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Abstract

Methane is the second most important greenhouse gas after carbon dioxide contributing to human-made global warming. Keeping to the Paris Agreement of staying well below two degrees warming will require a concerted effort to curb methane emissions in addition to necessary decarbonization of the energy systems. The fastest way to achieve emission reductions in the 2050 timeframe is likely through implementation of various technical options. The focus of this study is to explore the technical abatement and cost pathways for reducing global methane emissions, breaking reductions down to regional and sector levels using the most recent version of IIASA's Greenhouse gas and Air pollution Interactions and Synergies (GAINS) model. The diverse human activities that contribute to methane emissions make detailed information on potential global impacts of actions at the regional and sectoral levels particularly valuable for policy-makers. With a global annual inventory for 1990–2015 as starting point for projections, we produce a baseline emission scenario to 2050 against which future technical abatement potentials and costs are assessed at a country and sector/technology level. We find it technically feasible in year 2050 to remove 54 percent of global methane emissions below baseline, however, due to locked in capital in the short run, the cumulative removal potential over the period 2020–2050 is estimated at 38 percent below baseline. This leaves 7.7 Pg methane released globally between today and 2050 that will likely be difficult to remove through technical solutions. There are extensive technical opportunities at low costs to control emissions from waste and wastewater handling and from fossil fuel production and use. A considerably more limited technical abatement potential is found for agricultural emissions, in particular from extensive livestock rearing in developing countries. This calls for widespread implementation in the 2050 timeframe of institutional and behavioural options in addition to technical solutions.

1. Introduction

Methane (CH_4) is the second most important greenhouse gas after carbon dioxide (CO_2) contributing to human-made global warming. Keeping to the Paris Agreement of staying well below two degrees warming above the pre-industrial average, will require a concerted effort to curb CH_4 emissions in addition to necessary decarbonization and efficiency enhancements of the energy systems. In the long-term, any remaining anthropogenic CH_4 emissions, e.g., linked to food production, must be offset through negative emission options (IPCC 2018). Compared to CO_2, CH_4 contributes 28 times more per ton to global warming over 100 years when excluding climate-carbon feedbacks (IPCC 2013). Because of its shorter lifetime in the atmosphere of 12 years,

CH_4's warming potential over twenty years is 84 times that of CO_2 per ton. This means CH_4 accounts for about 40 percent of greenhouse gases' contribution to short-term global warming, which makes it an obvious candidate to target for fast climate change mitigation in the 2050 timeframe (Shindell *et al* 2012). Human activities contribute more to CH_4 emissions than natural sources (Saunois *et al* 2016) and a swift reduction in anthropogenic CH_4 can even offset climate change impacts of a massive release of natural CH_4 from smelting Arctic permafrost (Christensen *et al* 2019).

The fastest way to achieve CH_4 emission reductions in the 2050 timeframe is likely through implementation of various technical options (Pacala and Socolow 2004). Further abatement potential from institutional changes (Evans and Steven 2009) and behavioural changes (Abrahamse and Steg 2013, Camilleri *et al* 2019) will be necessary but may take longer to realize. Therefore, the focus of this study is to explore the technical abatement and cost pathways for reducing global CH_4 emissions in the 2020–2050 timeframe, breaking reductions down to regional and sector levels using the most recent version of IIASA's Greenhouse gas and Air pollution Interactions and Synergies (GAINS) model (Amann *et al* 2011), denoted GAINSv4 (2019). The diverse human activities that contribute to CH_4 emissions make it particularly valuable with detailed information to inform policy-makers about the potential global impacts of fast actions at the regional and sectoral levels. In addition, we provide insights on sensitivities related to the time and opportunity cost perspectives of the social planner versus private investors.

This study builds on Höglund-Isaksson (2012) by extending the timeframe from 2030 to 2050, updating statistics for historical years to 2015, reflecting recent findings from the literature, and including several methodological improvements of emission estimations, e.g., for the oil and gas sectors (Höglund-Isaksson 2017, Dalsøren *et al* 2018) and waste and wastewater sectors (Gómez-Sanabria *et al* 2018). The extended timeframes of this study, to 2015 for historical emissions and to 2050 for future projections, allow for two important insights. First, our bottom-up emission inventory to 2015 attributes a strong increase in atmospheric CH_4 emissions after 2007 (Nisbet *et al* 2014, 2019) to a combination of factors; rapid growth in extraction of unconventional gas in North America, extended coal mining in Indonesia, and accentuated growth in waste and wastewater emissions in rapidly developing world regions. Second, the technical mitigation potential of global CH_4 emissions will not be enough for meeting the targets in 2050 of the Paris Agreement. In addition, institutional and behavioural changes will be needed. The GAINSv4 model results add to a limited number of independently developed bottom-up estimates of technical abatement potentials and costs to reduce global CH_4 emissions in the 2050 timeframe (Lucas *et al* 2007, Harmsen *et al* 2019). Similar efforts have been presented for the 2030 timeframe, e.g., Höglund-Isaksson (2012) estimated marginal abatement cost curves using an earlier version of the GAINS model and USEPA (2006, 2012) presented corresponding cost curves for all non-CO_2 greenhouse gases with (Beach *et al* 2015, Beach *et al* 2008) and Frank *et al* (2018) presenting results specifically for the agricultural sector.

2. Methodology

2.1. Emission estimation

The GAINS model estimates emissions bottom-up, i.e., quantifications of human activities contributing to emissions are multiplied by an emission factor representing the average emissions per unit of activity. Such estimates rely on a wealth of publicly available information to develop internally consistent emission factors across countries, sectors and technologies. The starting point for estimations of anthropogenic CH_4 is the methodology recommended in the IPCC (2006) guidelines, for most source sectors using country-specific information to allow for deriving country- and sector/technology- specific emission factors at a Tier 2 level. For some source sectors consistent methodologies were further developed, e.g., for oil and gas systems (Höglund-Isaksson 2017) and solid waste sectors (Gómez-Sanabria *et al* 2018). The resulting emission estimates are thereby well comparable across geographic and temporal scales and with a possibility to provide plausible explanations for deviations in past emissions. CH_4 emissions are estimated for 174 countries/regions, with the possibility to aggregate to a global emission estimate, and spanning a timeframe from 1990 to 2050 in five-year intervals. For the purpose of better evaluating historical CH_4 emissions, annual estimates for 1990–2015 were produced for this study. Following the general GAINS methodology (Amann *et al* 2011), emissions from source *s* in region *i* and year *t* are calculated as the activity data A_{its} times an emission factor ef_{ism}. If emissions are controlled through implementation of technology *m*, the fraction of the activity controlled is specified by $Appl_{itsm}$, i.e.,

$$E_{its} = \sum_{m} [A_{its} * ef_{ism} * Appl_{itsm}], \tag{1}$$

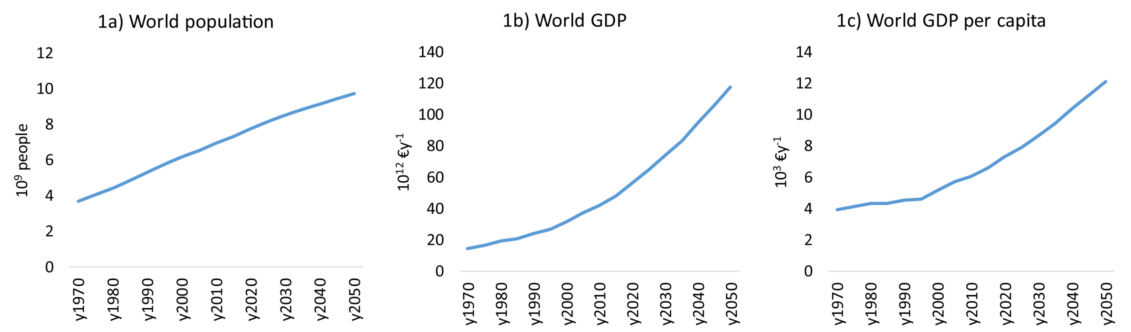

Figure 1. Global projections for population (panel 1a), Gross Domestic Product GDP (panel 1b) and average GDP per capita (panel 1c) 1970–2050. Sources: World Bank (2018) for historical years and projections consistent with IEA-WEO 2018.

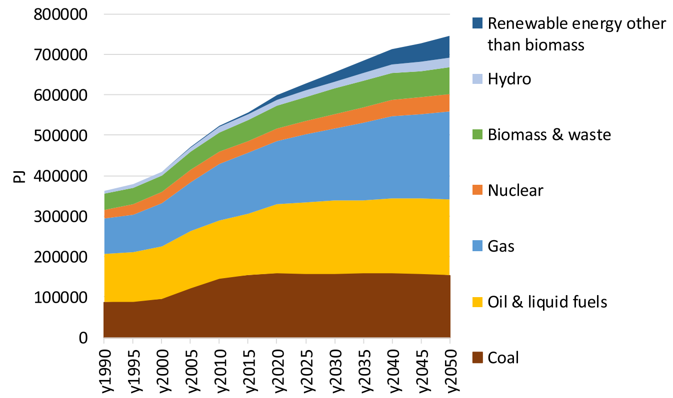

Figure 2. Global energy consumption by fuel in the IEA-WEO2018 New Policies Scenario.

where

$$\sum_m Appl_{its} = 1, \tag{2}$$

and where A_{its} is the activity (e.g., number of animals, tons of waste, PJ gas produced),

ef_{ism} is the emission factor for the fraction of the activity subject to control by technology m,

$Appl_{itsm}$is the application rate of technology m to activity s.

Hence, for each emission source sector, country-and year- specific sets of application rates for all the possible technologies (including no control) are defined such that application rates always sum to unity.

2.2. Activity data

The GAINSv4 model structure covers all relevant source sectors for anthropogenic CH_4 emissions, for details see tables S1–1 in the supplement information (SI) is available online at stacks.iop.org/ERC/2/025004/mmedia. Activity drivers for macroeconomic development, energy supply and demand, and agricultural activities are entered externally in GAINS. For the baseline scenario presented here, the macroeconomic and energy sector activity drivers are consistent with the IEA World Energy Outlook 2018 New Policies Scenario (IEA-WEO 2018). Growth in global population, Gross Domestic Product (GDP) and GDP per capita are illustrated in figure 1. This energy scenario assumes that countries comply with the Intended National Determined Contributions (INDCs) to climate change mitigation they pledged in the lead-up to the UNFCCC's COP21 in Paris in 2015, however, it should be noted that these pledges fall short of the Paris Agreement of keeping the Earth's warming well below 2 °C above the pre-industrial average. How this energy scenario translates into global consumption of different types of fuels is illustrated in figure 2. Note that for the purpose of this study of improving the understanding of the technical mitigation potentials at the sectoral and regional level, only one baseline has been developed against which future emission reductions are assessed. To provide a full range of possible future developments of global anthropogenic methane emissions, a set of alternative activity scenarios would be required. This is however considered out of scope of this paper, as the relative technical mitigation potentials at the sector and regional level will be comparable irrespective of the baseline emission level.

Table 1. Principal sources of information for CH_4 emission factors in the GAINSv4 model.

Major source sector	Source sector	Emission factors -prinicpal sources of information
Agriculture	Beef cattle, Dairy cows, Pigs, Poultry, Sheep and other livestock	Livestock emission factors consistent with national reporting to UNFCCC 2016, 2018, complemented with national sources e.g., Xue *et al* 2014, FAO 2017a, 2017b, Yu *et al* 2018, Hansen *et al* 2018. For details, see Section S6.4 in SI.
	Agr waste burning	IPCC (2006) guidelines Section 5.4.2.
Rice cultivation	IPCC (2006) guidelines (Vol.4, pp 5.45–5.49), complemented with national reporting to (UNFCCC 2016, UNFCCC 2018) on water regimes and flooding days per year when available.	
Energy	Coal mining	Emission factors aligned with national reporting to UNFCCC (2016) with revisions for China (Peng *et al* 2016, China BUR to UNFCCC 2017, Miller *et al* 2019, Sheng *et al* 2019), see Section 6.1 in SI and Section 2.6 in SI of Höglund-Isaksson (2012) for details.
	Abandoned coal mines	USEPA (2017) and emissions reported to UNFCCC (2018) for Annex-1 countries, complemented with the assumption of 10% of active hard coal mine emissions, as derived from USEPA (2017), see Section S6.2 in SI for details.
	Domestic energy use-firewood, Domestic energy use -other non-gas fuels, Industry energy use -non-gas fuels, Power plant energy use -non-gas fuels	For residential sources, emission factors specified by type of boiler and fuel (Delmas 1994, Johansson *et al* 2004, Kjäll-strand and Olsson 2004, Olsson and Kjällstrand 2006). For non-residential stationary sources and mobile sources, default emission factors from IPCC 2006, (Vol.2, pp.2.16–2.23 and p.3.24).
	Domestic energy use-gas fuel, Industry energy use -gas fuel, Power plant energy use -gas fuel, Long-distance gas transmission	Emission factors for long-distance gas transmission and gas distribution networks (residential and non-residential, respectively) have been aligned with national reporting to UNFCCC (2016) when available, complemented with default factors from IPCC 2006, (Vol 2, pp4.48–4.62, Tables 4.2.4 and 4.2.5).
	Gas production	Emission factors from Höglund-Isaksson (2017); US emission factors updated (Zavala-Araiza *et al* 2015, Omara *et al* 2016, Alvarez *et al* 2018), corresponding to average leakage rates of 1% for conventional natural gas, 2.66% for shale gas, 0.58% for coal bed methane (CBM), and 1.65% for tight gas, see Section S6.3 in SI for detials.
	Oil production	Emission factors from Höglund-Isaksson (2017) in consistency with Dalsøren *et al* (2018), but with updates for Russian associated gas composition (Huang *et al* 2015) and flared gas volumes in 2015 (Elvidge *et al* 2016), see Section S6.3 in SI for details.
	Oil refinery	Default emission factors from IPCC (2006, Vol.2, p.4.34, pp.4.52–4.61). For details see section 2.2. in SI of Höglund-Isaksson (2012)
	Transport Road and Off-Road	COPERT (EMISIA 2013)
Industry	Industry Brick kilns	AIT (2003)
Waste	Industrial solid waste, , Municipal solid waste, Industrial wastewater, Domestic wastewater	Emission factors are specified by waste flow for fourteen different waste treatment options, see Gomez-Sanabria *et al* (2018) and Höglund-Isaksson *et al* (2018) for details on references.

Agricultural activity data are taken from FAOSTAT (2018) with projections aligned to the most recent forecast of FAO (Alexandratos and Bruisma 2012) and complemented with data from national sources e.g., reporting to UNFCCC (2018) and EUROSTAT (2016) for information about manure management practices, farm sizes etc. The historical and projected changes in global livestock numbers are illustrated in figure 3.

Activity data for the waste and wastewater sectors are derived in GAINSv4 using the methodology described in the Supplement of Gómez-Sanabria *et al* (2018). Drivers for the generation of municipal solid waste (MSW) are GDP per capita and urbanization rate, here in consistency with macroeconomic assumptions of the

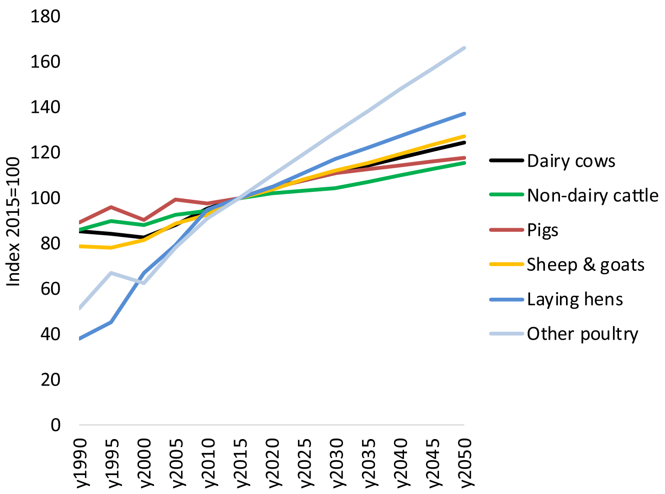

Figure 3. Changes in global livestock numbers relative year 2015 (=100) (FAOSTAT 2018 and Alexandratos and Bruisma 2012).

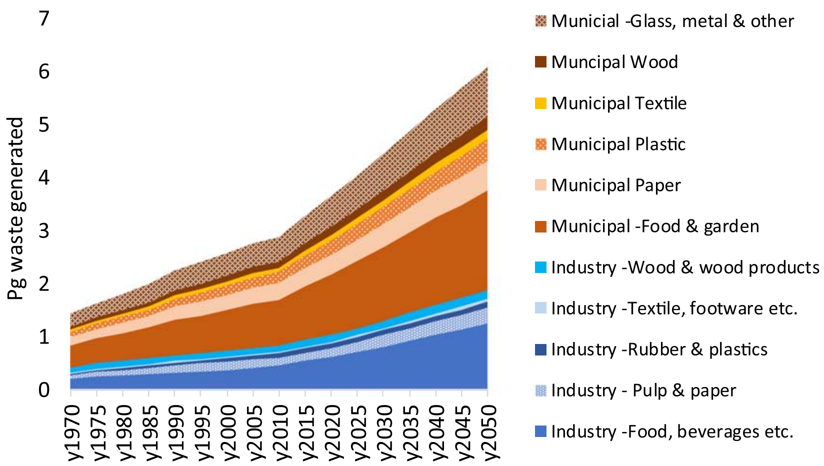

Figure 4. Global generation of solid waste 1970–2050 from municipal and manufacturing industry sources (gross, i.e., before recycling or treatment). Estimated in GAINSv4 in consistency with population and macroeconomic projections of the IEA-WEO2018 following the methodology described in Gómez-Sanabria *et al* (2018).

IEA-WEO2018 (see figure 1). Elasticities for MSW generation by income group are estimated from historical data and reflect the relative increase in average per capita waste generated in response to a relative increase in the average per capita income and urbanization rate. As shown in Gómez-Sanabria *et al* higher waste generation elasticity estimates are found for countries with higher incomes. At lower income levels, households primarily generate food waste, while at higher average income levels it is primarily the generation of non-food waste that increase with income. Figure 3 illustrates the global gross generation of waste (i.e., before disposal through scattering, landfill, recycling, incineration or other treatment) for the period 1970–2050 as estimated within the GAINSv4 model. Because of slow decomposition of organic waste in landfills, we account for a time-lag of up to 20 years between disposal of waste to a landfill and the release of CH_4 emissions. To estimate emissions from the year 1990 onwards, it is therefore necessary to estimate waste generation already from the year 1970. As shown in figure 4, the growth rate for the generation of global municipal solid waste is estimated to increase after 2010, with global amounts growing by 4.5 percent between 2005–2010 and by 14 percent between 2010–2015. Note that for the waste sector the baseyear for projections is 2010 and the 2015 estimate is a model result. The strong increase in global MSW generation between 2010 and 2015 is mainly driven by an expected 20 percent increase in MSW generation in China and India, which follows from the application of a higher MSW generation elasticity as several provinces move into higher average income segments between 2010 and 2015. Although a model result in GAINSv4, the higher growth rate for China after 2010 is confirmed empirically by Chayy *et al* (2018) who find that collected and transported MSW in China increased by 1.5 percent between 2005 and 2010 and by 21 percent between 2010 and 2015.

2.3. Emission factors and current control legislation

Sector-specific emission factors are identified both for a no control case and for each control technology applicable to the specific sector in a country. Emission factors are adopted from country-specific information and/or derived in a consistent manner across countries from information on factors determining the country-specific emission factors. Table 2 presents a selection of the most important information sources for CH_4 emission factors in GAINSv4 with a focus on updates made after the publication of Höglund-Isaksson (2012). In addition, a wealth of national information has been fed into individual emission factor estimates, as documented in Höglund-Isaksson (2012, 2017), Höglund-Isaksson *et al* (2015, 2018), and Gómez-Sanabria *et al* (2018). More sector details are available in section S6 of the SI.

An implicit assumption in the development of the baseline scenario is that it considers effects on current and future CH_4 emissions from regulations and legislation already adopted as of Dec 2018. Tables S4–1 in the SI presents a list of implemented national and regional legislation with direct or indirect impacts on CH_4 emissions that have been considered in the GAINSv4 baseline scenario. Note that future mitigation potentials and associated costs are always assessed as additive to the baseline. Emission reductions and costs incurred by abatement options adopted already in the baseline are not reflected in the estimation of future mitigation potentials and costs.

2.4. Technical mitigation potential and costs

The mitigation potential assessed in the marginal abatement cost curves of the GAINSv4 model refers to feasible reductions in emissions through adoption of technologies defined as installations or applications of physical equipment or material, or modifications in physical parameters affecting emissions. In the short-run, immediate adoption of control technology is assumed constrained by lock-in of investments into existing technology, with successive phase in of new technology modelled by sector over the period 2020–2035 and with full effect on emissions from implementation of maximum technically feasible reductions (MFR) only achievable from 2040 onwards. The GAINSv4 baseline scenario assumes no effects on costs and removal efficiencies from technological development as it is assumed that any incentives to adopt (and therefore further develop) emission control technology rely heavily on the existence and stringency of policies directly addressing CH_4 emissions. Hence, without further policy incentives, there are assumed to be no further driver for technological development, which means emission factors for a given technology remain constant over time in the baseline. An exception could be technologies that simultaneously reduce CH_4 emissions and recover/save gas that can be utilized for energy purposes. Adoption of such technologies may arise spontaneously if the future price of gas become high enough to make gas recovery profitable. As the development in future fuel prices is highly uncertain, such technology uptake is not reflected in the baseline scenario, but treated as a future mitigation potential available at a negative cost. In contrast to the baseline scenario, GAINSv4 mitigation scenarios for CH_4 assume additional policy incentives are indeed put in place to stimulate both uptake and further development of CH_4 abatement technology. Assumptions in GAINSv4 about the effects of technological development on removal efficiency and costs for CH_4 mitigation options are presented in tables S5–1 of the SI. Justifications for these assumptions are based on empirical findings of observed developments in control technology following introductions of NOx and SO_2 regulations in the US (Popp 2003), Japan (Matsuno *et al* 2010) and Sweden (Höglund-Isaksson and Sterner 2010) in the 1990s, as presented in section 2.5.1 of Höglund-Isaksson *et al* (2018).

Unit costs for mitigation of CH_4 per unit of activity are in GAINSv4 calculated as the sum of investment costs, labour costs, non-labour operation and maintenance costs, cost-savings due to recovery or saving of electricity, heat or gas, and non-energy cost savings like avoidance of landfill fees. Unit costs are expressed in constant 2010 Euros per unit of activity. Country and sector specific annual average wages for the agricultural and manufacturing industry sectors are taken from LABORSTA (ILO 2010) for historical years. Growth in average future wages is proportional to the expected future development in GDP per capita with sector adjustments consistent with growth in sector value added as provided by IEA-WEO (2018). The cost-saving of energy recovery from biogas production or reduced leakage of natural gas during production, transmission and distribution is set equal to the expected future electricity or gas consumer price in industry as taken from the IEA-WEO (2018) New Policies Scenario. Gas recovery refers to the recovery of gas of an upgraded quality of 97 percent CH_4. For some mitigation options, e.g., when biogas is recovered from large-scale anaerobic digestion of food and organic waste, upgrading from 60 to 97 percent CH_4 is necessary for supplying the gas to the grid (Persson 2003). Costs for upgrading gas have in these cases been included in investment costs.

The total mitigation cost in sector s, country i and year t is defined for sets of application combinations of the possible technologies applicable to the sector. For a given country, year and sector, a technology setting is defined such that the sum of all application rates $Appl_{itsm}$ of possible technologies m (including the no control option) is always unity. The total cost of each technology setting is defined as:

Table 2. Global baseline and MFR CH_4 emissions in years 2015 and 2050 and cumulative emissions 2020–2050 by source sector.

Emission source sector	Technical abatement options implemented in MFR	Baseline 2015	Baseline 2050	Emissions in 2050 after Max technically feasible reduction (MFR)	Cumulative emissions 2020–2050			
		Tg CH_4	Tg CH_4	Tg CH_4	Technical abatement in % below 2050 Baseline	Baseline Tg CH_4	MFR Tg CH_4	Technical abatement in % below cumulative Baseline
Dairy cows	Enteric fermentation: feed changes and breeding to improve productivity and animal health/fertility. Manure management: treatment in biogas digester. Applicable to large farms > 100 LSU.	23.4	27.9	24.8	−11%	804	696	−14%
Non-dairy beef cattle	Enteric fermentation: feed changes and breeding to improve productivity and animal health/fertility. Manure management: treatment in biogas digester. Applicable to large farms > 100 LSU.	55.0	64.0	53.5	−16%	1857	1561	−16%
Pigs	Manure management: treatment in biogas digester.	5.3	5.5	3.2	−42%	165	112	−32%
Sheep & other livestock	Enteric fermentation: feed changes and breeding to improve productivity and animal health/fertility.	26.7	34.3	34.1	-1%	967	881	−9%
Rice cultivation	Improved water management, use of alternative hybrids and soil amendments	32.0	32.1	16.3	-49%	994	659	−34%
Agricultural waste burning	Ban and enforcement of existing bans on agricultural wasre burning.	3.5	3.5	0.0	-100%	110	37	−66%
Combustion of biomass fuels	No technical abatement option identified.	8.5	8.0	8.0	0%	246	220	−10%
Combustion of fossil fuels	No technical abatement option identified.	3.4	5.3	5.3	0%	130	120	−8%
Coal mining	Pre-mining degasification. Ventilation air methane oxidation with improved ventilation.	37.1	36.2	15.3	-58%	1145	666	−42%
Abandoned coal mines	Flooding.	3.5	3.8	0.3	−92%	118	46	−61%
Oil production	Extended recovery of associated gas. Leakage detection and repair programs (LDAR) for unintended leakage.	43.5	51.9	6.1	−88%	1460	612	−58%
Oil refinery & storage	Leakage detection and repair programs (LDAR) for unintended leakage.	0.2	0.2	0.1	−66%	6	3	−46%
Natural gas production		9.4	13.8	2.2	−84%	370	162	−56%

Table 2. (Continued.)

Emission source sector	Technical abatement options implemented in MFR	Baseline 2015	Baseline 2050	Emissions in 2050 after Max technically feasible reduction (MFR)	Cumulative emissions 2020–2050			
		Tg CH_4	Tg CH_4	Tg CH_4	Technical abatement in % below 2050 Baseline	Baseline Tg CH_4	MFR Tg CH_4	Technical abatement in % below cumulative Baseline
	Leakage detection and repair programs (LDAR) for unintended leakage.							
Unconventional gas production	Leakage detection and repair programs (LDAR) for unintended leakage.	10.8	22.3	6.6	-70%	592	320	−46%
Gas transmission	Leakage detection and repair programs (LDAR) for unintended leakage.	9.1	10.3	3.8	−63%	305	174	−43%
Gas distribution	Replacement of grey cast iron pipes and doubling of control frequency. Leak Detection and Repair (LDAR) programs.	11.2	17.3	0.4	−98%	461	161	−65%
Municipal solid waste	Source separation with recycling or treatment with energy recovery. No landfill of organic waste.	31.9	60.4	10.9	−82%	1431	653	−54%
Industrial solid waste	Recycling or treatment with energy recovery. No landfill of organic waste.	11.3	23.8	6.2	−74%	533	271	−49%
Domestic wastewater	Upgrade of primary treatment to secondary/tertiary anaerobic treatment with biogas recovery and utilization.	8.0	10.6	7.9	-26%	294	224	−24%
Industrial wastewater	Upgrade of treatment to two-stage treatment, i.e., anaerobic with biogas recovery followed by aerobic treatment.	10.0	18.8	0.2	−99%	464	159	−66%
Total		**344**	**450**	**205**	**−54%**	**12451**	**7736**	**−38%**
whereof biogenic sources		204	277	157	−43%	7511	5215	−31%
whereof fossil sources		133	164	43	−74%	4700	2364	−50%
whereof biomass burning sources		7	9	5	−40%	240	157	−35%

$$TC_{its} = \sum_{m} [A_{its} * C_{itm} * Appl_{itsm}], \tag{3}$$

where A_{its} is the activity level, C_{itm} is the cost per unit of activity and $\sum_m Appl_{itsm} = 1$.

The country- and year- specific average cost per unit of reduced emissions is first calculated for each technology available by dividing the unit cost with the difference between the technology emission factor and the no control emission factor, such that:

$$AC_{itm} = \frac{C_{itm}}{ef_{it}^{No\_control} - ef_{itm}}. \tag{4}$$

Within a sector, the available technologies are first sorted by increasing average cost. The technology with the lowest average cost is ranked the first-best technology and assumed adopted to its maximum applicability in a given sector. The second-best technology has the second lowest average cost and is assumed available for adoption provided it can achieve an emission factor that is lower than the first-best technology. The marginal cost of the second-best technology when implemented in the marginal abatement cost curve (MACC) is the unit cost divided by the additional emission reduction still available for a given sector, i.e.

$$MC_{it2} = \frac{C_{it2} - C_{it1}}{ef_{it1} - ef_{it2}}. \tag{5}$$

In a similar manner, each additional technology available in a sector is added on top of the next best available technology. The result is a MACC built up technology-wise by sector, country and year. Note that if most of the technical abatement potential is exhausted with the first-bejst technology, the marginal cost of subsequent technologies becomes very high due to the limited additional emission reduction potential. Note also that a technology with both a higher average cost and a higher emission factor than another technology available to a sector will not be adopted at all, since it is both less effective in reducing emissions and comes at a higher cost than other available technologies. Finally, abatement technologies are not always additive, but can also be partly complementary. This is the case e.g., for measures addressing emissions from rice cultivation and enteric fermentation in cattle. For these sectors, we have constructed 'combined technologies', which reflect the overall effect on emissions and costs when more than one measure are implemented simultaneously. For rice cultivation, the first-best technology is improved water management by extending the periods fields are dried out. The second-best technology is improved water management combined with low-CH_4 hybrids and use of soil enhancing amendments. For enteric fermentation in cattle, the first-best technology is breeding for enhanced productivity and animal health and fertility, while the second-best option is to combine breeding with different animal feed changes.

2.5. Uncertainty

Uncertainty is prevalent along many different dimensions both in the estimations of emissions, abatement potentials and costs. When constructing global bottom-up emission inventories at a detailed country and source level, it is inevitable that some information gaps will be bridged using default assumptions. As it is difficult to speculate about how such sources of uncertainty affect resulting historical and future emission estimates, we instead address uncertainty in historical emissions by making comparisons to estimates by other publicly available and independently developed bottom-up inventories, i.e., EDGARv4.3.2 (2018) and CEDS-CMIP6 (2017), and various top-down estimates consistent with atmospheric measurements and inverse model results (e.g., Saunois *et al* 2016). Comparisons of global historical CH_4 emission estimates are presented in section 3.1 and by World region in section S2 of the SI. The bottom-up inventories adhere to the recommended guidelines of the IPCC (2006), however the flexibility in the recommended methodologies is large as it depends on the availability and quality of the gathered source information. There is accordingly a wide range of possible sources of uncertainty built into estimations in these comprehensive efforts. Having a pool of independently developed inventories, each with its own strengths and weaknesses, can improve the understanding of the scope for uncertainty in these estimates.

Regarding uncertainty in emission projections and as already discussed in section 2.2, we only produce one baseline scenario, which is consistent with the economic and energy sector developments of the IEA-WEO (2018) New Policies Scenario. Providing a range of baselines describing different future developments in the activity drivers is out of scope of this study as the intention here is to focus on the relative technical mitigation potentials and costs for reducing emissions at the region, sector and technology level.

Uncertainty in cost estimations is generally high. This is partly a feature of the many dimensions along which uncertainty enters into cost estimates and partly a general lack of detailed information on abatement costs in the literature. There are some uncertainty features that are more systematic than other as they derive from more general assumptions about how investors make decisions about adoption of control technologies. To account for the uncertainty range caused by these particular assumptions, we estimate a range for the marginal abatement cost curves (MACCs). The upper range limit represents the most pessimistic case in the sense that we assume no further technological development and that marginal abatement costs reflect a private investor perspective. Private investors are assumed to operate with a ten percent interest rate on fixed investments, a maximum investment perspective limited to ten years, and no speculation about an expected future increase in energy prices but only considering current (here referring to projected 2020) energy prices when deciding on investments. The lower range limit of the MACC represents the most optimistic case assuming the cost perspective of a social planner and with improving removal efficiencies and declining abatement costs over time due to technological development. A social planner is assumed to take decisions based on a four percent interest rate for fixed investments, considering the entire expected lifetime of the technology, and a future increase in energy prices as expected in the projections of the IEA-WEO (2018) New Energy Policies scenario. Why is it of interest from a climate policy point of view to consider both private investor and social planner perspectives on future abatement costs ? The reason is that a social planner, when looking to balance the costs and benefits of climate change mitigation against those of other areas of public spending, e.g., health and education, will need to make such trade-offs on the basis of a low discounting of future values in order to secure opportunities for decent lives also for coming generations. Hence, the social planner's MACCs are suitable for taking decisions about targets for emission reductions that will optimize social welfare. When considering implementation of policies that will actually achieve the socially optimal emission reduction targets, policy maker ought to rely on MACCs estimated from the private investor perspective. These reflect better the higher marginal abatement costs (and higher carbon price levels) needed for private investors to find it profitable to invest in abatement at a level that meets the desired emission reduction targets (Baumol and Oates 1971).

3. Results

3.1. Historical anthropogenic CH_4 emissions 1990–2015 in GAINSv4

For a good understanding of future emissions, we must first understand the current level and source attribution of emissions. We therefore develop a global inventory of annual CH_4 emissions 1990–2015 and compare it to other global bottom-up inventories as well as to top-down inverse model results. GAINSv4 bottom-up estimates of global anthropogenic CH_4 emissions 1990–2015 are presented in figure 5. GAINSv4 does not include estimates of emissions from forest fires and savannah burning due to a lack of detailed country-specific information. For the purpose of illustrating total anthropogenic CH_4 emissions in figure 5, the GAINSv4 estimate of all other CH_4 sources has been complemented with the global estimates of emissions from forest fires and savannah burning from the GFEDv4.0 database (Randerson *et al* 2018).

GAINSv4 estimates a decline in global CH_4 emissions in the first half of the 1990s, primarily a consequence of the collapse of the Soviet Union and the associated general decline in production levels in agriculture and fossil fuels (see Regional emission illustrations in figures S2–1 of the SI). In addition, as described by Evans and Roshchanka (2014) and assumed in Höglund-Isaksson (2017), venting of associated petroleum gas declined significantly in Russia due to an increase in flaring. It is unclear why this happened, but a possible explanation could be that the privatization of oil production in this period meant that the new private owners were less willing to take the security risks of venting and invested in flaring devices to avoid potential production disruptions. This hypothesis is however yet to be confirmed. Global CH_4 emissions are estimated to remain relatively constant in the second half of the 1990s, but then start to increase in the first few years of the new millennia. This time the primary drivers for growth in emissions are a mix of sources; increased coal mining in China, increased oil and/or gas production in Russia and Africa, rapidly expanding cattle rearing in Latin America, and increased generation of waste and wastewater in China, India and the rest of South-East Asia. The latter driven by population and rapid economic growth. Between 2008 and 2010 there is a brief downturn in emissions following a general decline in economic activity in response to the global financial crisis. After 2010 emissions increase again with principal drivers being; rapidly growing extraction of unconventional gas in North America, increased coal mining in Indonesia, and accentuated growth in waste and wastewater emissions in all rapidly developing regions of the world, including China, India, the rest of South-East Asia, Latin America, and Africa. The latter development would offer a possible explanation to observed increases in atmospheric CH_4 from biogenic sources in tropical regions (Nisbet *et al* 2014, 2019). It should however be noted that there is also a small but steady increase in global emissions from livestock, in particular beef and dairy. Emissions from pigs have however seen a slight decline in the last decade due to an expansion in the use of biogas digesters in Europe for treatment of pig manure.

In figure 5, the GAINSv4 bottom-up estimates are compared with the average top-down estimates of anthropogenic emissions following from inverse model results reconciling bottom-up with top-down measurements of the CH_4 concentration in the atmosphere. Saunois *et al* (2016) provide such estimates for three time periods: 2000–2009, 2003–2012, and 2012. As shown, these estimates align quite well with the GAINSv4 bottom-up estimates. Figure 6 illustrates the average and full uncertainty ranges for top-down estimates of

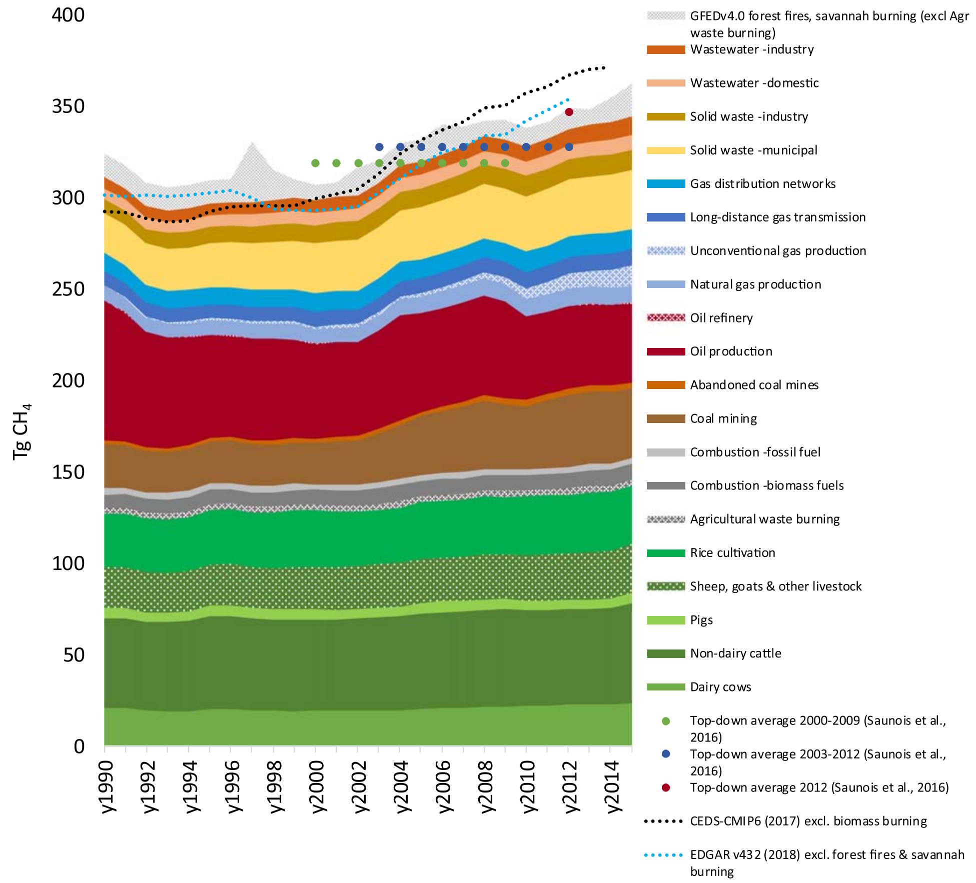

Figure 5. Annual bottom-up estimates of global anthropogenic CH_4 emissions 1990–2015 in GAINSv4 and in comparison to top-down average estimates from Saunois *et al* 2016. Note that global CH_4 emissions from forest fires and savannah burning are taken from GFEDv4 (Randerson *et al* 2018).

emissions by groups of CH_4 isotopic signatures identifiable in the atmosphere and mentioned e.g., in Saunois *et al* (2016) and Dlugokencky *et al* (2011). The isotopic signatures make it possible to distinguish between atmospheric CH_4 from biogenic (agriculture and waste) sources, fossil fuel sources, and burning of biomass sources. GAINSv4 estimates fall within the uncertainty ranges of the atmospheric measurements for all three CH_4 isotopic signature groups. For the biogenic sources presented in figure 6(a), GAINSv4 estimates are close to those by CEDS-CMIP6 (2017) and lower than those by EDGARv4.3.2 (2018). The higher CH_4 emissions from biogenic sources in EDGARv4.3.2 can primarily be attributed to higher annual emissions from wastewater sources than in GAINSv4 (see table 5.3 in Höglund-Isaksson *et al* 2015), in particular for Africa and South-East Asia where GAINSv4 assumes poor conditions for CH_4 formation in areas lacking proper infrastructure for centralized wastewater collection. For fossil fuel sources presented in figure 6(b), the average top-down estimate of CH_4 by Saunois *et al* is somewhat lower than the GAINSv4 estimate from year 2000 onwards and considerably lower than the CEDS-CMIP6 estimate for the later years, as discussed in detail below. For emissions from burning of biomass and biofuels presented in figure 6(c), the sum of the GAINSv4 estimate of CH_4 emissions from burning of agricultural waste residuals and the GFEDv4.0 estimate of global CH_4 emissions from forest fires and savannah burning, reveals that the GAINSv4 estimate for these sources falls somewhat short of the average top-down estimate.

Figure 7 displays the estimates of CH_4 emissions from fossil fuel sources by hydrocarbon source and global bottom-up inventory (for further details see section S3.3 of the SI). In panel 7a, GAINSv4 shows fairly constant estimates of annual emissions of about 80 Tg CH_4 from global oil and gas systems between 1995–2015. Looking closer we see that this seemingly stable emission level is the result of steadily increasing emissions from natural gas extraction, driven by increased gas production in general and shale gas production in particular, and a simultaneous steady decline in emissions from oil extraction. The latter is referred to increased recovery rates for associated petroleum gas, particularly in Russia and parts of Africa (Höglund-Isaksson 2017). Emissions from oil and gas systems are in the CEDS-CMIP6 and EDGAR v4.3.2 inventories reported as aggregates and it is therefore difficult to know whether the same developments in oil and gas production emissions, respectively, are prevalent

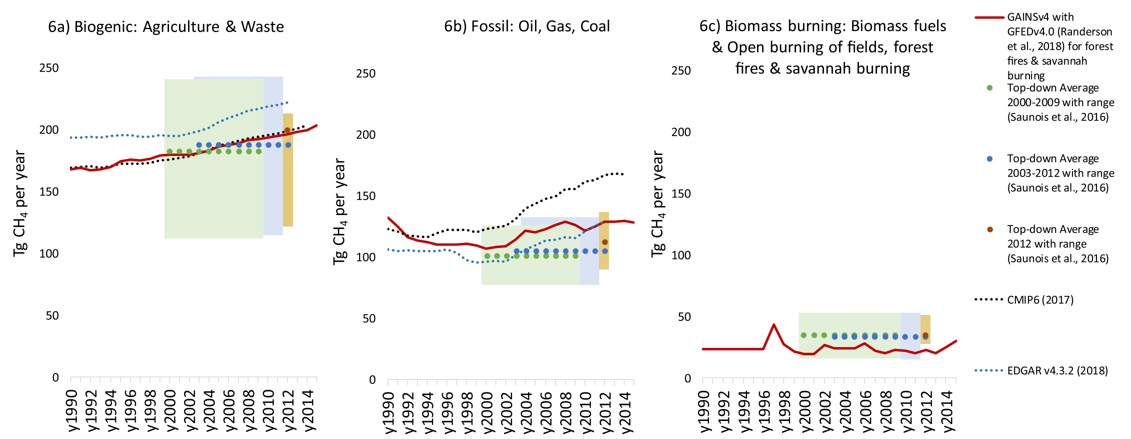

Figure 6. GAINSv4, CMIP6 and EDGARv4.3.2 bottom-up estimates of global anthropogenic CH_4 emissions by CH_4 isotopic signatures and in comparison to the uncertainty ranges (depicted as boxes) and average estimates (depicted as dots) for top-down atmospheric measurements as reported in Saunois *et al* 2016.

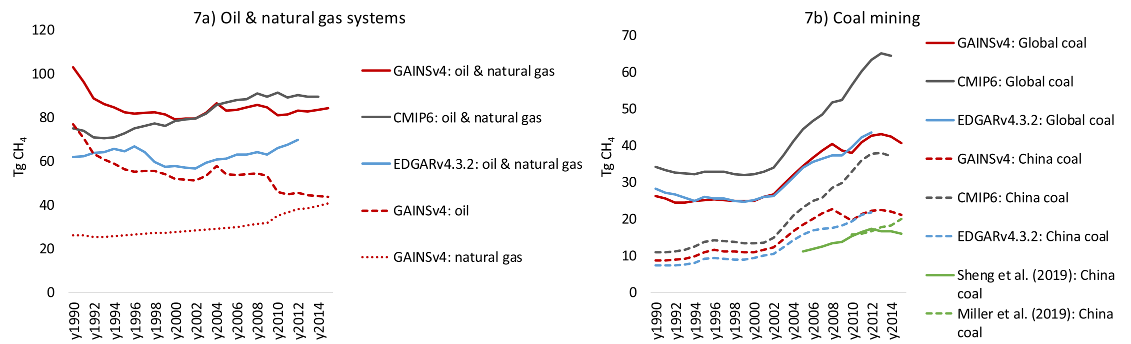

Figure 7. Global fossil fuel CH_4 emissions by source and bottom-up inventory. Global emissions from oil and natural gas systems in Panel 7a and from coal mining activities in Panel 7b.

also in these inventories. Panel 7b shows how global emissions from coal mining (including from abandoned coalmines) develop over time in the different bottom-up inventories. While GAINSv4 and EDGARv4.3.2 agree quite well, CEDS-CMIP6 estimates considerably higher emissions from this source, in particular for China in the period post-2005. The basis for the higher emissions from coal mining in China in CEDS-CMIP6 is not clear, however, consistent with higher emissions from this source in previous versions of EDGAR (see table 5.3 in Höglund-Isaksson *et al* 2015). Recent results of inverse models (Miller *et al* 2019, Sheng *et al* 2019) find considerably lower CH_4 emissions from coal mining in China, indicating that also estimates by GAINSv4 and EDGAR 4.3.2 may be on the higher side.

3.2. Baseline scenario for global anthropogenic CH_4 emissions 1990–2050

A global projection of baseline anthropogenic CH_4 emissions to 2050 consistent with the energy sector developments of the IEA-WEO (2018) New Policies Scenario, is presented in the left panel in figure 8 in five-year intervals. Baseline emissions are expected to increase close to linearly by about 3 Tg CH_4 per year or 30 percent between 2015 and 2050. Global emission increases are primarily driven by an expected increase in solid waste generation as population grows and countries become richer and by an expected increased extraction of unconventional natural gas. The latter is partly a reflection of a substitution of coal with natural gas and renewables projected in the IEA-WEO (2018) New Policies Scenario and goes together with a decline in emissions from coal mining in the period post-2030 in that particular energy scenario.

Baseline emission developments at a regional level are presented in figures S3–1 in the SI. For China, baseline CH_4 emissions are expected to continue growing to 2040, but then level off at an annual emission level of about 65 Tg CH_4 due to a decline in coal mining. A strong increase in CH_4 emissions from shale gas production in North America is expected to continue until 2045, when emissions decline due to a projected drop in gas demand in the IEA-WEO2018 New Policies scenario. Due to already adopted climate policy strategies, the European Union is expected to be on track for a decline in CH_4 emissions by about 20 percent between 2015 and

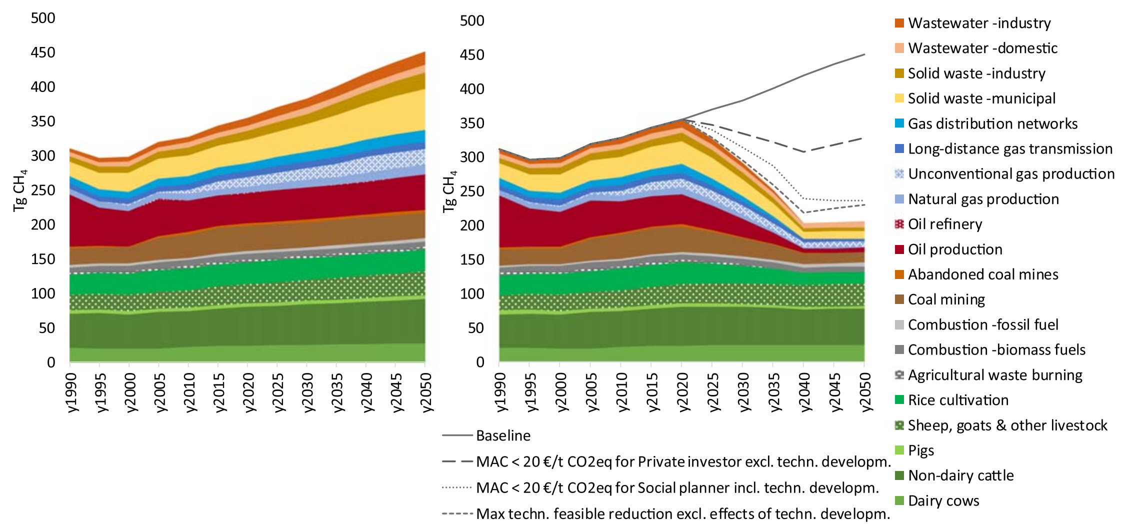

Figure 8. Global anthropogenic CH_4 emissions 1990–2050 in the Baseline scenario (left panel) and with Maximum technically feasible reduction (MFR) including effects of technological development (right panel).

2030, however, further reductions will need implementation of additional policy incentives. Continued growth in population and income are expected to drive increases in waste and wastewater CH_4 emissions in Africa, India & South-East Asia. A continued increase in demand for beef is expected to be the prime driver for increased CH_4 emissions in Latin & Central America, while a continued demand for oil drives emission increases in the Middle East. An expected rapid growth in natural gas production in Australia coupled with no phase-out of coal mining, translate into a steady increase in emissions in Oceanian OECD (Australia, New Zealand and Japan) in the period leading up to 2050.

3.3. Technical mitigation potentials in the 2050 timeframe

The maximum technically feasible reduction (MFR) of global anthropogenic CH_4 in year 2050 is estimated at 54 percent below baseline emissions of that year. This corresponds to a global emission level that is 40 percent below the 2015 level and reflects that baseline emissions are expected to grow by 30 percent between 2015 and 2050 (see right panel of figure 8). The MFR for fossil fuel sources is assessed at 74 percent below baseline in 2050 (see table 3), assuming full implementation worldwide of at least 98 percent recovery of associated petroleum gas and, in addition, leakage detection and repair (LDAR) programs to reduce unintended leakage during extraction, transmission and distribution of natural gas. Investments into control of fossil fuel emissions would of course become redundant should the World decide on a massive phase-out of fossil fuel use in the next few decades. High technical abatement potentials at about 80 percent below baseline emissions in 2050 are considered feasible for CH_4 emissions from solid waste management. This assumes it possible in a twenty years perspective to extend the infrastructure for source separation, recycling and energy recovery schemes globally, including a ban on all landfill of organic waste and allowing for useful utilization of the carbon content of the waste (Gómez-Sanabria *et al* 2018).

The technical abatement potential for agricultural sources is assessed at 21 percent below baseline emissions in year 2050. This includes relatively limited abatement potentials for livestock of 12 percent due to applicability limitations (see section S3.4. in the SI for details). Large farms with more than 100 LSU contribute about a third of global CH_4 emissions from livestock and for this group we find it technically feasible to reduce emissions by just over 30 percent below baseline emissions in year 2050 (see figures S6–2 in the SI). The available options include reduction of enteric fermentation emissions through animal feed changes (Gerber *et al* 2013, Hristov *et al* 2013) combined with implementation of breeding schemes that simultaneously target genetic traits for improved productivity and enhanced animal health/longevity and fertility. Increased productivity reduces system emissions by enabling the production of the same amount of milk using fewer animals. The dual objective in breeding schemes is important as a one-eyed focus on increased productivity leads to deteriorating animal health and fertility and a risk that system emissions increase due to a need to keep a larger fraction of unproductive replacement animals in the stock (Lovett *et al* 2006, Berglund 2008, Bell *et al* 2011). The enteric fermentation options are considered economically feasible for commercial/industrial farms with more than 100 LSU but not for smaller- and medium- sized farms. Breeding schemes are assumed to deliver impacts on emissions only after 20 years and feed changes are assumed applicable only while animals are housed indoor. Emissions from manure management can be reduced through treatment of manure in anaerobic digesters (ADs)

Table 3. Absolute MFR emission reduction potentials below baseline in 2030 and 2050 for global CH_4 from the agricultural sector, as estimated in GAINSv4 and by Beach *et al* (2015), Frank *et al* (2018) and Harmsen *et al* (2019).

	Maximum technical mitigation potential for CH_4 from global agricultural sources					
	2030			2050		
CH_4 sources	Beach *et al* 2015 Pg CO_2eq	Frank *et al* 2018 Pg CO_2eq	GAINSv4 Pg CO_2eq	Harmsen *et al* 2019 Pg CO_2eq	Frank *et al* 2018 Pg CO_2eq	GAINSv4 Pg CO_2eq
Rice cultivation	0.2	0.2–0.35	0.17	0.37	0.27	0.44
Manure management	0.27	0.04–0.1	0.034	0.13	0.15	0.074
Enteric fermentation		0.03–0.1	0.086	1.2	0.09	0.37
Agric. waste burning	0	0	0.05	0	0	0.10
Total agriculture	0.47	0.27–0.55	0.34	1.7	0.52	0.99

with biogas recovery. To be efficient from both an economic and environmental point of view, a certain scale is needed to accommodate both the fixed investment of the AD plant and the time farmers spend carefully attending to and maintaining the process (for details see section 3.3.1.3 in Höglund-Isaksson *et al* 2018). About a third of global livestock CH_4 emissions can be attributed to smallholder farmers particularly prevalent in Africa and South-East Asia. These livestock typically have low productivity and emissions per head and are well adapted genetically to local conditions. We do not consider any technical abatement potential for this group of farmers, because enhanced productivity may not be of primary interest when considering that livestock often fills a dual purpose; beside providing milk and meat it also functions as a mean to store assets and manage risks over time (FAO 2008, Udo *et al* 2011). In absence of access to credit markets and publicly provided health care, the robustness of indigenous breeds may become more important than the increased production that can be achieved by introducing highly productive breeds from abroad. Hence, control of these emissions are closely linked to more general institutional and economic reforms. For CH_4 emissions from rice cultivation, a halving of global emissions is considered possible through improved water management that shorten the period of continuous flooding of fields, combined with a use of low-CH_4 generating hybrids and different soil amendments (see section S6.5 of the SI for details).

Due to locked in capital of existing technology in the short-run, the cumulative emissions in the MFR scenario is assessed at 38 percent below baseline between 2020 and 2050 (see table 3). This leaves 7.7 Pg CH_4 or 216 Pg CO_2eq using GWP_{100} from AR5 (IPCC 2013) released globally between today and 2050 that will likely be difficult to remove through technical solutions. In 2050, MFR leaves 5.7 Pg CO_2eq of CH_4 still released. This is a lot if we consider that to stay at 1.5 degrees warming, IPCC (2018) estimates we must not exceed 10 Pg CO_2eq for all greenhouse gases in 2050 (and be at zero net emissions around 2075). In addition to technical solutions, this calls for widespread implementation in the 2050 timeframe of behavioural options, e.g., human diet changes that reduce meat and milk consumption (e.g, Springmann *et al* 2016, Clune *et al* 2017, Willett *et al* 2019) and general institutional and social reforms indirectly mitigating greenhouse gas emissions in developing countries (Evans and Steven 2009).

Figure 9 illustrates the technical CH_4 abatement potentials 2020–2050 by major World region. As expected, the technical abatement potentials are highly region-specific with the largest relative reduction potentials possible in major fossil fuel supplying regions like Russia and the Middle East. Significantly lower reduction potentials are found for regions where agricultural sources dominate CH_4 emissions, i.e., India, Latin America, Oceanian OECD and South-East Asia.

3.4. Marginal abatement cost curves for global CH_4 abatement in the 2050 timeframe

The estimated range for the global MACC for CH_4 in year 2050 is presented in figure 10. The lower range limit of the MACC corresponds to a social planner's perspective and include impacts of technological development, while the upper range limit corresponds to a private investor's perspective and excluding impacts from technological development (see section 2.5). Starting from a baseline emission level of 450 Tg CH_4 in 2050, a 35 percent reduction is estimated as possible at a zero or negative marginal cost (i.e., at a net profit) at the lower range limit of the MACC, while the same relative reduction would only be possible with the introduction of an additional policy incentive equivalent to 82 €/t CO_2eq at the upper range limit of the MACC. At the lower range limit it is considered possible to almost halve baseline emissions in 2050 at a marginal cost below 20 €/t CO_2eq, while at the upper range limit three quarters of the full baseline emissions are expected to remain at the same marginal cost level. Hence, the marginal abatement costs are highly sensitive to the time and opportunity cost perspective of the investor and to the potential impact from technological development on costs and removal efficiencies. Although policy makers must have a social planner's perspective when determining the optimal

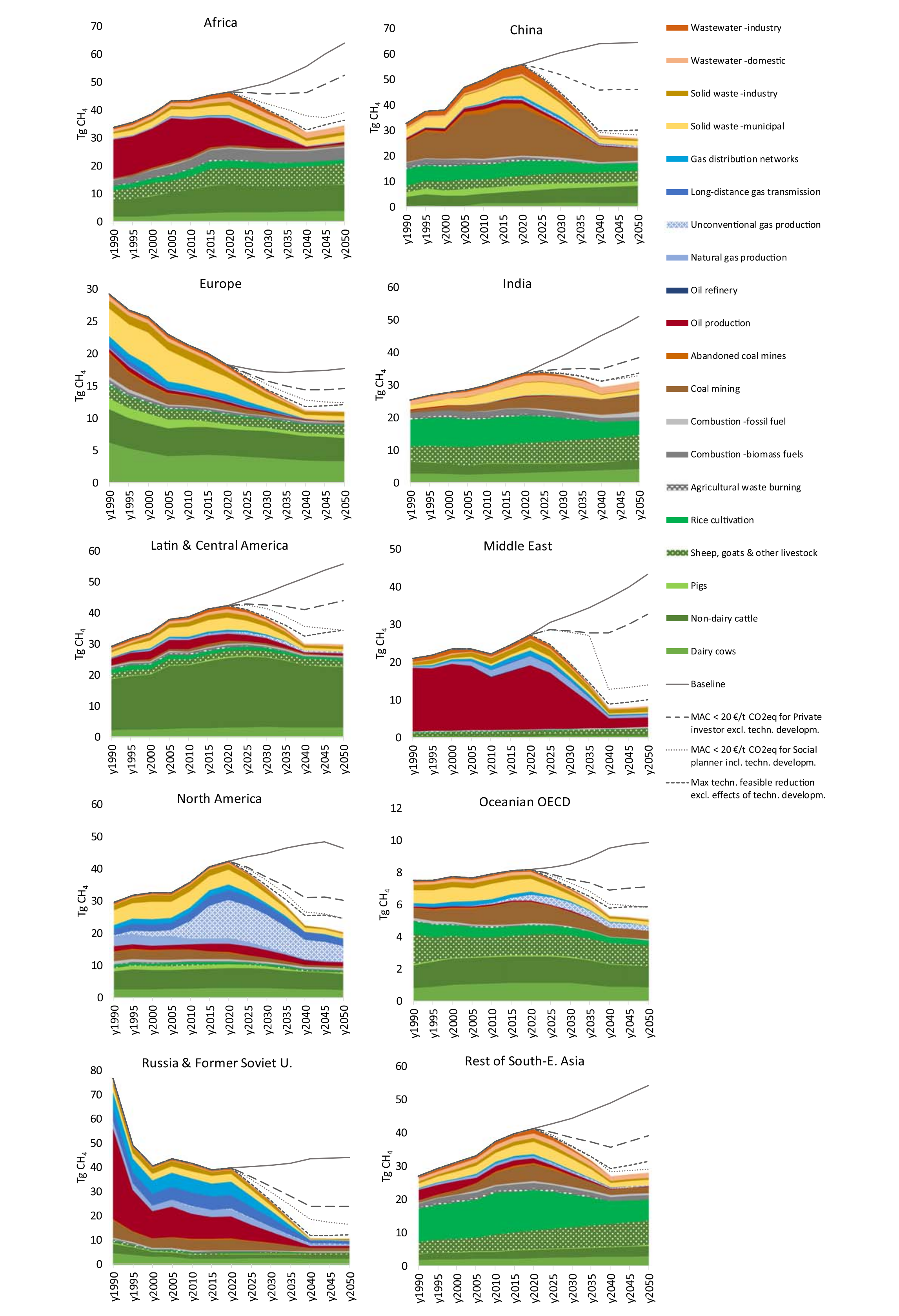

Figure 9. Technical CH_4 abatement pathways to 2050 by major world region and source sector.

allocation of resources to emission abatement in relation to other public goods, they must let a higher MACC guide the setting of carbon price levels to provide enough incentives for private investors to achieve the desired emission reductions in various sectors and regions.

The ranges for the MACCs differ significantly between major source sectors both at a global scale (see figure 11) and across World regions (see figure 12). At the lower range limit, more than 85 percent of the global

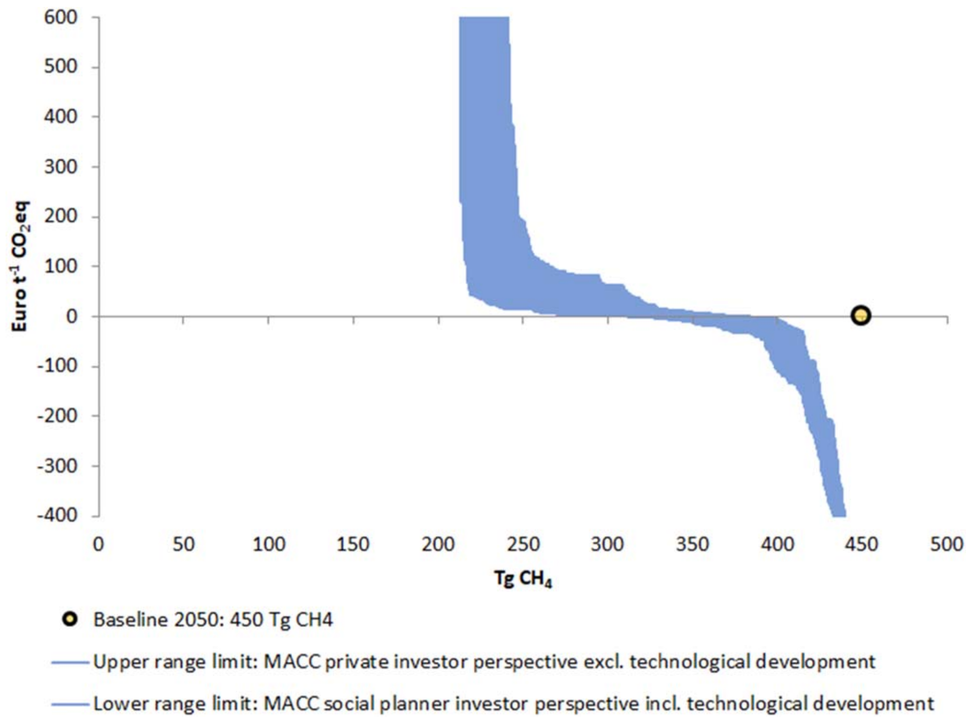

Figure 10. Range of global marginal abatement cost curve (MACC) for CH_4 in year 2050.

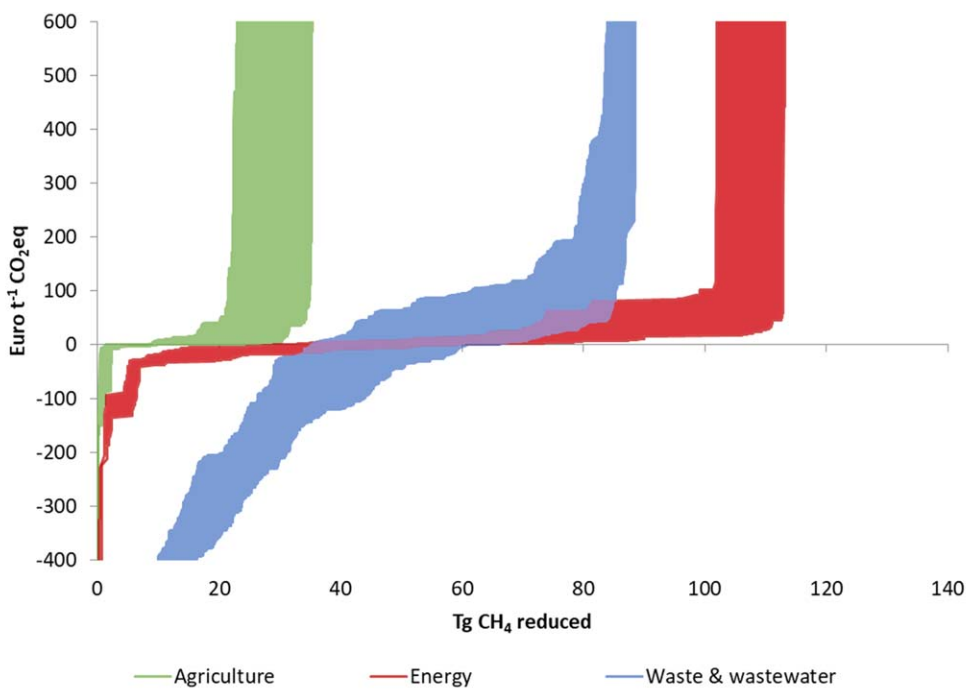

Figure 11. Ranges for global marginal abatement cost curves for reducing CH_4 emissions in 2050 by major source sector.

MFR is found attainable at a marginal cost below 20 €/t CO_2eq for all three major source sectors Energy, Agriculture and Waste. At the upper range limit, however, a policy incentive equivalent to the same carbon price level achieves the more modest emission reductions of 57, 71 and 50 percent, respectively. It is evident from the regional analysis that extensive potentials to reduce CH_4 emissions at low costs exist in the fossil fuel production sectors in Russia and the Middle East. Targeting these two sources alone could remove more than 10 percent of global baseline emissions in 2050. An additional almost 10 percent of baseline emissions in 2050 could be

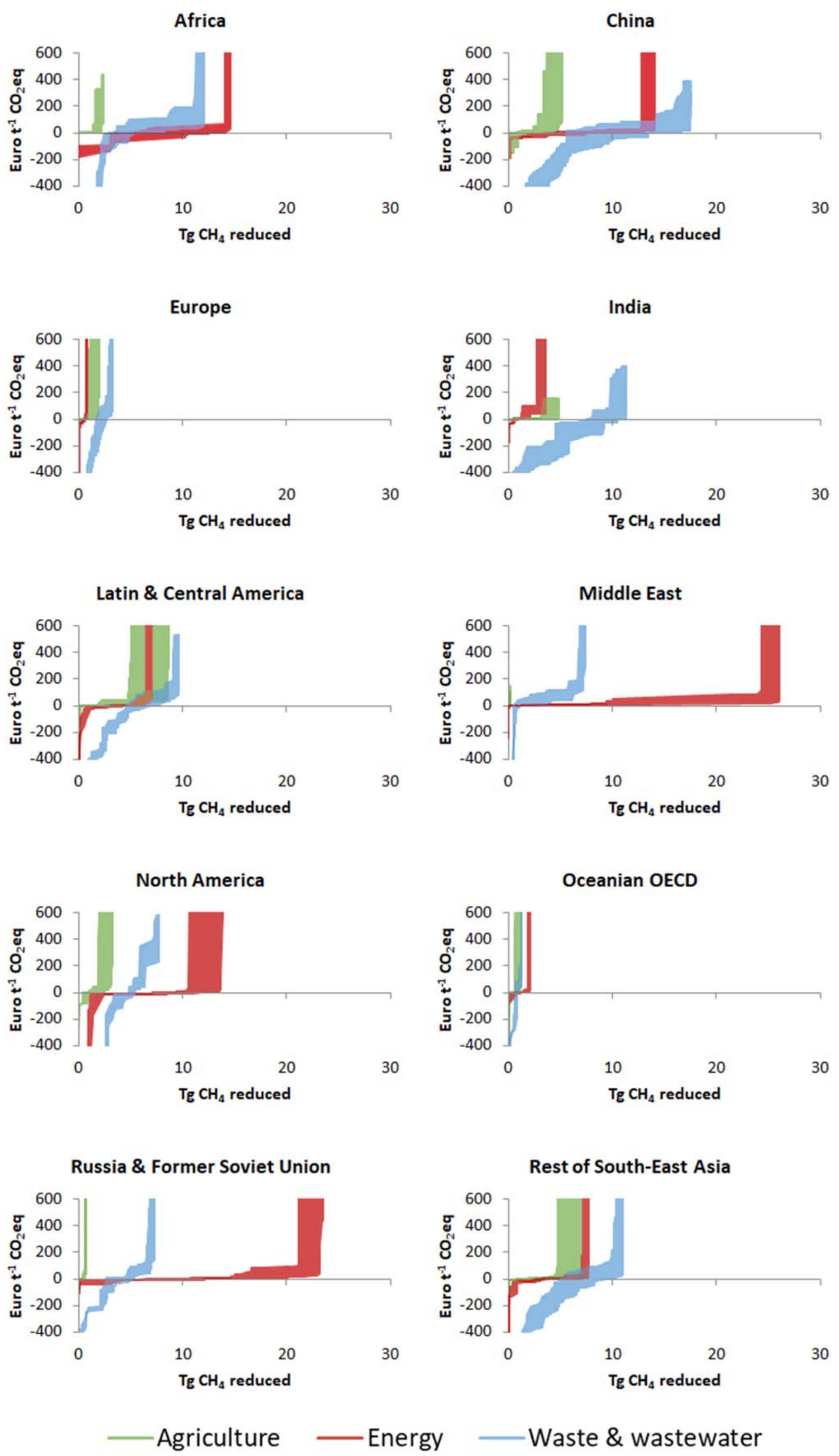

Figure 12. Ranges for marginal abatement cost curves (MACCs) in 2050 by major source sector and world region.

removed at a marginal cost below 20 €/t CO_2eq by implementing proper waste and wastewater handling in China, India and the rest of South-East Asia. This would likely come with considerable co-benefits in the form of reduced air and water pollution.

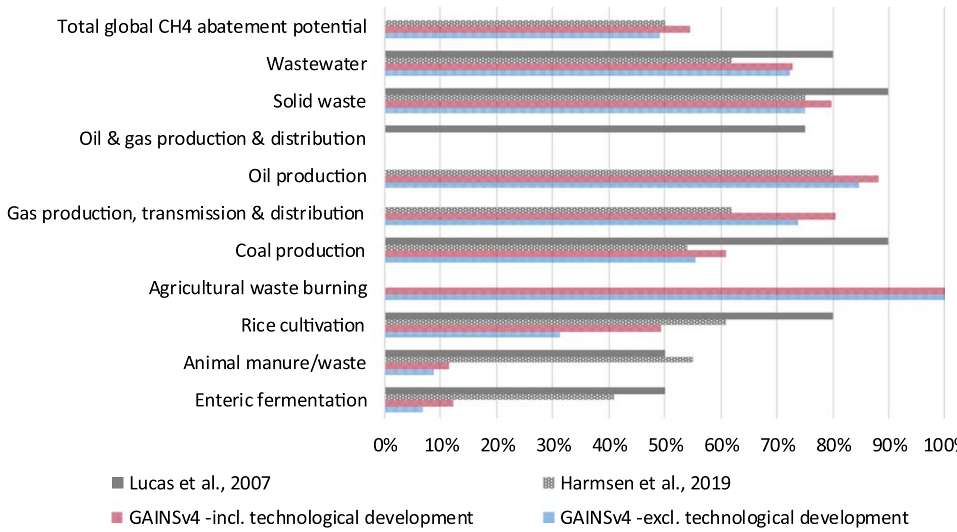

Figure 13. Relative MFR potentials below baseline in year 2050 for global CH_4 emissions in total and by source sector as estimated in GAINSv4 and by Harmsen *et al* (2019) and Lucas *et al* (2007).

3.5. Comparison to other studies

The long-run technical abatement potential for global CH_4 emissions in year 2050 has been assessed by Lucas *et al* (2007) and Harmsen *et al* (2019). Figure 13 illustrates the MFR in total and by sector as estimated in these two studies in comparison to GAINSv4. The different assessments agree fairly well on the long-run technical abatement potential in non-agricultural sectors. Lucas *et al* appears generally to be more optimistic than both Harmsen *et al* and GAINSv4. The most notable difference is in the assessment of the technical abatement potential for the agricultural sector. Table 3 presents recent estimates from four different studies of global CH_4 mitigation potentials in 2030 and 2050 for this sector. GAINSv4 is slightly more conservative than Beach *et al* (2015) in the estimate for 2030, but well within the range estimated in Frank *et al* (2018). In the 2050 timeframe, the maximum technically feasible reduction of about 1 Pg CO_2eq in GAINS v4 appears as a middle estimate between the Frank *et al* estimate of 0.52 and the Harmsen *et al* estimate of 1.7 Pg CO_2eq. The discrepancy can mainly be referred to differences in livestock sector mitigation potentials, where GAINSv4 estimates maximum 12 percent reductions in global manure management and enteric fermentation emissions, respectively. Harmsen *et al* estimates 55 and 41 percent reductions for the respective sources and Lucas *et al* 50 percent for both sources. This difference can be referred to the applicability limitations introduced in GAINSv4 on the basis of farm size and intensive/extensive systems as discussed in section 3.3 and sections S6–4 in the SI. Harmsen *et al* and Lucas *et al* assume almost the same applicability rates for livestock mitigation options across different World regions and no applicability constraints for implementation of enteric fermentation (breeding and animal feed changes) options to the about one third of livestock emissions attributable to smallholder farmers in developing countries. Such applicability constraints apply in GAINSv4 due to the important role livestock herds play in the management of risks for smallholder farmers in Africa and South-East Asia (see section S6.4 in the SI). GAINSv4 is however considerably more optimistic than Frank *et al* about the mitigation potentials of breeding and animal feed changes in year 2050.

4. Conclusions

Keeping to the Paris Agreement of staying well below two degrees global warming will require a concerted effort to curb methane (CH_4) emissions in the period leading up to 2050. The many diverse sources of CH_4 makes it particularly challenging to design policy instruments that effectively achieve deep emission reductions. A key piece of information for policy-makers is the potential and costs for lowering emissions relatively fast through implementation of technical solutions in various source sectors and world regions. The purpose of this study is to provide such information by exploring future technical abatement pathways for CH_4 using the most recent version of IIASA's Greenhouse gas and Air pollution Interactions and Synergies (GAINS) model.

With a global annual inventory for 1990–2015 as starting point for future projections, a baseline emission scenario to 2050 is developed against which the technical abatement potentials and costs are assessed at a country, sector and technology level. Globally, we find extensive technical opportunities at low costs to control fugitive emissions from fossil fuel production and use. E.g., addressing fossil fuel extraction sources in Russia and the Middle East would remove more than 10 percent of baseline emissions in 2050. An almost as large reduction is expected below 20 €/t CO_2eq from implementing infrastructure for source separation and treatment of solid waste and proper wastewater treatment in China, India and the rest of South-East Asia. The technical abatement potential is considerably more limited for agricultural sources, due in particular to difficulties addressing CH_4 emissions from extensive livestock rearing in developing countries, where the keeping of large herds of robust but relatively unproductive animals often fills a vital function in farmers' risk management.

Overall, we find it technically feasible in year 2050 to remove 54 percent of CH_4 emissions below baseline, thereby leaving 5.7 Pg CO_2eq still released in 2050. This is cause for concern, considering that to stay at 1.5 degrees warming, IPCC estimates we must not exceed 10 Pg CO_2eq for all greenhouse gases in 2050. In addition to technical solutions, this calls for widespread implementation in the 2050 timeframe of institutional reforms e.g., to improve smallholder farmers' access to credit markets and public health services, and behavioural options, e.g., human diet changes that reduce milk and beef consumption.

Finally, we find the marginal abatement costs highly sensitive to the time and opportunity cost perspectives of investors and to the impacts of technological development. Policy makers will need to consider this when setting future reduction targets and carbon price levels to address CH_4 emission reductions. In general, a higher carbon price level than the one found optimal from a social planner's perspective will be needed to stimulate private investors to make market decisions that achieve the desired emission reductions.

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Author contributions

LHI developed the model code, performed emission and cost simulations, and prepared the manuscript with contributions from all co-authors. AGS developed waste and wastewater sector emission estimates and projections. ZK prepared and implemented FAO activity data projections for the agricultural sectors, PR prepared and implemented the IEA-WEO activity data projections for the energy sectors, and WS provided input to methodological discussions and model structure developments throughout the study.

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