical Applicability	Reduction efficiency	Correction for overlap			Abatement potential *		
			2020	2050	2100	2020	2050	Max 2100
								/
<b>Decrease manure storage time</b>	100%	35%	100%	100%	100%	7%	18%	25%
<b>Reduced dietary protein</b>	50%	25%	93%	83%	76%	2%	5%	7%
<b>Manure storage covering</b>	100%	30%	45%	39%	34%	3%	6%	7%
<b>Housing and bedding</b>	100%	35%	88%	72%	62%	6%	13%	15%
<b>Max reduction potential</b>						<b>18%</b>	<b>41%</b>	<b>53%</b>

\* Excluding technological progress and correction for baseline emission reductions

Implementation potential 2020	20%
Implementation potential 2050	50%
Max Abatement Potential (2100)	70%

The mitigation measures that have been used to construct the MAC curve are the following (taking into account overlap between measures and aiming for the highest MRP):

1. Reduced dietary protein: An important opportunity to reduce N<sub>2</sub>O emissions from animal manure is to maintain dietary protein close to animal requirements. Studies with pigs, poultry, and beef and dairy cattle have consistently shown that a reduction in dietary protein results in a reduction of excreta N losses, which results in reduced NH<sub>3</sub> and potentially N<sub>2</sub>O emissions from manure. **Low cost, average cost-effectiveness 86 \$/tCO<sub>2</sub>eq** (McKinsey, 2010) **average N<sub>2</sub>O reduction efficiency 25%** (Hristov et al., 2013).
2. Manure storage\_ decreased storage time: Reduced storage time through frequent land application to avoid the anaerobic conditions that create CH<sub>4</sub>; can also reduce N<sub>2</sub>O emissions depending on application timing. **Low to medium cost, average cost-effectiveness 30 \$/tCO<sub>2</sub>eq (No data, estimated value used), average N<sub>2</sub>O reduction efficiency 35%** (Hristov et al., 2013)
3. Manure storage covering: Covering manure storages with permeable or impermeable covers is an effective mitigation practice. However with an impermeable cover the CH<sub>4</sub> captured under the cover is burned using a flare system or engine-generator to produce electricity; otherwise the captured CH<sub>4</sub> would build pressure inside the storage creating an explosion hazard and/or escape through leaks and cover ruptures. **Low cost, average cost-effectiveness 70 \$/tCO<sub>2</sub>eq** (Weiske and Michel, 2007) **average N<sub>2</sub>O reduction efficiency 30%** (Dickie et al., 2014; Hristov et al., 2013)
4. Housing systems and bedding: Concrete slatted floors with drainage/flush systems result in fewer emissions than solid floors with hay or other bedding may reduce both CH<sub>4</sub> and N<sub>2</sub>O emission. **Varies (depends on existing system), average cost-effectiveness 149 \$/tCO<sub>2</sub>eq** (Weiske and Michel, 2007), **average N<sub>2</sub>O reduction efficiency 35%** (Dickie et al., 2014)

The following measure has been excluded from the MAC curve (due to overlap with the measures above and/or lower reduction potentials):



1. Manure separation and composting of solid manure: Separation of manure into liquid and solids and aerobically composting the solids has been shown to reduce CH<sub>4</sub> but may have a variable effect on N<sub>2</sub>O emissions and will increase NH<sub>3</sub> and total manure N losses.  
*Estimated N<sub>2</sub>O, average N<sub>2</sub>O reduction efficiency 35%*

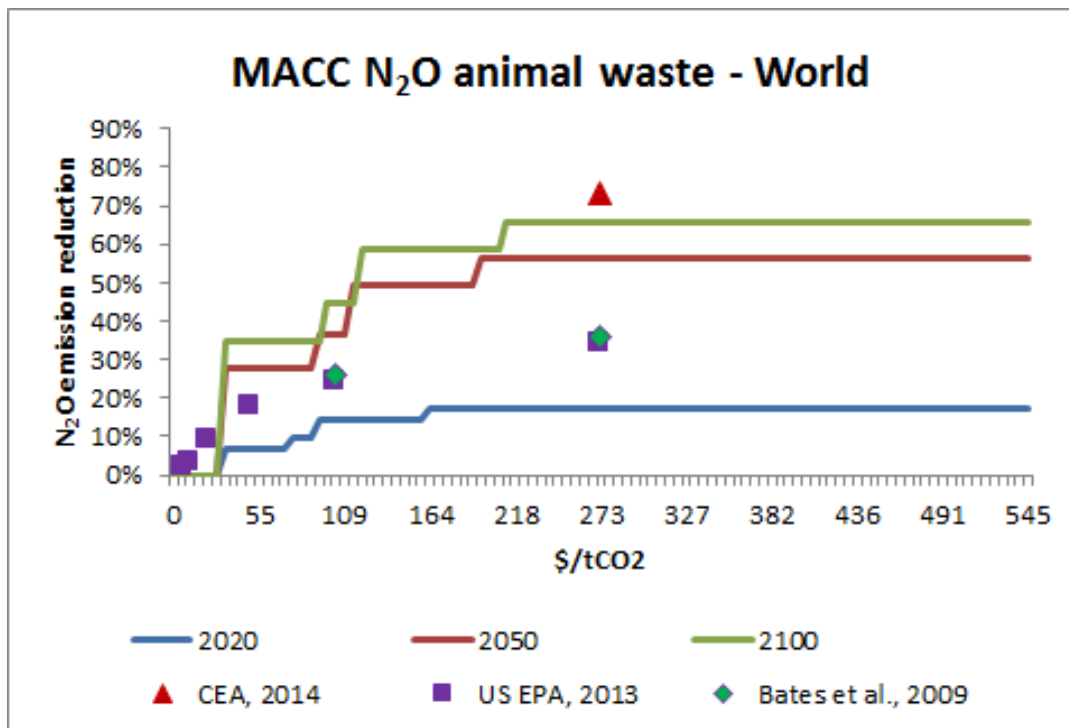


Figure S3.25. MAC curve for animal waste N<sub>2</sub>O

#### S4. Interactions between mitigation measures in agriculture

Agricultural mitigation measures can either be applied independently (stand-alone) or in combination with other measures. In practical situations, a combination of mitigation measures are applied together either on the same piece of land or livestock production system. However, the integrated mitigation potential is rarely the sum of the potential of individual measures implemented independently, because when measures are applied in combination, they interact and their mitigation potential changes in response to the measures that they combine with. Complex biological processes in the agricultural system are primarily responsible for such interactions.

Example 1: (Moran et al., 2008; Macleod et al., 2010)

If a farm implements measure A (biological fixation), then less N fertiliser will be required, lessening the extent to which N fertiliser can be reduced (measure B).

$$\text{Interaction factor (AB)} = \frac{\text{Abatement rate of measure B when applied after A}}{\text{Stand alone abatement rate of measure B}}$$

When considering potential interactions between two measures, it is also necessary to consider whether one measure enables the second rather than if it directly competes for a direct reduction in the pollutant. For example, the improvement of field drainage would enable spring application of manure and therefore allow for the full impact of the improved manure timing method to be achieved. However, field drainage would not enable improved timing of mineral N fertiliser with respect to crop need.

Example 2: (Eckard et al., 2010)

A hypothetical example of how mitigation practices may have a cumulative effect in decreasing GHG emissions from a dairy production system has been given by Eckard et al. (2010). In their example, improved feed conversion efficiency through breeding (10 percent less CH<sub>4</sub> when applied alone), feeding of dietary lipids (10 percent less CH<sub>4</sub> when applied alone), extended lactation management system (10 percent less CH<sub>4</sub> when applied alone) and use of a nitrification inhibitor on the paddocks twice a year (61 percent less N<sub>2</sub>O when applied alone), could result in a cumulative reduction of 40 percent in whole-farm GHG emissions (versus 91 percent, if considered to be mutually exclusive and/or additive).

Mitigation interaction for Rice CH<sub>4</sub> emission

Mitigation measures	Alternate flooding/ drainage	Mid-season drainage	Mid-season drainage /no organic matter	Conservation tillage	Direct seeding	Direct seeding/mid-season drainage	Off season straw	Phosphogypsum	Replace urea with Ammonium sulphate	Straw compost	Straw mulching
Alternate flooding/drainage	H*										
Mid-season drainage	H*	H*									
Mid-season drainage/no organic matter	H*	H	H*								
Conservation tillage	N	N	H*	H*							
Direct seeding	N	N	N	L	H*						
Direct seeding/mid-season drainage	H*	H	H	L	H	H*					
Off season straw	N	N	H*	H*	N	N	H*				
Phosphogypsum	N	N	N	N	N	N	N	H*			
Replace urea with Ammonium sulphate	N	N	N	N	N	N	N	N	H*		
Straw compost	N	N	H*	H*	N	N	H*	N	N	H*	
Straw mulching	N	N	H*	H*	N	N	H*	N	N	H*	H*

H: High, indicates strong interaction, may not be able to do together, if applied together mitigation potential for the second measure could be only 20% of the real potential (Interaction factor = 0.2).

M: Medium interaction, can be practised together, if applied together mitigation potential for the second measure could be only 50% of the real potential (Interaction factor = 0.5).

L: low level interaction, can be practised together, if applied together mitigation potential for the second measure could be only 70% of the real potential (Interaction factor = 0.5).

N: No interaction, can be used together, mitigation potential are additive, if applied together mitigation potential for the second measure could be 100% of the real potential (Interaction factor = 1).

\*: unlikely that these measures would be applied at the same time.

Mitigation measures interaction for fertilizer N<sub>2</sub>O

	Fertilizer free zone	Sub-optimal fertilizer application	Spreader maintenance	Nitrification inhibitors	Controlled release fertilizer	Optimizing timing of N application	Improved placement of N	Improved land manure application	Improved agronomy practices								
Fertilizer free zone																	
Sub-optimal fertilizer application										N							
Spreader maintenance										N	M						
Nitrification inhibitors										N	L	L					
Controlled release fertilizer										N	L	L	H*				
Optimizing timing of N application										N	N	L	N	M			
Improved placement of N										N	L	L	N	M	N		
Improved land manure application										N	L	N	N	N	M	M	
Improved agronomy practices										N	M	L	L	L	L	L	N

H: High, indicates strong interaction, may not be able to do together, if applied together mitigation potential for the second measure could be only 20% of the real potential (Interaction factor = 0.2).

M: Medium interaction, can be practised together, if applied together mitigation potential for the second measure could be only 50% of the real potential (Interaction factor = 0.5).

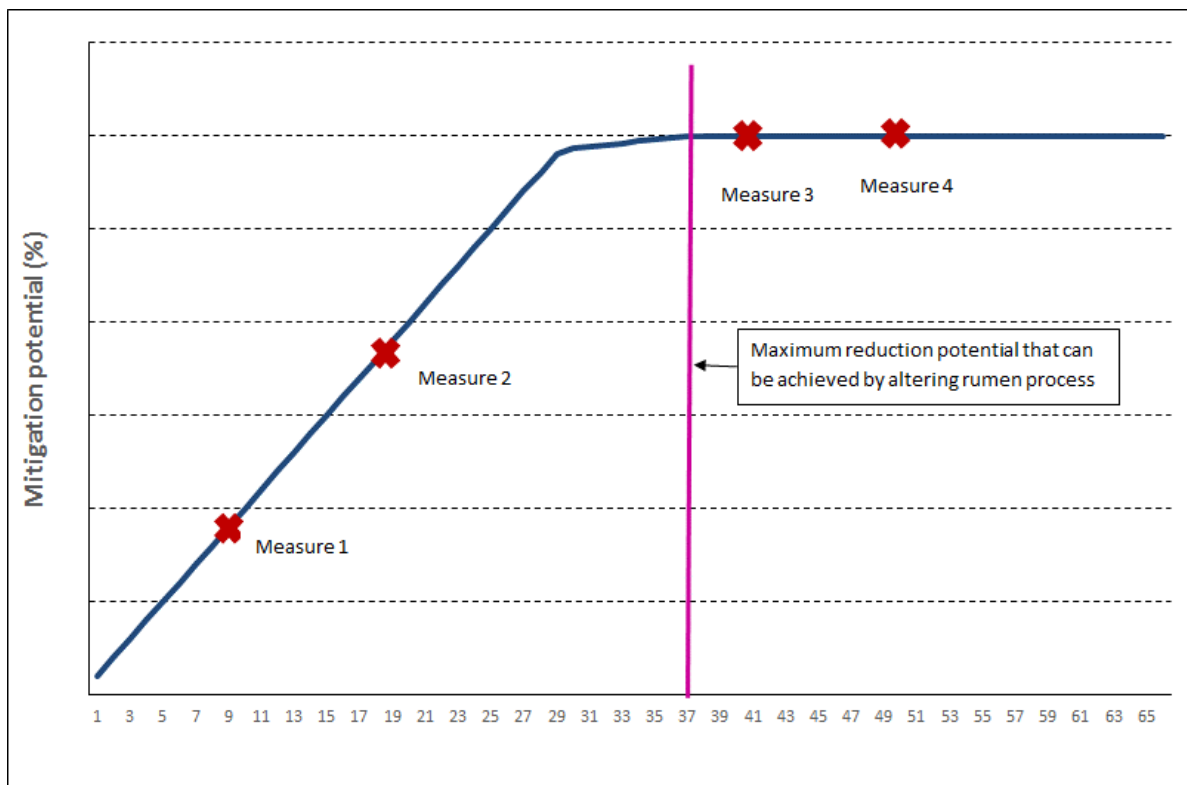
L: low level interaction, can be practised together, if applied together mitigation potential for the second measure could be only 70% of the real potential (Interaction factor = 0.5).

N: No interaction, can be used together, mitigation potential are additive, if applied together mitigation potential for the second measure could be 100% of the real potential (Interaction factor = 1).

\*: unlikely that these measures would be applied at the same time.

## Mitigation interaction for enteric CH<sub>4</sub> emissions

The rumen ecosystem has a limit to how much imbalance can be tolerated before feed intake, digestibility and animal production are negatively affected, and thus has a limitation to how much enteric CH<sub>4</sub> emission could be reduced with implementation of various measures. While, considering interaction between mitigation measures, it is important to consider the magnitude of the potential. For example in Figure 1 measure 3 and 4 would not be applied with other measures as they have a high mitigation potential and has a limitation; however measure 1 and 2 can be applied together and based on their impact on different processes, their interaction level i.e. high, medium or low was decided. Based on this concept, the limitation of implementation potential of a measure and interaction factors for enteric CH<sub>4</sub> mitigation measures were determined.



## Process:

Improved production through altered nutrition: Increase production per animal by altering nutrition. Applies to dairy.

Bovine Somatotropin: BST is a genetically engineered metabolic modifier approved for use in some countries to enhance milk production from dairy cows. Again, this is not a popular consumer choice for enhancing animal productivity and its use now banned by all EU Member States

Increased body weight at slaughter: Increase the body weight of cattle to 29% at time of slaughter. Applies to non-dairy.

Intensive grazing: Change the feeding to include grazing in pasture rather than all processed feed mixture. Applies to non-dairy.

Reduce herd size: Reduce herd size while maintaining beef production. Applies to non-dairy.

Skipping stocker phase: Placing young cattle directly into the feedlot rather than allowing them to develop for a few years in a stocker program. Applies to non-dairy.

Antibiotics: Feed antibiotics (e.g., monensin) to promote increased weight gain (growth stimulation) and reduce feed intake per metric ton of meat produced. It can also induce a shift in the pattern of rumen fermentation in favour of propionate, thus reducing methane emissions.

Nitrate: Nitrate is a proven additive that reduces enteric methane production (Van Zijderveld et al., 2010). Nitrate has a higher affinity for H<sub>2</sub> than CO<sub>2</sub> and thus acts as a H<sub>2</sub> sink, diverting from methane formation to nitrite and ammonia (Ungerfeld and Kohn, 2006; Nolan et al., 2010). Nitrate inclusion as a feed additive has the advantage of adding ammonia nitrogen (ammonia-N) to the rumen, which is the end-product in nitrate reduction, and is important for microbial growth.

Tannins: plant secondary compounds that reduces CH<sub>4</sub> emission. Condensed (and hydrolysable) tannins are widely distributed in browse and warm climate forages and are usually considered anti-nutritional although they can have considerable potential to reduce intestinal nematode numbers and allow acceptable production in the presence of a parasite burden. Detrimental effects when dietary CP (crude protein) is marginal or inadequate or when condensed tannins are astringent and in high concentrations, but with adequate dietary CP some condensed tannins can have wide ranging benefits.

Feed processing: In ruminants, forage particle size reduction, through mechanical processing or chewing, is an important component of enhancing forage digestibility, providing greater microbial access to the substrate, reducing energy expenditures and increasing passage rate, feed intake and animal productivity. Forage processing must be balanced between enhancing passage rate to increase intake and utilization of easily-digestible nutrients, which may not be easy to achieve for lower-quality feeds.

Longer-term management changes, animal breeding: Increasing productivity through breeding and better management practices spreads the energy cost of maintenance across a greater feed intake, often reducing methane output per kilogram of animal product.

Improved health monitoring: Controlling or eradicating endemic livestock diseases represents an opportunity to reduce emission intensity of livestock products without compromising productivity. Identification and prioritization of region specific target diseases, estimating their abatement potential and cost would be important to assess contribution of this mitigation measure to reduce GHG emission from global livestock sector.

Extended productive life: Extending productive lifetime of animals can decrease total GHG emissions per total product over the animal's lifetime and is already classified as a best practice (Joint report by GRA and SAI)

Improved feed intake and genetics: Increasing the level of voluntary feed intake for cattle can change the VFA composition of the rumen so that less acetate and more propionate is formed, leading to lower methane emissions per unit of animal product.

High Fat Diet: The addition of large amounts (up to 10%) of fats to dairy cows' diets meets energy requirements, and reduces methane production by increasing the proportion of propionic acid produced.

More non-structural diet: Research has shown that increasing the level of non-structural carbohydrate (NSC) or starch in the diet can reduce methane production by as much as 20% for a 25% increase in the level of NSC (Moss, 1994). This is because the NSC is readily fermented, and leads to a reduced protozoal population and lower rumen pH.

Replace roughage with concentrate: Replacement of roughage, which contains a high proportion of structural carbohydrate (fibres), with concentrates, can improve propionate generation in the rumen and decrease emissions of methane.

Propionate precursors: Within the rumen, hydrogen produced by the fermentation process may react to produce either methane or propionate. By increasing the presence of propionate precursors such as the organic acids, malate or fumarate, more of the hydrogen is used to produce propionate, and methane production is reduced.

### Mitigation measures interaction for Enteric CH<sub>4</sub> (For USA and Canada)

	Improved production through altered nutrition	Bovine Somatotropin	Increased body weight at slaughter	Intensive grazing	Reduce herd size	Skipping stocker phase	Antibiotics	Nitrate	Tannins	Grain processing	Longer-term management changes, animal breeding	Improved health monitoring	Extended productive life
Improved production through altered nutrition													
Bovine Somatotropin	M												
Increase d body weight at slaughte r	M	H											
Intensiv e grazing	H*	M	M										
Reduce herd size	L	L	L	L									
Skipping stocker phase	L	L	L	L	L								
Antibioti cs	H	H	H	H	L	L							
Nitrate	H	H	H	H	L	L	H						
Tannins	M	L	L	H	L	L	H	H					
Grain-processi ng	M	L	L	H	L	L	H	H					
Longer-term management changes, animal	L	L	H	L	L	L	L	L	L	L			



breeding	[Yellow]										[Grey]			
Improved health monitoring	L	L	M	L	L	L	L	L	L	L	L	[Grey]		
Extended productive life	L	L	H	L	L	L	L	L	L	L	H	L	[Grey]	

H: High, indicates strong interaction, may not be able to do together, if applied together mitigation potential for the second measure could be only 20% of the real potential (Interaction factor = 0.2).

M: Medium interaction, can be practised together, if applied together mitigation potential for the second measure could be only 50% of the real potential (Interaction factor = 0.5).

L: low level interaction, can be practised together, if applied together mitigation potential for the second measure could be only 50% of the real potential (Interaction factor = 0.5).

N: No interaction, can be used together, mitigation potential are additive, if applied together mitigation potential for the second measure could be only 100% of the real potential (Interaction factor = 1).

\*: unlikely that these measures would be applied at the same time.

## Mitigation measures interaction for Livestock manure management

	Anaerobic digesters both for developing and developed countries	Reduced dietary protein	Manure storage_ decreased storage time	Manure storage_covering	Manure separation and composting of solid manure	Housing system and bedding	Manure acidification
Anaerobic digesters both for developing and developed countries							
Reduced dietary protein	L						
Manure storage_ decreased storage time	H	L					
Manure storage_covering	H	L	L				
Manure separation and composting of solid manure	H	L	L	L			
Housing system and bedding	L	L	L	L	L		
Manure acidification	H	L	L	L	L	L	

H: High, indicates strong interaction, may not be able to do together, if applied together mitigation potential for the second measure could be only 20% of the real potential (Interaction factor = 0.2).

M: Medium interaction, can be practised together, if applied together mitigation potential for the second measure could be only 50% of the real potential (Interaction factor = 0.5).

L: low level interaction, can be practised together, if applied together mitigation potential for the second measure could be only 50% of the real potential (Interaction factor = 0.5).

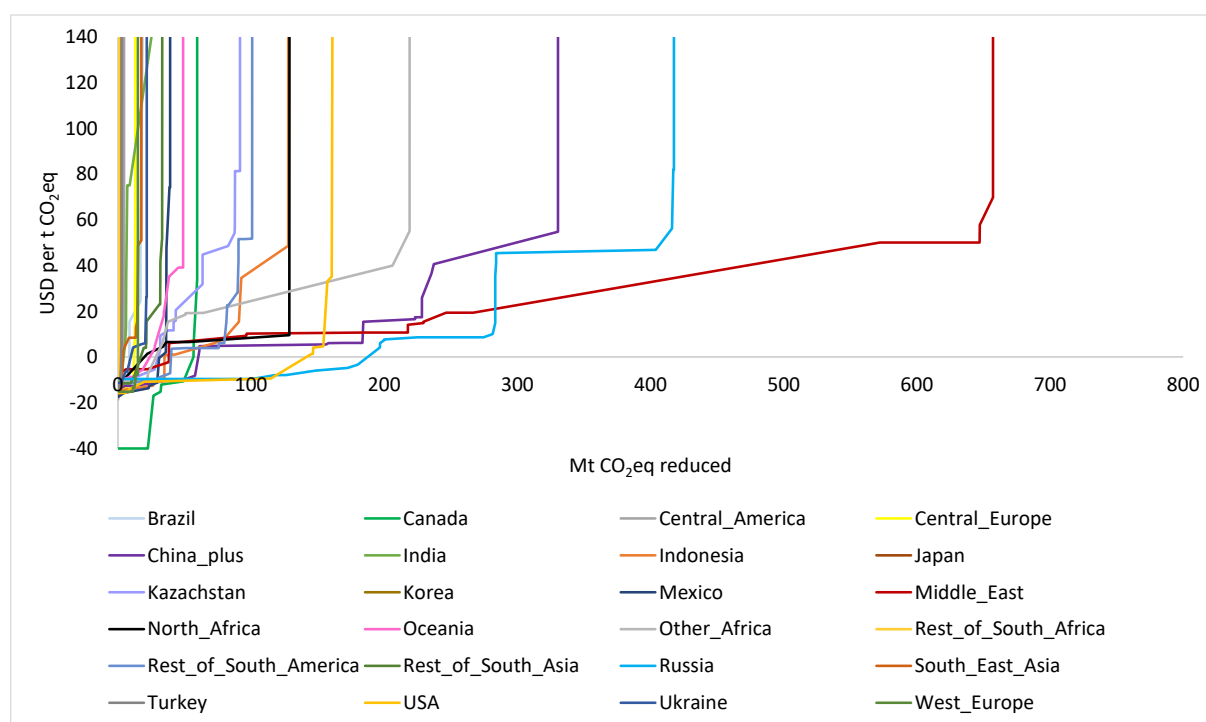
N: No interaction, can be used together, mitigation potential are additive, if applied together mitigation potential for the second measure could be only 100% of the real potential (Interaction factor = 1).

\*: unlikely that these measures would be applied at the same time.

## S5. Fossil CH<sub>4</sub> MAC curves GAINS

For the emission sources in the oil and gas industry, these MACs will be based on the work of Höglund-Isaksson (2012); (2017) presented below.

For the purpose of allowing for implementation in IAMs of the GAINS mitigation cost curves for upstream and downstream emissions from fossil fuel production and use, the IASA-GAINS team provided in July 2017 the IMAGE and MESSAGE model teams with respective input data sets. These data sets describe methane mitigation cost curves at the same regional resolution as the respective models, for a range of possible future gas price levels (2, 6, 10 and 14 USD/GJ), and with stated assumptions about activity levels. The latter should allow for adapting reduction potentials in the marginal abatement cost curves to any other level of activity consistent with the activity levels in different IMAGE and MESSAGE model scenarios. Likewise, the provision of a range of marginal cost curves at different gas price levels should allow for adapting the GAINS marginal cost curves to different future gas price levels. Figure S5.1 shows an example of the GAINS mitigation cost curves for fossil fuel sources in 2050 in the SSP2 REF scenario by IMAGE regions. Similar cost curves were generated for the IMAGE SSP2 REF and IMAGE SSP2 2.6 W/m<sup>2</sup> scenarios, as well as for the range of four different gas price levels, each adapted to the respective regional and activity type resolutions of the IMAGE and MESSAGE models.



**Figure S5.1:** Example of GAINS model MACC curves for control of CH<sub>4</sub> from fossil fuel sources in 2050 presented by IMAGE regions for the SSP2 REF scenario.

## S6. Impact of non-CO<sub>2</sub> mitigation on carbon budgets

**Table S6.1 - First order calculation of CO<sub>2</sub> concentration and carbon budget in the 2.6 scenario under different non-CO<sub>2</sub> mitigation assumptions, using this study's MAC curves in the IMAGE model.** The 2.6 scenario with the full non-CO<sub>2</sub> mitigation portfolio is compared with 4 diagnostic cases; three excluding the one of the different GHG groups (CH<sub>4</sub>, N<sub>2</sub>O, F-gases) and one excluding all non-CO<sub>2</sub> GHG mitigation (note that aerosol and CH<sub>4</sub> emissions are also reduced by CO<sub>2</sub> policy in all cases).

	Non-CO <sub>2</sub> RF, RCP2.6, 2100 (W/m <sup>2</sup> ) <sup>1</sup>	Remaining CO <sub>2</sub> RF in year 2100 (W/m <sup>2</sup> )	CO <sub>2</sub> RF 2015 (W/m <sup>2</sup> ) <sup>1</sup>	CO <sub>2</sub> RF, 2100 minus 2015 (W/m <sup>2</sup> ) <sup>2</sup>	CO <sub>2</sub> concentration 2100 (ppm) <sup>2</sup>	Diff. ppm 2015-2100 (ppm)	Budget 2015 -2100 (GtCO <sub>2</sub> ) <sup>3</sup>	Natural uptake 2015-2100 (GtCO <sub>2</sub> ) <sup>4</sup>	CO <sub>2</sub> budget 2015 - 2100, 2.6 W/m <sup>2</sup> scenario (GtCO <sub>2</sub> )	Difference with full non-CO <sub>2</sub> mitigation
<b>Total non-CO<sub>2</sub> RF (standard)</b>	0.37	2.23	1.98	0.25	<b>419</b>	19.0	147.7	922.3	<b>1070</b>	n.a.
<b>No CH<sub>4</sub> mitigation<sup>5</sup></b>	0.74	1.86	1.98	-0.12	<b>388</b>	-12.0	-93.2	922.3	<b>829</b>	241
<b>No F-gas mitigation</b>	0.76	1.84	1.98	-0.14	<b>390</b>	-10.0	-77.6	922.3	<b>845</b>	225
<b>No N<sub>2</sub>O mitigation</b>	0.49	2.11	1.98	0.13	<b>410</b>	10.0	77.8	922.3	<b>1000</b>	70
<b>No non-CO<sub>2</sub> mitigation<sup>6</sup></b>	1.25	1.35	1.98	-0.63	<b>356</b>	-44.0	-341.8	922.3	<b>580</b>	490
<b>50% less non-CO<sub>2</sub> mitigation</b>	0.81	1.79	1.98	-0.19	<b>386</b>	-14.0	-108.7	922.3	<b>814</b>	256
<b>25% less non-CO<sub>2</sub> mitigation</b>	0.59	2.01	1.98	0.03	<b>402</b>	2.0	15.6	922.3	<b>938</b>	132
<b>10% less non-CO<sub>2</sub> mitigation</b>	0.46	2.14	1.98	0.16	<b>412</b>	12.0	93.3	922.3	<b>1016</b>	54
<b>10% more non-CO<sub>2</sub> mitigation</b>	0.28	2.32	1.98	0.34	<b>426</b>	26.0	202.1	922.3	<b>1124</b>	-54

<sup>1</sup> From run in MAGICC 6.3, 50% probability pathway  
<sup>2</sup> Calculation based on the simplified first-order approximation expression for carbon dioxide (Myhre et al., 1998) New estimates of radiative forcing due to well mixed greenhouse gases, Geophysical Research Letters, Vol 25, No. 14, pp 2715–2718, 1998)  
<sup>2</sup> RF in 2015 is 1.82 W/m<sup>2</sup> at 400 ppm CO<sub>2</sub>  
<sup>3</sup> 1 ppm change in CO<sub>2</sub> is caused by the net increase of 7.77 GtCO<sub>2</sub> (net value after natural uptake) (IPCC, AR5)  
<sup>4</sup> Projected natural uptake between 2015 and 2100 is an average 10.85 GtCO<sub>2</sub>/yr in RCP2.6 (from MAGICC6.3 ). This is consistent with the 2000-2005 average 11.3 GtCO<sub>2</sub>/yr ([https://www.ipcc.ch/publications\\_and\\_data/ar4/wg1/en/tssts-2-1-1.html](https://www.ipcc.ch/publications_and_data/ar4/wg1/en/tssts-2-1-1.html)). Although the value is dependent on the CO<sub>2</sub> concentration, changes in land and sea uptake counteract each other at changing concentrations. Therefore, the fixed value is assumed here as a proxy.  
<sup>5</sup> Including indirect effects (O<sub>3</sub> forming, indirect CH<sub>4</sub> from stratospheric H<sub>2</sub>O) assumed to be 1.4 x direct CH<sub>4</sub> forcing (Smith et al., 2012), including CH<sub>4</sub> reduction from CO<sub>2</sub> policy, assumed to be 27% of total CH<sub>4</sub> emissions (Harmsen et al, 2018).  
<sup>6</sup> Including CH<sub>4</sub> reduction from CO<sub>2</sub> policy, assumed to be 27% of total CH<sub>4</sub> emissions (Harmsen et al, 2018). Including reduction of aerosols from CO<sub>2</sub> policy.

Harmsen M, et al. (2018) The role of methane in future climate strategies: Mitigation potentials and climate impacts. Climatic Change (EMF30 Special Edition, under review).

Myhre et al., (1998) New estimates of radiative forcing due to well mixed greenhouse gases, Geophysical Research Letters, Vol 25, No. 14, pp 2715–2718, 1998)

Smith SJ, et al. (2012) Equivalence of greenhouse-gas emissions for peak temperature limits. Nature Climate Change 2:535–538

## S7. Sensitivity analysis of inertia in implementation non-CO<sub>2</sub> mitigation (2.6 W/m<sup>2</sup>) scenario

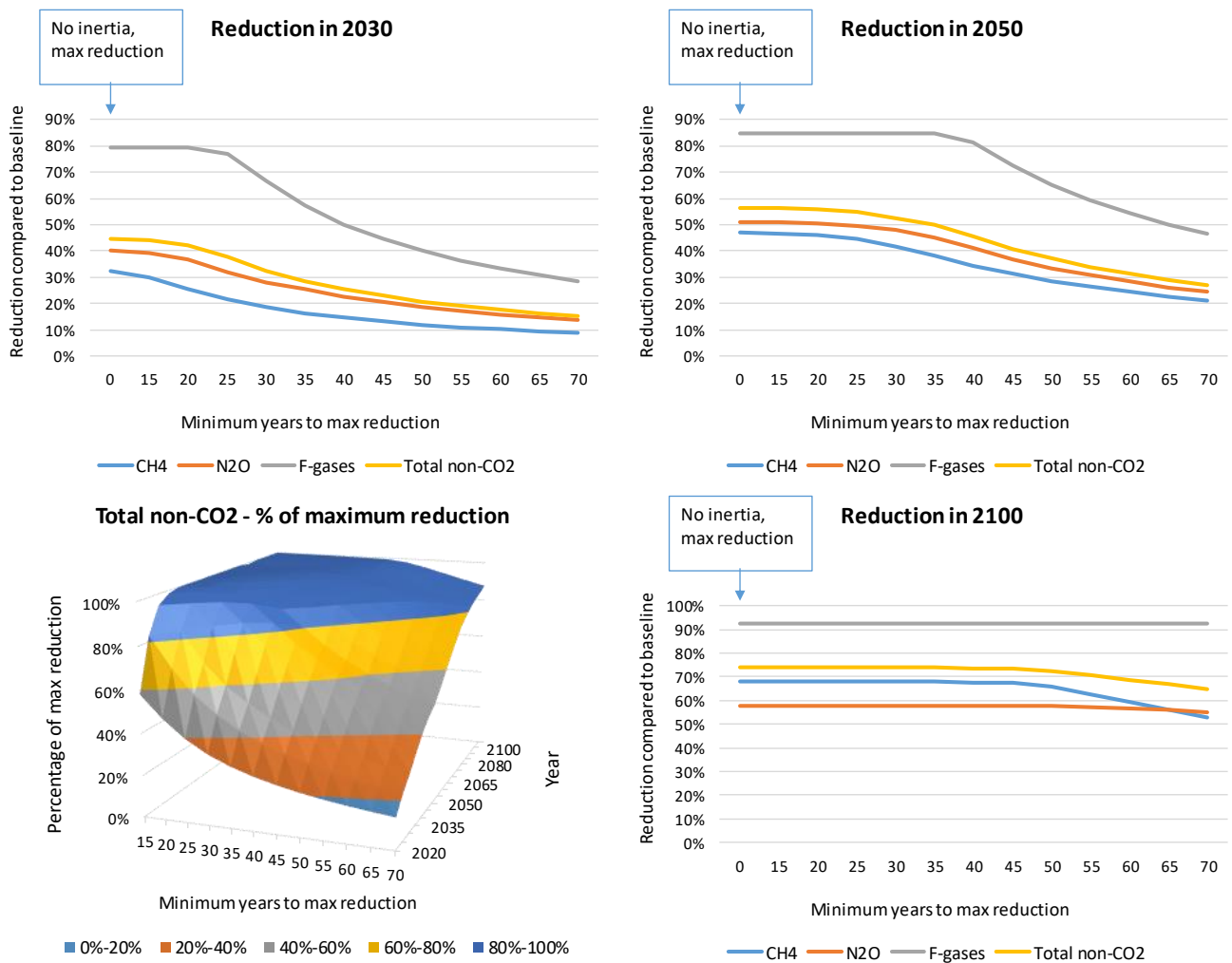
Figure S7 shows the results of the additional sensitivity analysis, using the 2.6 W/m<sup>2</sup> scenario. The upper two and lower right panels show the reductions of the three non-CO<sub>2</sub> GHG groups in three different years (2030, 2050, 2100). The x-axis represents the minimum years to maximum reduction. The shorter this period, the lower the inertia and the faster the model can increase reduction. At zero years, inertia is assumed to play no role. This is then the maximum reduction that can be reached in this year and this scenario (2.6 W/m<sup>2</sup> scenario, which has a specific carbon price profile).

In the short term (2030), inertia plays a substantial limiting role. Even a moderate constraint of 20 years leads to 5% lower total non-CO<sub>2</sub> reductions than the full potential (42% instead of 45% without inertia). In 2050, inertia has a much smaller effect on emissions (at a constraint of 20 years, there is 1% less reduction than the full potential). Inertia does not influence long-term (2100) emissions. Only at a constraint higher than 40 years, which is deemed unrealistically high, is there a substantial (>1%) difference between the inertia and no-inertia case. Note also the slight difference in results for CH<sub>4</sub> compared to F-gases and N<sub>2</sub>O. The reason is that CH<sub>4</sub> has a relatively larger marginal abatement at higher costs, and therefore less “available years” with a sufficiently high carbon tax in the 2.6 W/m<sup>2</sup> scenario.

The lower left panel summarizes the results. Here, the vertical axis shows the reduction of all non-CO<sub>2</sub> GHGs as the share of reduction compared to a no inertia case. Inertia starts to be influential in all future years when the constraint is set to 45 years or more, and plays an influential role until 2035 (with the maximum reduction reduced by 5%) when the minimum number of years to maximum reduction is 20.

Although non-CO<sub>2</sub> 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 forcings (N<sub>2</sub>O, PFCs, SF<sub>6</sub>), higher, inertia-induced short-term emissions leads to a larger atmospheric burden, making longer-term climate targets more difficult to reach. Furthermore, if policy is focussed on the short term, inertia can potentially hinder mitigation efforts of all non-CO<sub>2</sub> GHGs. Van den Berg et al. (2015) showed that the use of an alternative climate metric that promotes late CH<sub>4</sub> mitigation can result in higher CH<sub>4</sub> emissions resulting from inertia. Similarly, if, due to delayed climate action, climate targets become more stringent and short-term oriented, inertia could lead to unused non-CO<sub>2</sub> mitigation potential, shifting the burden to additional CO<sub>2</sub> mitigation.

**Figure S7 - Sensitivity analysis of inertia in non-CO<sub>2</sub> mitigation - 2.6 W/m<sup>2</sup> scenario**



## S8. Publically available datasets

Two sets of the MAC curves have been made available:

- 1) A baseline independent set (expressed in relative reductions compared to the source specific global average emission factors in 2015) (as described in 2.1.1)
- 2) A set that is consistent with the IMAGE SSP2 (also expressed in relative reductions).

Regarding the second set: When implementing the MAC curves in the IMAGE model and applying them to a reference scenario (here: in SSP2, but other reference scenarios can also be used), emission reductions that already take place the baseline case have been deducted from the reduction potentials in the baseline independent MACs, to create a new “SSP2 dependent” set of MACs. This ensured that the net emission reduction in a SSP2 based mitigation scenario still exactly represents the reductions from the baseline independent set of MACs. For this calculation step it was assumed that reductions in the baseline result from the least-cost measures, since these are measures that that are expected to occur without climate policy. For example, these are measures that have net zero cost, improve air quality or are associated with agricultural yield improvements. The emission reductions from these measures are now consistently taken into account in mitigation scenarios for all sources.

The following MAC curve documents have been made available as separate documents in this [supplement](#):

- Baseline independent MACs compared to global mean emission factor in 2015 (excluding F-gases) <sup>2</sup>
- MACs compared to SSP2 <sup>2</sup>
- SSP2 baseline emissions
- Background information (IMAGE 26 world regions and included countries, AR4-100 year GWP values, 2010-2005 and 2010-2015 \$ conversion factors)

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<sup>2</sup> Prices are given in 2010 USD/\$ using 201 price steps (from 0 to 4000\$). The CO<sub>2</sub> equivalent prices can be translated to non-CO<sub>2</sub> prices (tonnes of CO<sub>2</sub> to tonnes of non-CO<sub>2</sub> GHG) by using the AR4 100 yr GWP.

## S9. Abatement potential by emission source

### S9.1 Methane (CH<sub>4</sub>)

#### S9.1.1 CH<sub>4</sub> from coal production

Emission reduction measures exist for underground mining of hard coal, the largest source of CH<sub>4</sub> emissions in coal production. Emissions from surface mining of hard coal and lignite currently cannot be mitigated, but are also much lower per tonne of coal (and +/- 15% of total coal CH<sub>4</sub> emissions) owing to the low pressure and coal rank (Karakurt et al., 2012). Ventilation air methane (VAM, with a low concentration of 0.1-0.8% CH<sub>4</sub>) during underground mining operation constitutes the main emission source (50-60% of total coal CH<sub>4</sub> emissions), while the rest of the emissions come from pre-mining activities, post-mining activities and abandoned mines (sources of comparable size) (Hinde et al., 2016; Höglund-Isaksson, 2012). The mitigation potential for pre-mining degasification is assessed at 90%, which has been seen possible in the US and as such applied in the GAINS dataset. VAM is seen as difficult and uneconomic to combust and unlike the other sources, it is not a safety risk, so therefore less attractive to mitigate (Hinde et al., 2016). Since no future technological improvements are assumed in the GAINS dataset, it is assumed that only non-lean VAM (> 0.3% concentration, 66% of all VAM) can be reduced. However, in a recent study it was found that lower temperature catalytic thermal oxidation of methane led to a 100% removal of VAM CH<sub>4</sub>, which was maintained for 2 years (Hinde et al., 2016). Also, other studies describe high reduction efficiencies (90%-100%) in controlled experiments (Hui et al., 2010; Lebrero et al., 2016; Patel et al., 2016; Yusuf et al., 2012). The assumption in this study is therefore that VAM can be fully reduced by 2050. Similarly, CH<sub>4</sub> from abandoned mines is assumed to be fully abatable in 2050 in this study. Abandoned underground mines can liberate CH<sub>4</sub> at a low, but near-steady rate over an extended period of time. If the mine is flooded, this can be reduced to a few years. In addition, recovery or oxidation of CH<sub>4</sub> can in principle also be applied (Karakurt et al., 2012). The GAINS dataset does not include mitigation options for post-mining CH<sub>4</sub> emissions (i.e. further processing of coal). Although no known literature exists regarding this source, we assume that in 2100, due to technological advances it is likely that 50% can be reduced by moving some of these activities indoor and applying existing CH<sub>4</sub> removal technologies there. Following the assumptions above, the maximum global reduction potential of this source is estimated at 54% in 2050 and 79% in 2100. Cost assumptions are based on the GAINS dataset.

#### S9.1.2 CH<sub>4</sub> from oil and natural gas production and distribution

CH<sub>4</sub> emissions in the oil and natural gas industry partly originate from unintended leakage from pipelines, wells and facilities, and partly from intended safety induced venting and flaring during maintenance and (oil) drilling. For oil production, emission reduction measures are available that have proven to bring down emissions considerably (leading to a projected 80% in 2050): Recovery and utilization of vented gas and reduction of unintended leakage from wells and temporary storage of captured CH<sub>4</sub> (Bylin et al., 2010; Höglund-Isaksson, 2012, 2017). These measures are often cost-saving or are otherwise relatively economical (0-300 \$(2010)/tCeq). In addition to these measures included in the GAINS dataset, it is assumed that in 2100, small gas-to-liquid plants become available for remote oil fields. Such a development would make it economically sound to recover, liquefy and market as much as possible of the associated petroleum gas, instead of flaring and venting the gas (Lipsky, 2014).



This is estimated to reduce the remaining emissions by half, leading to a MRP of 90% in 2100 (Höglund-Isaksson, 2012, 2017).

Emission reduction measures for natural gas mainly involve reducing emissions during transmission and distribution and controlling emissions during extraction, in particular from unconventional gas wells. This is realized by: reducing leakage rates to levels currently observed in Western Europe, North America and Japan, and replacing grey cast iron pipes with PE and PVC networks (Höglund-Isaksson, 2012). Based on a case study of Russia, Lechtenböhmer and Dienst (2010) estimated that up to 60% of distribution emissions can be reduced in 2030. Consistent with this projection, in the GAINS dataset, the overall MRP for natural gas production and distribution is estimated at 62% in 2050. An important limitation for bringing emissions further down is late identification of leaks. A promising, yet not employed and fully tested technology is optical gas imaging (OGI) in periodic leak detection and repair (LDAR) programs. Here, infrared cameras are used to scan large gas infrastructures for leakages and promptly address the major ones to be cost-effective. The technology can be broadly used and is estimated to help reduce net emissions by 60%-80% (Ravikumar and Brandt, 2017). For this study's MAC curves, it is assumed that in 2100, residual emissions can cost-effectively be reduced by about half due to LDAR programs (or equivalent leakage prevention) in 2100, leading to an estimated MRP of 80%. Cost assumptions are based on the GAINS dataset.

### S9.1.3 CH<sub>4</sub> from landfills and solid waste

Anaerobic bacteria in landfills generate CH<sub>4</sub> emissions by processing organic waste. Reduction options include 1) CH<sub>4</sub> collection and flaring 2) CH<sub>4</sub> capture for energy use 3) Biological processing 4) Waste diversion through recycling or incineration of organic waste (US-EPA, 2013). The global MRP of all measures combined in the US-EPA (2013) dataset is found to be 61% in 2030, which excludes technological progress beyond the current state and full implementation of measures in all regions. Furthermore, waste diversion and the banning of landfills is assumed to play a minor part, while this option is currently introduced in the EU on an increasingly larger scale (EC, 2015), with the potential to almost fully reducing CH<sub>4</sub> emissions. In addition, biological processing has seen several developments that could potentially increase future reductions. Methanotrophic bacteria placed in layers can in ideal conditions (e.g. low CH<sub>4</sub> concentrations) remove generated CH<sub>4</sub> by 95%-100% (Han et al., 2010; Park et al., 2008). Covering low CH<sub>4</sub> producing landfills with vegetated soils has led to similar reductions at very low costs (29 to 58 \$(2010)/tCeq)(Abichou et al., 2016). After 2030, complementary to the US-EPA MACs, we assume a default increase in reduction potential of 2% per 5 years to simulate the effect of additional waste diversion and biological treatment. Although such options might not be suitable for all landfill conditions, it is considered likely that at medium high costs, emission reductions converge to the maximum in all regions. At 500 \$(2010)/tCeq, the reduction potential is assumed to be 73%, which represents the global reduction if all regions would have the minimum per capita emission intensity of the EU. In 2100, it is assumed that at 1000 \$(2010)/tCeq, the MRP is 90%, which is the reduction if all regions would have the minimum per-GDP emission intensity of the EU.

#### S9.1.4 CH<sub>4</sub> from sewage and wastewater

Wastewater CH<sub>4</sub> emissions, generated by anaerobic bacteria, can be reduced by 1) Anaerobic digestion combined with CH<sub>4</sub> collection 2) Aerobic wastewater treatment 3) Replacing latrines and disposal by wastewater treatment plants (WWTP). For all reduction measures, biological CH<sub>4</sub> removal is commonly applied. In a meta-study, Lopez et al. (2013) found that aerobic biofilters, which are most commonly used, have the highest reduction efficiencies (REs); in 9 studies, REs of 50% to 100% were found (average = 75.4%). This is in line with Barcon et al. (2015) who found a reduction potential of 76.5%. The main problem for the removal of wastewater CH<sub>4</sub> is the low implementation potential of WWTPs that can reach maximum reductions. To a only limited extent, a CH<sub>4</sub> price can function as a co-beneficial incentive to build WWTP infrastructure, next to health and sanitation. However, Reid et al. (2014) found that even without a sewage system, composting toilets and biogas digesters can in principle have reduction efficiencies up to 100%. The marginal costs of a composting toilet (calculated as the additional cost of a CH<sub>4</sub> mitigation technology beyond the cost of a pit latrine) is estimated at 169-3421 \$(2010)/tCeq (large range depending on location). The global MRP in the US-EPA MACs is found to be 36% in 2030. Similar to the assumptions for landfills CH<sub>4</sub>, technological progress is simulated by an increase in reduction potential of 2% every 5 years. The MRP at 2000 \$(2010)/tCeq is assumed to converge to 78% (lowest per capita emission intensity in the EU). At 4000 \$(2010)/tCeq in 2100 the MRP is assumed to be 90%, at the lowest per GDP emission intensity.

#### S9.1.5 CH<sub>4</sub> from rice production

CH<sub>4</sub> emissions result from the anaerobic breakdown of organic matter in wetland rice paddies. The mitigation measures that have been used to construct the MAC curve are: 1) *Alternate flooding and drainage of rice paddies*, which reduces anaerobic conditions. Costs vary, depending on the region, with an average cost-effectiveness of 543 \$(2010)/tCeq (Nalley et al., 2015; Thu et al., 2016). The average CH<sub>4</sub> reduction is found to be 57% (Feng et al., 2013; Graus et al., 2004; Jiao et al., 2006; Nalley et al., 2015; Nayak et al., 2015; Tariq et al., 2017; Thu et al., 2016; Towprayoon et al., 2005; Tyagi et al., 2010; Wassman et al., 2000; Yang et al., 2012; Yu et al., 2004; Yue et al., 2005)<sup>3</sup>. 2) *Direct seeding in wet conditions*, which replaces transplanting of seedlings. Average costs are estimated at 117 \$/tCO<sub>2</sub>eq (Graus et al., 2004), average CH<sub>4</sub> reduction efficiency at 20% (Graus et al., 2004; Wassman et al., 2000). 3) *Addition of Phosphogypsum*. This by-product releases sulphate, which inhibits methanogenesis. Costs are relatively high: 224–1412 \$(2010)/tCeq (Graus et al., 2004) as is the average CH<sub>4</sub> reduction efficiency: 39% (Graus et al., 2004; Linquist et al., 2012; Wassman et al., 2000). 4) *Replacement of urea with ammonium sulphate (AS)*. This replaces commonly used urea as a fertilizer, which also inhibits methanogenesis. Costs are estimated to be very low: 4–55 \$(2010)/tCeq (Graus et al., 2004). The average CH<sub>4</sub> reduction efficiency is 22% (Graus et al., 2004; Wassman et al., 2000). 5) *Rice straw compost*. This substitutes for fresh rice straw and thus lowers organic matter. Average costs are 103–521 \$(2010)/tCeq and the average CH<sub>4</sub> reduction efficiency: 48% (Graus et al.,

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<sup>3</sup> Note that these studies project a slight increase in N<sub>2</sub>O emissions from the CH<sub>4</sub> measures (estimated at 0.0067 MtN<sub>2</sub>O/MtCH<sub>4</sub> reduced). The IMAGE model corrects for this.

2004; Launio et al., 2016). When taking into account the overlap between measures and technological learning, the MRP in 2050 and 2100 is estimated at 61% and 77%, respectively.

#### S9.1.6 CH<sub>4</sub> from enteric fermentation in ruminants

CH<sub>4</sub> is generated as a by-product of microbial fermentation of plants and grains in ruminants (animals with multi-chambered stomachs; e.g. cattle and sheep). Solutions for bringing down emissions can come from changed animal diets and digestive processes, or changes in the productivity and physiology of the animals. The mitigation measures that have been used to construct the MAC curve are: 1) *Addition of nitrate to the feed*. As an electron receptor, nitrate can reduce CH<sub>4</sub> emissions during digestion. Note that the measure should be applied with care, because of health risks in case of high dosages. It is also less effective in regions that currently already have high animal intake of nitrate (e.g. EU and USA, which is reflected in the technical applicability). Average costs are: 392 \$(2010)/tCeq (Eory et al., 2016; Henderson et al., 2015), the average reduction efficiency: 26% (Dickie et al., 2014; Hulshof et al., 2012; Van Zijderveld et al., 2011). 2) *Genetic selection and breeding*, aimed at minimizing CH<sub>4</sub> generation and feed intake per unit of milk or meat produced. It is estimated to lead to net zero costs due to productivity gains (Graus et al., 2004). The average reduction efficiency: 21% (Bell et al., 2010). 3) *Adding Tannins as a food supplement*. These plant extracts are effective in reducing rumen CH<sub>4</sub>. Average costs are low: 50 \$(2010)/tCeq (McKinsey, 2010), the average reduction efficiency: 14% (Hristov et al., 2013; Nayak et al., 2015). 4) *Grain processing*, which improves starch digestibility of grain and can reduce feed requirement. Costs are estimated at 183 \$(2010)/tCeq (No data, medium cost estimate of 50 \$/tCO<sub>2</sub>eq), the average reduction efficiency: 10% (Hristov et al., 2013). 5) *Improved health monitoring and illness prevention*, aimed at controlling or eradicating endemic livestock diseases. Costs are negative and conservatively assumed to be 0 \$(2010)/tCeq (Eory et al., 2016; McKinsey, 2010), the average reduction efficiency: 15% (Eory et al., 2016). Note that one promising measure has not been included in the enteric fermentation MAC curves, as it has not been properly studied *in vitro*: adding small quantities of the seaweed *Asparagopsis taxiformis* (active chemical: bromoform) to ruminants feed. This potent anti-methanogenic has in first trials led to reduction potentials of 80% (in sheep) to 99% (in cows, *in vitro*) (Kinley et al., 2016; Li et al., 2016), but needs to be further studied. When taking into account the overlap between the included measures and technological learning, the MRP in 2050 and 2100 is estimated at 41% and 50%, respectively.

#### S9.1.7 CH<sub>4</sub> from manure

Livestock manure releases CH<sub>4</sub> produced by anaerobic microbial processing of organic material. The mitigation measures that have been used to construct the MAC curve are: 1) *Application of digester plants that process manure together with other organic waste and collection of CH<sub>4</sub>*. These can be either small-scale farm systems, or centralized plants in intensive agricultural areas. The biogas generated from anaerobic digestion is then used to produce heat or both heat and electricity. Average costs are: 0–191 \$(2010)/tCeq, the average reduction efficiency: 75% (warm climates), 50% (cool climates) (Graus et al., 2004). 2) *Emission reduction during collection and storage of manure*. This includes improved manure drainage systems and covering of manure, and reduction of storage time. Average costs are: 110–546 \$(2010)/tCeq, the reduction efficiencies: 30%–35% (Dickie et al., 2014; Graus et al., 2004; Weiske and Michel, 2007). 3) *Manure acidification*, which reduces the release of

both CH<sub>4</sub> and N<sub>2</sub>O. The cost is estimated at 304 \$(2010)/tCeq (Eory et al., 2016), the average reduction efficiency is 77% (Hristov et al., 2013; Ndegwa et al., 2008; Petersen et al., 2012). When taking into account the overlap between measures and technological learning, the MRP in 2050 and 2100 is estimated at 55% and 71%, respectively.

## S9.2 Nitrous Oxide (N<sub>2</sub>O)

### S9.2.1 N<sub>2</sub>O from transportation

The main sources of N<sub>2</sub>O in transportation are catalyst-equipped petrol cars, which generate N<sub>2</sub>O as a by-product of converting exhaust pollutants. Apart from a switch in fuel or propulsion system, the key reduction measure is the implementation of low-N<sub>2</sub>O catalytic converters (Lucas et al., 2007). To our knowledge, no recent publically available literature exists describing research and development of such converters. Therefore, we applied the same assumptions as Lucas et al. (2007). Implications of this assumption are expected to be relatively small, as the emission source is small. Short-term costs and reduction potentials are based on GECS (2002). The MRP in 2050 and 2100 is estimated at 85% at a cost of 635 \$(2010)/tCeq.

### S9.2.2 N<sub>2</sub>O from adipic acid and nitric acid production

N<sub>2</sub>O emissions from industry are mainly generated as a by-product of the production processes of adipic and nitric acid. For both processes, reduction potentials are found to be very high, at very low costs, when applying thermal or catalytic reduction. This study's MAC curves provide short-term reduction potentials and costs based on US-EPA (2013), which estimated the reduction potentials of adipic and nitric acid at 96% and 95%, respectively.

N<sub>2</sub>O from adipic acid production is assumed to be fully abatable in 2050 and 2100. While several studies estimate reduction potentials of 98%-99% at costs of 1-11\$(2010)/tCeq (Eom et al., 2016; Harnisch et al., 2006; Lucas et al., 2007; Winiwarter et al., 2018), recent studies also found that emissions can be reduced by 100% (Nunotani et al., 2016; Zhang et al., 2016) at high temperatures (600dC). It is assumed that this can be achieved at 50\$(2010)/tCeq.

The MRP of N<sub>2</sub>O from adipic acid production is assumed to be 94% in 2050 and 2100, based on the best available technology from Winiwarter et al. (2018). This reduction potential is higher than found by Li et al. (2014)(80%) and Frutos et al. (2017), but deemed likely due to the very low cost of the technology (2\$(2010)/tCeq). It is assumed that the MRP (including full technology implementation) can be achieved at 50\$(2010)/tCeq.

### S9.2.3 N<sub>2</sub>O from fertilizer application

Excess application of nitrogen-based fertilizer stimulates microbes in the soil to convert nitrogen (N) to N<sub>2</sub>O. Emission reductions can be achieved by minimizing fertilizer overuse and altered microbial conditions. The mitigation measures that have been used to construct the MAC curve are: 1) *Use of nitrification inhibitors*, which slow the conversion of ammonium to nitrate. Average costs are estimated at: 117–649 \$(2010)/tCeq (Basak, 2015; Eory et al., 2016), the average reduction efficiency at: 38%. (Akiyama et al., 2010; Bates et al., 2009; Dickie et al., 2014; Moran et al., 2008; Torralbo et al., 2017; US-EPA, 2013; Wu et al., 2017; Zhu et al., 2016). 2) *Various measures to reduce and optimize fertilizer application and N run-off*, such as targeted application (precision farming), maintenance on

fertilizer spreaders and fertilizer free zones. Average costs are estimated at: 0–3799 \$(2010)/tCeq (most measures are near zero cost), the average reduction efficiency at: 4% to 26% (Graus et al., 2004). 3) *Improved land manure application*. This includes reducing inorganic N-application, improved timing of manure application, applying manure to dry rather than wet areas and applying solid rather than liquid manure. Estimated costs are mostly negative and estimated at 0\$(2010)/tCeq (Bates et al., 2009; MacLeod et al., 2010; Moran et al., 2008), the average reduction efficiency is 14% (Dickie et al., 2014; Eagle et al., 2012; Moran et al., 2008). 4) *Improved agronomy practices*, aimed at reducing the need for N-application. This includes: e.g. the adoption of plant varieties with improved N-use efficiency and the use of rotations with legume crops. Average costs are estimated at: 11 \$(2010)/tCeq (Eory et al., 2016; Smith et al., 2008), the reduction efficiency at 20% (Moran et al., 2008). When taking into account the overlap between measures and technological learning, the MRP in 2050 and 2100 is estimated at 47% and 64%, respectively.

#### S9.2.4 N<sub>2</sub>O from manure

N<sub>2</sub>O is generated during the composting of manure by ammonia (NH<sub>3</sub>)-oxidizing bacteria. The mitigation measures that have been used to construct the MAC curve are: 1) *Reduced dietary protein*: aimed at reducing animal protein intake beyond what they require. Studies with pigs, poultry, and cattle have shown reduced NH<sub>3</sub> and potentially N<sub>2</sub>O emissions from manure. Costs are estimated at: 86 \$/tCO<sub>2</sub>eq (McKinsey, 2010), the reduction efficiency at: 25% (Hristov et al., 2013). 2) *Decreased manure storage time*, through frequent land application avoids anaerobic conditions that create CH<sub>4</sub>, but can also reduce N<sub>2</sub>O emissions depending on application timing. Costs are estimated to be relatively low: 110 \$(2010)/tCeq, the average reduction efficiency is: 35% (Hristov et al., 2013). 3) *Manure storage covering*, to capture emissions. Average costs are estimated at 257 \$(2010)/tCeq (Weiske and Michel, 2007), the reduction efficiency at: 30% (Dickie et al., 2014; Hristov et al., 2013). 4) *Improved animal housing systems and bedding*, to allow for better manure drainage. Average costs are estimated at: 546 \$(2010)/tCeq (Weiske and Michel, 2007), the average reduction efficiency at: 35% (Dickie et al., 2014). When taking into account the overlap between measures and technological learning, the MRP in 2050 and 2100 is estimated at 47% and 63%, respectively.

#### S9.2.6 N<sub>2</sub>O from sewage and wastewater

In wastewater and sewage systems, N<sub>2</sub>O is generated at different nitrification and denitrification stages of the nutrients in the water, either *via* biological or chemical processes. Measures to reduce N<sub>2</sub>O generation mainly need to be implemented in wastewater treatment plants (WWTPs). Therefore, the reduction potential for this source can be severely limited by low implementation potentials in developing regions where WWTPs are scarce. For this source, the MAC curve dataset by Lucas et al. (2007) is used as a basis, which represents emission reductions by 1) increasing favourable conditions for N<sub>2</sub> as opposed to N<sub>2</sub>O generation in WWTPs, and 2) applying N-enriched wastewater in crop production as an alternative to fertilisers. A recent meta study (Sun et al., 2017) has shown that the N<sub>2</sub>O reduction efficiency (RE) in WWTPs has dramatically increased in recent years (average of 12 studies: 80%, compared to 20% in 2002 (Lucas et al., 2007)). Following the approach of Lucas et al., the MAC curves were constructed using this higher RE, assuming a technical applicability of 90% in OECD countries, and 20%, 40%, 70% in non-OECD countries in 2020, 2050 and 2100, respectively. The

assumed implementation potential is 20%, 70% and 90% in 2020, 2050 and 2100, respectively, which represents a strong expected increase in WWTPs over the course of the century. This leads to a MRP of 50% in 2050 and 65% in 2100 (assumed at 635\$(2010)/tCe<sub>q</sub>).

## S9.3 Fluorinated gases

### S9.3.1 Hydrofluorocarbons (HFCs)

HFCs are mainly used as propellant in foams and refrigerant in a wide range of cooling applications, and can be emitted during and after use. In addition, HFC23 is emitted as a by-product in the production of HCFC-22, used as feedstock in industry and as refrigerant, although the latter use is being phased-out in accordance with the Montreal Protocol. In an extensive study, Schwarz et al. (2011) identified very high reduction potentials for all HFC species and applications, at low costs and equal functional performance of alternative solutions; HFCs used for foam blowing can be 100% substituted by zero GWP substances for estimated costs of 52 \$/tC. The by-product HFC23 can very effectively be thermally destructed (estimated at 98% in 2100) at very low costs (below 2 \$(2010)/tCeq) (IPCC/TEAP, 2005). HFCs for other applications (mainly refrigeration related, but also use as solvents, aerosols and firefighting agents) can mainly be reduced by substitution with (near) zero GWP substances, complemented by better sealed systems and recovery after use, which is estimated to lead to a reduction efficiency of 97% at 258 \$(2010)/tCeq.

The likelihood of realizing the emission reductions has increased due to the 2016 Kigali Amendment to the Montreal protocol, in which all countries in the United Nations agreed to ambitious HFC abatement towards 2043.

### S9.3.2 Perfluorocarbons (PFCs)

PFCs are largely emitted as a by-product of primary aluminium production, followed by the use and loss of PFCs in semiconductor manufacturing. In smaller quantities, PFCs are emitted when used as solvents, refrigerants and firefighting agents. For PFC mitigation in aluminium production, several options exist. Point-Feed Prebake technology (PFPB) leads to high reductions at moderate costs. Following Lucas et al. (2007), these are assumed to lead to a MRP of 80% in 2050 at 635 \$(2010)/tCeq. A reduction efficiency of 100% is in principle possible, when applying Inert Anode (IA) technology, but this is yet to be fully developed and likely to come at a much higher cost (Purohit and Höglund-Isaksson, 2017). For 2100, an overall MRP of 90% is assumed, which includes technological improvement of presently available PFPB and partial introduction of new technologies such as IA. PFC emissions from semiconductor manufacturing can be near 99% mitigated, either by thermal destruction or substitution (Lucas et al., 2007; Purohit and Höglund-Isaksson, 2017). An overall MRP is assumed of 80% and 100% in 2050 and 2100, respectively (assuming full implementation in the latter year), at 254 \$(2010)/tCeq. For all other PFC sources, the main mitigation option is substitution by zero GWP substances. The MRP in 2100 is assumed to be slightly lower (95%), due to a larger diversity in sources, also at 254\$(2010)/tCeq.

### S9.3.3 Sulphur hexafluoride (SF<sub>6</sub>)

SF<sub>6</sub> emissions occur during the production and use of electrical switchgear equipment and the decommissioning of sound-proof windows, and is released as a by-product of industrial activities, mainly of magnesium production. For SF<sub>6</sub>, the same assumptions have been applied as by Lucas et al. (2007), as they closely resemble estimates found in recent work (Purohit and Höglund-Isaksson, 2017).



Emissions from the production, as well as the decommissioning of, electrical equipment can be mitigated by “good practice”: improved recovery and recycling, reduced leakage and improved handling. The MRP is estimated at 80% and 90% in 2050 and 2100, respectively at 317 \$(2010)/tCeq. Emissions from magnesium production can be reduced by replacing SF<sub>6</sub> as a protective gas during magnesium casting and is estimated to lead to an MRP of 90% in 2050 and 2100 at 127 \$(2010)/tCeq. Mitigation options for other sources also involve good practice or even the ban of SF<sub>6</sub> use in the case of sound-proof windows (Purohit and Höglund-Isaksson, 2017). The MRP is estimated at 90% and 100% in 2050 and 2100, respectively, at 508 \$(2010)/tCeq.

## References

- Abichou, T., Kormi, T., Marsh, A., Wang, C. (2016) Phytocaps for Landfill Emission Reduction in Australia. 222-231.
- Akiyama, H., Yan, X., Yagi, K. (2010) Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N<sub>2</sub>O and NO emissions from agricultural soils: meta-analysis. *Global Change Biology* 16, 1837–1846.
- Bajželj, B., Richards, K.S., Allwood, J.M., Smith, P., Dennis, J.S., Curmi, E., Gilligan, C.A. (2014) Importance of food-demand management for climate mitigation. *Nature Climate Change* 4, 924-929.
- Barcon, T., Hernandez, J., Gomez-Cuervo, S., Garrido, J.M., Omil, F. (2015) Characterization and biological abatement of diffuse methane emissions and odour in an innovative wastewater treatment plant. *Environ Technol* 36, 2105-2114.
- Basak, R. (2015) Benefits and costs of nitrogen fertilizer management for climate change mitigation Focus on India and Mexico. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) Working Paper No. 161.
- Bates, J., Brophy, N., Harfoot, M., Webb, J. (2009) Sectoral Emission Reduction Potentials and Economic Costs for Climate Change (SERPEC-CC) Agriculture: methane and nitrous oxide.
- Bell, M.J., Wall, E., Russell, G., Morgan, C., Simm, G. (2010) Effect of breeding for milk yield, diet and management on enteric methane emissions from dairy cows. *Animal production science* 50, 817 - 826.
- Bylin, C., Zachary Schaffer, Vivek Goel, Donald Robinson, Alexandre do N. Campos, Fernando Borensztein, (2010) Designing the Ideal Offshore Platform Methane Mitigation Strategy. US Environmental Protection Agency, SPE.
- Carrara, S., Marangoni, G. (2013) Non-CO<sub>2</sub> Greenhouse Gas Mitigation Modeling with Marginal Abatement Cost Curves: Technical Change, Emission Scenarios and Policy Costs. FEEM Working Paper No. 110.2013.
- Clarke, L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Löschel, D. McCollum, S. Paltsev, S. Rose, P. R. Shukla, M. Tavoni, B. C. C. van der Zwaan, Vuuren, D.P.v. (2014) Assessing Transformation Pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*
- Den Elzen, M.G.J., Meinshausen, M., Van Vuuren, D.P. (2007) Multi-gas emission envelopes to meet greenhouse gas concentration targets: costs versus certainty of limiting temperature increase. *Global Environmental Change* 17, 260-280.
- Dickie, A., Streck, C., Roe, S., Zurek, M., Haupt, F., Dolginow, A. (2014) Strategies for Mitigating Climate Change in Agriculture: Abridged Report. Climate Focus and California Environmental Associates, prepared with the support of the Climate and Land Use Alliance. Report and supplementary.
- Eagle, A.J., Olander, L.P., Henry, L.R., Haugen-Kozyra, K., Millar, N., Robertson, G.P. (2012) Technical Working Group on agricultural Greenhouse Gases (T-AGG ) REPORT Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States A Synthesis of the Literature.
- EC (2015) Closing the loop - An EU action plan for the Circular Economy, European Commission Communication to the European Parliament. COM(2015) 614.
- Ecofys (2006) Development of F-gas module for TIMER model. Authors: Dr. Jochen Harnisch, Sebastian Klaus, Sina Wartmann and Jan-Martin Rhiemeier. Project number: PECSDE082196 Client: Netherlands Environmental Assessment Agency MNP.
- Eom, W.-H., Ayoub, M., Yoo, K.-S. (2016) Catalytic Decomposition of N<sub>2</sub>O at Low Temperature by Reduced Cobalt Oxides. *Journal of Nanoscience and Nanotechnology* 16, 4647-4654.

Eory, V., Rees, B., Topp, K., Dewhurst, R., MacLeod, M., Morgan-Davies, C., Watson, C., Waterhouse, T., Moran, D., Sharp, M.J., Ball, B., Campbell, J., Crooks, B., Bell, J., Petersen, S.O. (2016) ClimateXChange study: On-farm technologies for the reduction of greenhouse gas emissions in Scotland.

Feng, J., Chen, C., Zhang, Y., Song, Z., Deng, A., Zheng, C., Zhanga, W. (2013) Impacts of cropping practices on yield-scaled greenhouse gas emissions from rice fields in China: A meta-analysis. *Agriculture, Ecosystems and Environment* 164, 220–228.

Frutos, O.D., Barriguin, G., Lebrero, R., Munoz, R. (2017) Assessing the influence of the carbon source on the abatement of industrial N<sub>2</sub>O emissions coupled with the synthesis of added-value bioproducts. *Sci Total Environ* 598, 765-771.

GECS (2002) Greenhouse Gas Emission Control Strategies - Research Project N° EVK2-CT-1999-00010, Thematic Programme : Environment and Sustainable Development of the DG Research Fifth Framework Programme.

Gernaat, D.E.H.J., Van Vuuren, D.P., Van den Berg, M., Calvin, K., Lucas, P.L., Luderer, G., Otto, S., Rao, S., Strefler, J. (2015) Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Global Environmental Change* 33, 142-153.

Graus, W.J., Harmelink, M., Hendriks, C. (2004) Marginal GHG-Abatement Curves for Agriculture. *Ecofys report, EEP030339, April 2004.*

Han, D., Zhao, Y., Xue, B., Chai, X. (2010) Effect of bio-column composed of aged refuse on methane abatement – A novel configuration of biological oxidation in refuse landfill. *Journal of Environmental Sciences* 22, 769-776.

Hansen, J., Sato, M., Ruedy, R., Lacis, A., Oinas, V. (2000) Global warming in the twentyfirst century: an alternative scenario. *Proc. Natl Acad. Sci.*, 9875–9880.

Harmesen, M., Vuuren, D.P.v., Bodirsky, B.L., Chateau, J., Durand-Lasserve, O., Drouet, L., Fricko, O., Fujimori, S., Gernaat, D.E.H.J., Hanaoka, T., Hilaire, J., Keramidas, K., Luderer, G., Moura, M.C.P., Sano, F., Smith, S.J., Wada, K. (2019) The role of methane in future climate strategies: Mitigation potentials and climate impacts. *Climatic Change (EMF30 Special Edition, in press).*

Harnisch, J., Jubb, C., Nakhutin, A., Cianci, V.C.S., Lanza, R., Martinsen, T., Mohammad, A.K.W., Santos, M.M.O., McCulloch, A., Mader, B.T., Pérez-Ramírez, J., Neelis, M., Patel, M. (2006) IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 3 Chemical Industry.

Henderson, B.B., Gerber, P.J., Hilinski, T.E., Alessandra Falcucci, Ojima, D.S., Salvatore, M., Conant, R.T. (2015) Greenhouse gas mitigation potential of the world’s grazing lands: Modeling soil carbon and nitrogen fluxes of mitigation practices. *Agriculture, Ecosystems and Environment* 207, 91-100.

Hinde, B.P., Mitchell, I., Riddell, M. (2016) COMETTM - A New Ventilation Air Methane (VAM) Abatement Technology. *Johnson Matthey Technology Review* 60, 211-221.

Höglund-Isaksson, L. (2012) Global anthropogenic methane emissions 2005–2030: technical mitigation potentials and costs. *Atmos. Chem. Phys.* 12, 9079-9096.

Höglund-Isaksson, L. (2017) Bottom-up simulations of methane and ethane emissions from global oil and gas systems 1980 to 2012. *Environmental Research Letters* 12.

Hristov, A.N., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E., Waghorn, G., Dijkstra, J., Oosting, S. (2013) Mitigation of Greenhouse Gas Emissions in Livestock Production, A review of technical options for non-CO<sub>2</sub> emissions. *FAO Animal Production and Health.*

Hui, K.S., Kwong, C.W., Chao, C.Y.H. (2010) Methane emission abatement by Pd-ion-exchanged zeolite 13X with ozone. *Energy & Environmental Science* 3, 1092.

Hulshof, R.B.A., A. Berndt, W. J. J. Gerrits, J. Dijkstra, S. M. van Zijderveld, J. R. Newbold, Perdok, H.B. (2012) Dietary nitrate supplementation reduces methane emission in beef cattle fed sugarcane-based diets. *J. Anim. Sci.* 90, 2317–2323.

Hussain, M., Deorsola, F.A., Russo, N., Fino, D., Pirone, R. (2015) Abatement of CH<sub>4</sub> emitted by CNG vehicles using Pd-SBA-15 and Pd-KIT-6 catalysts. *Fuel* 149, 2-7.

- IEA (2016) World Energy Outlook, 2016, IEA PUBLICATIONS, 9 rue de la Fédération, 75739 PARIS CEDEX 15.
- IPCC/TEAP (2005) IPCC/TEAP special report on safeguarding the ozone layer and the global climate system : issues related to hydrofluorocarbons and perfluorocarbons : prepared by Working Groups I and III of the Intergovernmental Panel on Climate Change and the Technical and Economic Assessment Panel. Cambridge University Press, Cambridge.
- Jiao, Z., Hou, A., Shi, Y., Huang, G., Wang, Y., Chen, X. (2006) Water Management Influencing Methane and Nitrous Oxide Emissions from Rice Field in Relation to Soil Redox and Microbial Community. *Communications in Soil Science and Plant Analysis* 37.
- Karakurt, I., Aydin, G., Aydiner, K. (2012) Sources and mitigation of methane emissions by sectors: A critical review. *Renewable Energy* 39, 40-48.
- Kesicki, F., Ekins, P. (2012) Marginal abatement cost curves: a call for caution. *Climate Policy* 12, 219-236.
- Kinley, R.D., Nys, R.d., Vucko, M.J., Machado, L., Tomkins, N.W. (2016) The red macroalgae *Asparagopsis taxiformis* is a potent natural antimethanogenic that reduces methane production during in vitro fermentation with rumen fluid. *Animal production science* 56, 282-289.
- Launio, C.C., Asisc, C.A., Manalili, R.G., Javier, E.F. (2016) Cost-effectiveness analysis of farmers' rice straw management practices considering CH<sub>4</sub> and N<sub>2</sub>O emissions. *Journal of Environmental Management* 183, 245-252.
- Lebrero, R., Lopez, J.C., Lehtinen, I., Perez, R., Quijano, G., Munoz, R. (2016) Exploring the potential of fungi for methane abatement: Performance evaluation of a fungal-bacterial biofilter. *Chemosphere* 144, 97-106.
- Lechtenböhmer, S., Dienst, C. (2010) Future development of the upstream greenhouse gas emissions from natural gas industry, focussing on Russian gas fields and export pipelines. *Journal of Integrative Environmental Sciences* 7, 39-48.
- Li, L., Xu, J., Hu, J., Han, J. (2014) Reducing nitrous oxide emissions to mitigate climate change and protect the ozone layer. *Environ Sci Technol* 48, 5290-5297.
- Li, X., Norman, H.C., Kinley, R.D., Laurence, M., Wilmot, M., Bender, H., Nys, R.d., Tomkins, N. (2016) *Asparagopsis taxiformis* decreases enteric methane production from sheep. *Animal production science* 58, 681-688
- Linquist, B.A., Adviento-Borbe, M.A., Pittelkow, C.M., Kessel, C.v., Groenigen, K.J.v. (2012) Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis. *Field Crops Research* 135, 10–21.
- Lipsky, R. (2014) Gas-to-Liquids Technology Offers Solution for Stranded Gas. The American oil and gas reported.
- Lopez, J.C., Quijano, G., Souza, T.S., Estrada, J.M., Lebrero, R., Munoz, R. (2013) Biotechnologies for greenhouse gases (CH<sub>4</sub>), N<sub>2</sub>O, and CO<sub>2</sub>) abatement: state of the art and challenges. *Appl Microbiol Biotechnol* 97, 2277-2303.
- Lucas, P.L., Van Vuuren, D.P., Olivier, J.G.J., Den Elzen, M.G.J. (2007) Long-term reduction potential of non-CO<sub>2</sub> greenhouse gases. *Environmental Science & Policy* 10, 85 - 103.
- MacLeod, M., Moran, D., Eory, V., Rees, R.M., Barnes, A., Topp, C.F.E., Ball, B., Hoad, S., Wall, E., McVittie, A., Pajot, G., Robin Matthews, Smith, P., Moxey, A. (2010) Developing greenhouse gas marginal abatement cost curves for agricultural emissions from crops and soils in the UK. *Agricultural Systems* 103, 198–209.
- McKinsey (2010) Impact of the financial crisis on carbon economics. Version 2.1 of the Global Greenhouse Gas Abatement Cost Curve. McKinsey&Company.
- Moran, D., MacLeod, M., Wall, E., Eory, V., Pajot, G., Matthews, R., McVittie, A., Barnes, A., Rees, B., Moxey, A., Williams, A., Smith, P. (2008) UK marginal cost curves for the agriculture, forestry, land-use and land-use change sector out to 2022 and to provide scenario analysis for possible abatement options out to 2050 –RMP4950.Defra.

- Nalley, L., Bruce Linquist, Kent Kovacs, Anders, M. (2015) The Economic Viability of Alternative Wetting and Drying Irrigation in Arkansas Rice Production. *Crop Economics, Production & Management*.
- Nayak, D., Saetnan, E., Cheng, K., Wang, W., Koslowski, F., Cheng, Y.-F., Zhu, W.Y., Wang, J.-K., Liu, J.-X., Moran, D., Yan, X., Cardenas, L., Newbold, J., Pan, G., Lu, Y., Smith, P. (2015) Management opportunities to mitigate greenhouse gas emissions from Chinese agriculture. *Agriculture, Ecosystems and Environment* 209, 108-124.
- Nayak, D., Smith, P., Harmsen, J.H.M., Stehfest, E., Vuuren, D.P.v. (2018) GHG mitigation measures for Agriculture: a review of potential and cost (in prep.).
- Ndegwa, P.M., Hristov, A.N., Arogo, J., Sheffield, R.E. (2008) A review of ammonia emission mitigation techniques for concentrated animal feeding operations. *Biosyst. Eng.* 100, 453-469.
- Nunotani, N., Nagai, R., Imanaka, N. (2016) Direct catalytic decomposition of nitrous oxide gas over rhodium supported on lanthanum silicate. *Catalysis Communications* 87, 53-56.
- Park, S., Lee, C.-H., Ryu, C.-R., Sung, K. (2008) Biofiltration for Reducing Methane Emissions from Modern Sanitary Landfills at the Low Methane Generation Stage. *Water, Air, and Soil Pollution* 196, 19-27.
- Patel, S., Tremain, P., Sandford, J., Moghtaderi, B., Shah, K. (2016) Empirical Kinetic Model of a Stone Dust Looping Carbonator for Ventilation Air Methane Abatement. *Energy & Fuels* 30, 1869-1878.
- Petersen, S.O., Andersen, A.J., Eriksen, J. (2012) Effects of Cattle Slurry Acidification on Ammonia and Methane Evolution during Storage. *Journal of Environmental Quality Abstract - Atmospheric Pollutants and Trace Gases* 41, 88-94.
- Purohit, P., Höglund-Isaksson, L. (2017) Global emissions of fluorinated greenhouse gases 2005–2050 with abatement potentials and costs. *Atmos. Chem. Phys.* 17, 2795-2816.
- Rao, S., Riahi, K. (2006) The Role of Non-CO<sub>2</sub> Greenhouse Gases in Climate Change Mitigation: Long-term Scenarios for the 21st Century. *The Energy Journal Special Issue #3*, 177-200.
- Ravikumar, A.P., Brandt, A.R. (2017) Designing better methane mitigation policies: the challenge of distributed small sources in the natural gas sector. *Environmental Research Letters* 12, 044023.
- Reid, M.C., Guan, K., Wagner, F., Mauzerall, D.L. (2014) Global methane emissions from pit latrines. *Environ Sci Technol* 48, 8727-8734.
- Russo, N., Palmisano, P., Fino, D. (2009) Pd-Perovskite Catalysts for Methane Emissions Abatement: Study of Pd Substitution Effects. *Topics in Catalysis* 52, 2001-2006.
- Schwarz, W., Gschrey, B., Leisewitz, A., Herold, A., Gores, S. (2011) Preparatory study for a review of Regulation (EC) No 842/2006 on certain fluorinated greenhouse gases"; Final Report Prepared for the European Commission in the context of Service Contract No 070307/2009/548866/SER/C4; September 2011.
- Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J. (2008) Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society of London. Biological Sciences* 363, 789–813.
- Stehfest, E., van Vuuren, D.P., Kram, T., Bouwman, A.F., (eds.) (2014) *Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications*. The Hague: PBL Netherlands Environmental Assessment Agency.
- Sun, Y., Guan, Y., Pan, M., Zhan, X., Hu, Z., Wu, G. (2017) Enhanced biological nitrogen removal and N<sub>2</sub>O emission characteristics of the intermittent aeration activated sludge process. *Reviews in Environmental Science and Bio/Technology* 16, 761-780.
- Tariq, A., Vu, Q.D., Jensen, L.S., Tourdonnet, S.d., Sander, B.O., Wassmann, R., Mai, T.V., Neergaard, A.d. (2017) Mitigating CH<sub>4</sub> and N<sub>2</sub>O emissions from intensive rice production systems in northern Vietnam: Efficiency of drainage patterns in combination with rice residue incorporation. *Agriculture, Ecosystems and Environment* 249, 101–111.

Thu, T.N., Phuong, L.B.T., Van, T.M., Hong, S.N. (2016) Effect of Water Regimes and Organic Matter Strategies on Mitigating Green House Gas Emission from Rice Cultivation and Co-benefits in Agriculture in Vietnam. *International Journal of Environmental Science and Development* 7.

Torrallbo, F., Menéndez, S., Barrena, I., Estavillo, J.M., Marino, D., González-Murua, C. (2017) Dimethyl pyrazol-based nitrification inhibitors effect on nitrifying and denitrifying bacteria to mitigate N<sub>2</sub>O emission. *Nature Scientific reports*.

Towprayoon, S., Smakgahn, K., Poonkaew, S. (2005) Mitigation of methane and nitrous oxide emissions from drained irrigated rice fields. *Chemosphere* 59, 1547–1556.

Tyagi, L., Kumari, B., Singh, S.N. (2010) Water management — A tool for methane mitigation from irrigated paddy fields. *Science of the Total Environment* 408, 1085–1090.

US-EPA (2006) Global Mitigation of Non-CO<sub>2</sub> Greenhouse Gases. United States Environmental Protection Agency, EPA 430-R-06-005, Washington, D.C. .

US-EPA (2013) United States Environmental Protection Agency (USEPA), Global Mitigation of Non-CO<sub>2</sub> Greenhouse Gases: 2010-2030.

Van den Berg, M., Hof, A.F., van Vliet, J., van Vuuren, D.P. (2015) Impact of the choice of emission metric on greenhouse gas abatement and costs. *Environmental Research Letters* 10, 024001.

Van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., Doelman, J.C., Berg, M.v.d., Harmsen, M., Boer, H.S.d., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P.L., Meijl, H.v., Müller, C., Ruijven, B.J.v., Sluis, S.v.d., Tabeau, A. (2017) Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change* 42, 237-250.

van Vuuren, D.P., Weyant, J., de la Chesnaye, F. (2006) Multi-gas scenarios to stabilize radiative forcing. *Energy Economics* 28, 102-120.

Van Zijderveld, S.M., W. J. J. Gerrits, J. Dijkstra, J. R. Newbold, R. B. A. Hulshof, Perdok, H.B. (2011) Persistency of methane mitigation by dietary nitrate supplementation in dairy cows. *J. Dairy Sci.* 94, 4028–4038.

Velders, G.J.M., Fahey, D.W., Daniel, J.S., Andersen, S.O., McFarland, M. (2015) Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. *Atmospheric Environment* 123, 200-209.

Vogt-Schilb, A., Hallegatte, S., de Gouvello, C. (2014) Marginal abatement cost curves and the quality of emission reductions: a case study on Brazil. *Climate Policy* 15, 703-723.

Vogt-Schilb, A., Meunier, G., Hallegatte, S. (2018) When starting with the most expensive option makes sense: Optimal timing, cost and sectoral allocation of abatement investment. *Journal of Environmental Economics and Management* 88, 210-233.

Wassman, R., Lantin, R.S., Neue, H.U., Buendia, L.V., Corton, T.M., Lu, Y. (2000) Characterization of Methane Emissions from Rice Fields in Asia. III. Mitigation Options and Future Research Needs. *Nutrient Cycling in Agroecosystems* 58, 23–36.

Weiske, A., Michel, J. (2007) Greenhouse gas emissions and mitigation costs of selected mitigation measures in agricultural production. MEACAP WP3 D15a.

Weyant, J., Delachesnaye, P., Blanford, G. (2006) An overview of EMF-21: multigas mitigation and climate change. *Energy Journal*.

Winiwarter, W., Höglund-Isaksson, L., Klimont, Z., Schöpp, W., Amann, M. (2018) Technical opportunities to reduce global anthropogenic emissions of nitrous oxide. *Environmental Research Letters* 13, 014011.

Wu, D., Senbayram, M., Well, R., Brüggemann, N., Pfeiffer, B., Loick, N., Stempfhuber, B., Dittert, K., Bol, R. (2017) Nitrification inhibitors mitigate N<sub>2</sub>O emissions more effectively under straw-induced conditions favoring denitrification *Soil Biology & Biochemistry* 104, 197-207.

Yang, S., Peng, S., Xu, J., Luo, Y., Li, D. (2012) Methane and nitrous oxide emissions from paddy field as affected by water-saving irrigation. *Physics and Chemistry of the Earth, Parts A/B/C* 53-54, 30-37.

Yu, K., Chen, G., Jr, W.H.P. (2004) Reduction of global warming potential contribution from a rice field by irrigation, organic matter, and fertilizer management. *Global Biogeochemical cycles* 18.

- Yue, J., Yi Shi, Wei Liang, Jie Wu, Chenrui Wang, Huang, G. (2005) Methane and nitrous oxide emissions from rice field and related microorganism in black soil, northeastern China. *Nutrient Cycling in Agroecosystems* 73, 293–301.
- Yusuf, R.O., Noor, Z.Z., Abba, A.H., Hassan, M.A.A., Din, M.F.M. (2012) Methane emission by sectors: A comprehensive review of emission sources and mitigation methods. *Renewable and Sustainable Energy Reviews* 16, 5059-5070.
- Zhang, R., Hua, C., Wang, B., Jiang, Y. (2016) N<sub>2</sub>O Decomposition over Cu–Zn/γ–Al<sub>2</sub>O<sub>3</sub> Catalysts. *Catalysts* 6, 200.
- Zhu, K., Bruun, S., Jensen, L.S. (2016) Nitrogen transformations in and N<sub>2</sub>O emissions from soil amended with manure solids and nitrification inhibitor. *European Journal of Soil Science* 67, 792–803.