GLOBAL METHANE ASSESSMENT: 2030 BASELINE REPORT

WHY ACT NOW: A NEW ERA FOR ACCELERATED IMPLEMENTATION

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CLIMATE & CLEAN AIR COALITION TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

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AUTHORS

Drew Shindell* (Duke University, USA), Lena Höglund-Isaksson◊ (International Institute for Applied Systems Analysis, Austria), A.R. Ravishankara* (Colorado State University, USA), Ben Poulter (NASA Goddard Space Flight Center, USA), Marielle Saunois* (Laboratoire des Sciences du Climat et de l'Environnement, France), Shaun Ragnauth (US Environmental Protection Agency, USA), Jared Creason (US Environmental Protection Agency, USA), Jameel Alsalam (US Environmental Protection Agency, USA), Christophe McGlade (International Energy Agency, France), Mathijs Harmsen (PBL Netherlands Environmental Assessment Agency, Netherlands), Steven P Hamburg◊ (Environmental Defense Fund, USA), Daniel Zavala-Araiza (Environmental Defense Fund, USA), Stefan Schwietzke (Environmental Defense Fund, USA), Ilse Aben* (Netherlands Institute for Space Research, Netherlands), Oksana Tarasova (World Meteorological Organization, Switzerland), Nathan Borgford-Parnell (UN Environment Programme/Climate and Clean Air Coalition, France)

* CCAC Scientific Advisory Panel member

◊ IMEO Scientific Oversight Committee member

GRAPHIC DESIGN AND LAYOUT: Katharine Mugridge

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

This report is a product of the Global Methane Assessment (GMA) that details projections of anthropogenic methane emissions through 2030 under various baseline scenarios and assesses the climate benefits of achieving the Global Methane Pledge target compared to the impacts of those baseline emissions.

In 2021 the CCAC and UNEP published the *Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions* (UNEP,CCAC 2021) which identified methane mitigation as one of the most cost-effective strategies to rapidly reduce the rate of warming and contribute substantially to global efforts to limit temperature rise to 1.5°C. One of the key conclusions of the GMA was that currently available technological measures and policies could reduce emissions from the three main anthropogenic methane emitting sectors by as much as 45 per cent of baseline emissions levels by 2030 (approximately 180 Mt per year in 2030). Baseline emissions scenarios assume implementation of existing policies and commitments but do not include additional mitigation action. Furthermore, such a reduction would be consistent with the range of methane mitigation called for in the Intergovernmental Panel on Climate Change's (IPCC) least cost-pathways that limit global warming to 1.5°C in this century so long as it occurs alongside simultaneous reductions of other major climate forcers including carbon dioxide and short-lived climate pollutants.

Catalyzed by the conclusions of the 2021 Global Methane Assessment, the Global Methane Pledge (GMP) launched at the Nov 2021 Conference of the Parties (COP26) in Glasgow. Participants joining the Pledge agree to take voluntary actions to contribute to a collective effort to reduce global anthropogenic methane emissions at least 30 per cent from 2020 levels by 2030 (GMP 2022).

In 2022 GMP Partners requested that UNEP perform further analysis of baseline emissions scenarios to establish a harmonized estimate of the expected growth in methane emissions through 2030 absent additional action as well as to compare the impacts of the GMP with those baseline emissions. The objectives of this Report include a more complete characterization of future baseline emissions, as well as easing comparison of GMA conclusions, which are communicated against approximate baseline emission levels in 2030, against the GMP target, which is set against 2020 emissions levels. This analysis also allows us to highlight the importance of early and targeted methane mitigation by assessing the climate benefits of the GMP target against expected increasing methane emissions under the baseline emissions scenarios, and compare them to the impact of addressing methane solely through a decarbonization strategy.

In Chapter 1, we update the 2021 GMA data on the latest knowledge of atmospheric abundances of methane and recent trends. This Chapter also explores the latest estimates of anthropogenic and natural sources of methane emissions and uncertainties related to these estimates.

In Chapter 2, we detail the eleven different models used in this GMA Report and establish a methodology to harmonize them. In Chapter 3, we analyze the global, regional and sectoral projected changes in anthropogenic methane emissions from each model. We detail the average change in emissions among the model results as well as the projections of the individual models.

In Chapter 4, we analyze the climate impacts of the GMP relative to the average baseline projections as well as present the climate response to both broad decarbonization efforts and to rapid and deep reductions in methane emissions to illustrate the differing and complementary influences of these strategies.

1. INTRODUCTION

CURRENT METHANE ATMOSPHERIC CONCENTRATIONS, SOURCES & POLICIES

1.1 METHANE CONCENTRATION IN THE ATMOSPHERE

The Global Methane Assessment (GMA) 2021 reported that atmospheric methane abundances rose rapidly during the 2010s, reaching by the end of that decade five-year average growth rates not seen since the 1980s, and these methane amounts were well above those in the 2ºC scenario used in the Intergovernmental Panel on Climate Change's (IPCC) 2013 Assessment (UNEP and CCAC 2021). Since the publication of the GMA in 2021, further analyses have produced official atmospheric values for 2020, with the World Meteorological Organization (WMO) Global Atmosphere Watch Programme (GAW) in situ observational network showing that globally averaged surface values for methane reached 1889 ± 2 parts per billion (ppb) in 2020. This value constitutes 262per cent of pre-industrial (before 1750) level. The increase from 2019 to 2020 which is calculated as a difference between two annual mean values (11 ppb) was higher than that observed from 2018 to 2019 and higher than the average annual growth rate over the last decade (WMO Greenhouse Gas Bulletin 2021). The analysis of data from U.S. National Oceanic and Atmospheric Administration (NOAA) marine boundary layers sites (that constitute about 40per cent of the GAW network) finds that the methane increase in 2021 (from 1 January to 31 December) was 17.0 ppb, the highest in the 38 year record (https://gml.noaa.gov/ccgg/trends_ch4/). The numbers from WMO and NOAA cannot be compared directly as they include different set of sites and represent averages for different periods.

Preliminary analysis of the methane growth rate from satellite total column data (based on the SCIAMACHY/ENVISAT and TANSO-FTS/GOSAT products from SRON: https://cds.climate.copernicus.eu/) shows that this rate rose to 16.3 ppb per year in 2021, the highest value in the 2003-2021 record. Hence based on both the ground-based and satellite observations, atmospheric methane continues to increase very rapidly as the world has entered the 2020s.

1.2 METHANE ANTHROPOGENIC EMISSIONS ACROSS SOURCES AND REGIONS

The main sources of methane to the atmosphere are documented and periodically reviewed by the Global Carbon Project (Kirschke et al. 2013, Saunois et al. 2016, Saunois et al. 2020). Bottom-up inventories produce estimates largely by relying on activity data (e.g. number of landfills) and emissions factors (e.g. emissions per landfill) for individual sources, with UNFCCC including country-reported data while other inventories incorporate unofficial data sources as well. The latter include the CEDS inventory (Hoesly et al. 2018), the EDGAR inventory (Crippa et al. 2018), US EPA's Global Non-CO_2 Projections (EPA 2019) and the IIASA inventory (Höglund-Isaksson et al. 2020).[1] This report relies largely on those four existing inventories in its assessment of near-present day (2020) methane emissions by sector and region. In addition, top-down inventories are produced from atmospheric measurements with models used to infer the contribution of specific sources to the totals seen in the observations. Those do not typically cover all countries of the world, however. Anthropogenic sources include agriculture (ruminants, manure, and rice), waste management (landfills, waste and wastewater treatment), energy (fossil fuels, i.e., production and use of coal, oil, and natural gas; biofuels combustion), and open biomass burning. Natural sources are dominated by wetlands, but also include inland freshwater systems (lakes, rivers, reservoirs, estuaries, etc.), geologic seeps, termites, and wild animals. At the global level, anthropogenic sources are fairly well known, with bottom-up and top-down estimates both showing emissions of ~360 Mt per year for 2008-2017 (uncertainty range 340-380 Mt/yr; Canadell et al. 2021). Global total emissions are fairly well constrained by global atmospheric in-situ methane concentration measurements and methyl chloroform measurements that constrain the main methane sink by OH, as conservation requires that the total emissions must equal the total removal plus any atmospheric growth.

1. See annex Definitions/Models for a short summary of the inventories and models described in this section.

At the sectoral level, uncertainties are substantial for the anthropogenic sources (Table 1.1). Isotopic measurements provide evidence to address source attribution (e.g. Zhang et al. 2021) but uncertainties related to isotopic source signatures (Howarth 2019; Lan et al. 2021) and the magnitude of some natural sources (e.g. Hmiel et al. 2020); Thornton et al. 2021) persist. Top-down estimates for specific sectors remain limited (Deng et al. 2022). Uncertainties are also large at the regional level (Table 1.1). Inverse modeling studies produce regional emissions estimates, but in-situ measurement density is insufficient in most regions to provide highly accurate information, particularly over the tropics (Tunnicliffe et al. 2020). Major advances in satellite-based remote sensing of methane that have occurred over recent years along with an increased collection of relevant activity data will help to understand the processes leading to emissions across types of sources, to better guide mitigation efforts, and to inform projections of future emissions (see Box 1 for additional discussion).

Despite substantial divergence across emission estimates and the limitations of current data to better constrain those values, many characteristics of current methane emissions are clear. Agriculture and Energy are comparable in magnitude and have roughly twice the emissions of the Waste sector (Table 1.1). Analyses produced by the International Energy Agency (IEA)—based on similar bottom-up, emission factor-based approaches— for the energy sector show similar values to those in the full inventories; IEA reports 130 Mt per year for Energy in 2020 (120 Mt from fossil fuels, of which 44 Mt is from coal, and 9 Mt from bioenergy). Guidance on the partitioning of methane emissions between fossil sources, biogenic sources and biomass burning is supported by methods based on identification of methane isotopes and hydrocarbon ratios in the atmosphere, see Start Box 1 for further discussion. At the subsector level, there can be very large differences across the inventories, such as for emissions from oil and gas infrastructure that can differ by more than a factor of two. Examining individual research studies that evaluated emissions from single sectors or subsectors can also show large divergence, with, for example, values for fossil fuel-related or coal-related emissions substantially larger than those in these inventories (120-170 and 86 Mt per year; Schwietzke et al. 2016 and Kholod et al. 2020, respectively).

None of the inventories can objectively be considered ‘better’ than the others, so this report treats all as equally valid despite the potential for bias in any given study. In the waste and gas sectors, the values in the US EPA global estimate are slightly lower than those in other estimates and their total is near the low end of the range reported by IPCC AR6 for 2008-2017 (Canadell et al. 2021; and emissions have increased since that earlier period). The extrapolated EDGAR values are at the upper end of the range of other estimates, especially for the agriculture sector (totals are higher than the range given in IPCC AR6, but as these are for a later year they still appear consistent). The US EPA utilizes country reported data to underpin the baseline/projection, as does UNFCCC. As these are a different methodology than that used by other groups, they can lead to distinct values. For instance, values reported to the UNFCCC for the OECD90+EU countries are 56 Mt per year, substantially lower than the values in any of the inventories other than US EPA. This is consistent with the findings of the IEA that total methane in UNFCCC reports appears to underestimate the total and especially energy-sector emissions compared with virtually all other inventories, showing values of 130 Mt per year for agriculture, 79 Mt per year for energy and 55 Mt per year for waste (IEA 2022). While current data allows countries to take mitigation action across sectors, the uncertainty in the magnitude and location of emissions—as illustrated by divergence between estimates—emphasizes the importance of incorporating measurement-based approaches as the world tracks progress on emission reduction efforts and looks for further mitigation opportunities.

Table 1.1. Sample of near present-day emissions estimates from different entities

SECTORS	AVERAGE	EPA 2020	IIASA 2020	CEDS 2019	EDGAR 2020
Agriculture	147	143	149	133	161
Livestock	114	114	113	107	123
Rice	30	25	32	25	38
Waste	73	60	65	83	84
Solid waste	43	40	45	40	47
Wastewater	30	20	20	41	37
Energy	134	128	140	146	121
Gas	35	21	44	32	43
Oil	43	47	44	53	29
Coal	41	38	41	46	37
Total (including 16 Mt/yr biomass burning)	372	348	371	378	391
REGIONAL DATA (EXCLUDING BIOMASS BURNING)					
ASIA	132	118	133	127	149
LAM	48	41	43	54	53
MAF	74	65	75	71	84
OECD90+EU	64	57	70	63	64
FSU	37	48	41	35	24

US EPA and IIASA include projections of a few years starting from recent data. CEDS data is from v2021-04-21. EDGAR data are 2018 values extrapolated to 2020 based on FAO and BP statistics for agriculture and energy, respectively, and linearly extrapolated for waste. Subsectors may not add to sector totals as not all subsectors are shown (e.g. biofuels, agricultural waste burning, industry, etc.). Biomass burning refers to large-scale open fires. Latin America (LAM), Middle East and Africa (MAF), Asia (countries in Asia that are not in another category), the former Soviet Union (FSU) and the advanced economies that are members of the EU or countries that joined the OECD by 1990 (OECD90+EU).

1.3 NATURAL METHANE EMISSIONS AND SINKS

In addition to anthropogenic emissions, the concentration of methane in the atmosphere is affected by natural emissions and by the removal rate, or sink, of methane. There is a substantial discrepancy between estimates of natural global annual methane emissions from bottom-up and top-down methods, which yield values of ~370 Mt and ~215 Mt, respectively (Saunois et al. 2020). This top-down/bottom-up discrepancy is mainly due to overestimates of natural methane sources by bottom-up methods (including overlap in source categorization, UNEP and CCAC 2021). In addition, many national bottom-up estimates do not include estimates of all unmanaged lands. The roughly 50per cent top-down/ bottom-up difference highlights the difficulty for process models to accurately quantify natural emissions at the source level. Similarly, top-down estimates include uncertainties associated with inverse modeling going from atmospheric concentrations, back to inferred emissions (prior knowledge of emissions and sinks, atmospheric transport and the concentrations themselves).

Changes in natural emissions are difficult to project with confidence, and so are not included in the quantitative projections of methane emissions assessed in this Report. Changes in methane chemical sinks are included in modeling of methane's future concentration but may not include all processes affecting sinks (e.g., soil sinks). A brief description of these factors and how they might affect the projections discussed in this report is presented in this sub-section to acknowledge that these might affect the baseline total emissions projections.

Beginning with natural emissions, there is evidence that methane emissions from wetlands generally increase with warming due to enhanced decomposition with higher temperatures (Zhang et al. 2017; Dean et al. 2018). The Intergovernmental Panel on Climate Change's (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC 2019b) found that there is high agreement across model simulations that wetland methane emissions will increase in the 21st century, but low agreement in the magnitude of the change. The IPCC Sixth Assessment Report (AR6) reports the strength of climate feedbacks in terms of their impact on radiative forcing (units of W m^{-2} °C-1), with a positive value corresponding to a positive feedback. That report evaluates the wetland methane-climate feedback as 0.03 ± 0.01 W m-2 °C-1 (mean ± 1 standard deviation; limited evidence, high agreement), with potentially larger values (up to 0.16 W m-2 °C-1; Gedney et al. 2019; Thornhill et al. 2021) based on models that also account for the effects of CO2 changes on productivity (Canadell et al. 2021). Additional research since the AR6 supports the notion of potentially large increases in natural methane emissions under a warming climate (Kleinen et al. 2021). IPCC AR6 concludes that methane emissions resulting from permafrost thaw contribute an additional methane-climate feedback of 0.01 [0.003–0.04, 5–95th percentile range] W m-2 °C-1 (limited evidence, moderate agreement; Canadell et al. 2021). Additional methane releases from increased wildfires and Arctic freshwaters are also likely but are expected to be very small whereas emissions from hydrates are expected to remain at approximately current levels (Canadell et al. 2021). Combining the AR6 estimates for wetland and permafrost release these processes would add ~2per cent to methane radiative forcing (1-10per cent including the potentially larger feedbacks) to the climate impact of methane.

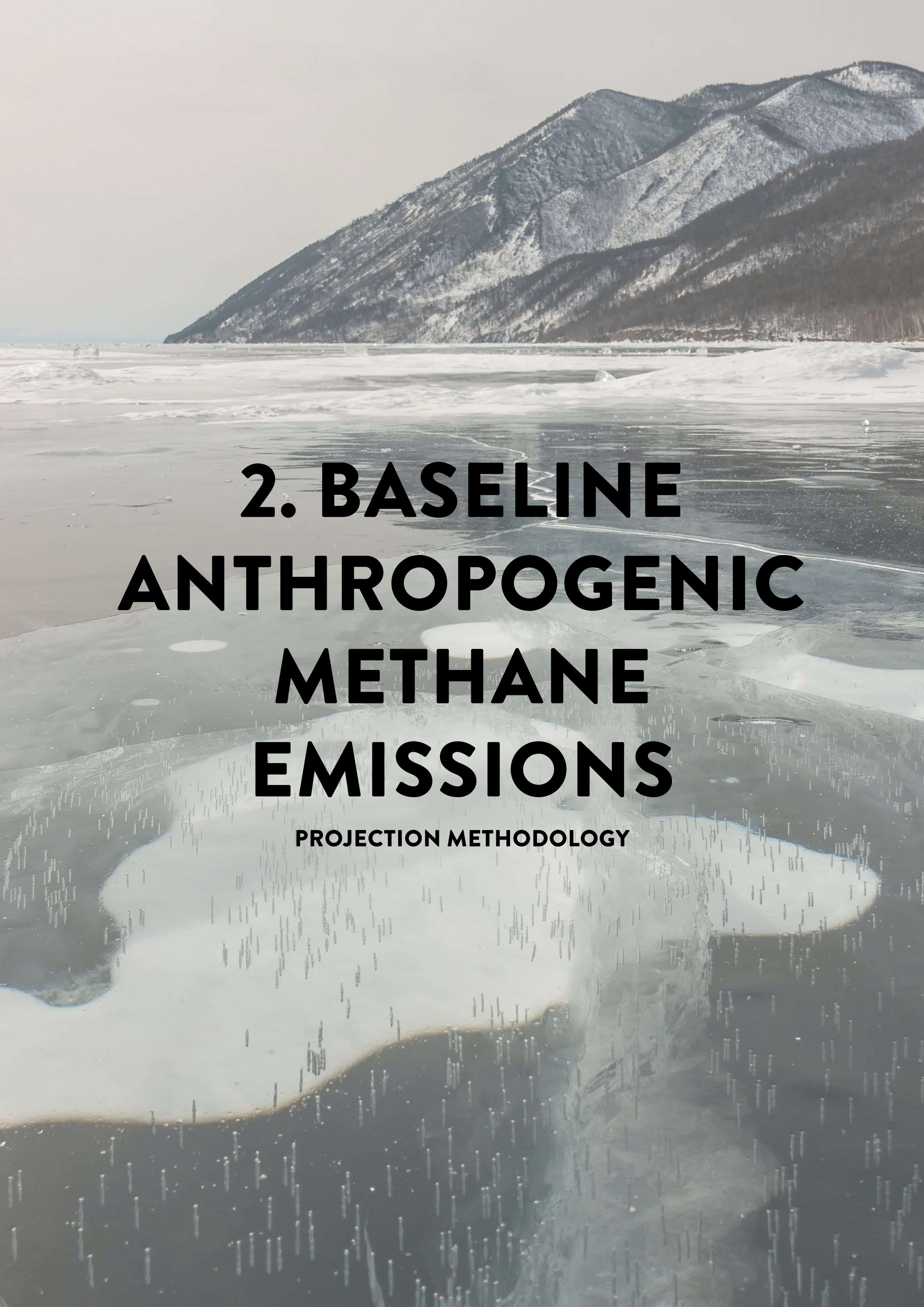
Projections of future methane concentration typically include the response to anthropogenic emissions such as carbon monoxide and nitrogen oxides that influence methane's lifetime. Recent analysis of the large emission changes associated with the COVID lockdowns provide preliminary constraints on the methane response to decreases in nitrogen oxide emissions (Laughner et al. 2021; Stevenson et al. 2021) which may help improve future projections. Changes in natural emissions of nitrogen oxides and volatile organic compounds are difficult to project, however, as are changes in removal rates of soluble short-lived species, making projection of the total methane sink in the future quite challenging. Changes in these climate-related processes affecting the chemical methane sink are typically not included in projected methane concentrations using simple energy-balance models. They are included in complex composition-climate models but have large uncertainties.

Given the uncertainties in both natural methane emissions and the methane sink, it is unclear to what extent these may influence the future atmospheric concentrations, but changes in the natural emissions at least would be expected to lead to higher baseline concentrations than those due to changes in anthropogenic emissions alone. Given the relatively small magnitude of feedbacks seen in observations or most models, the effect of this response is likely to be small through 2030 although we have low confidence in such a projection. Therefore, evaluation of the future success of efforts to reduce anthropogenic methane emissions based on the response of atmospheric methane will need to account for any changes in both natural emissions and the chemical methane sink.

1.4 LATEST METHANE-RELATED POLICIES

Over 120 countries have joined the Global Methane Pledge as of August 2022. Several countries have also announced additional actions to reduce methane emissions, building upon and expanding beyond the GMP. For example, in the November 2021 U.S.-China Joint Glasgow Declaration on Enhancing Climate Action the two countries agreed to develop additional measures to enhance methane emission control in 2022 (US 2021). China also pledged to develop a comprehensive and ambitious National Action Plan on methane, aiming to achieve a significant effect on methane emissions control and reductions in the 2020s. In November 2021, the U.S. published its U.S. Methane Emissions Reduction Action Plan which details actions the government is taking to achieve the objectives of the Global Methane Pledge (US 2021). In December 2021 the European Commission adopted a proposed regulation aimed at reducing methane emission in the energy sector as a first step of the 2020 EU Methane Strategy (EC 2021).

As of May 2022, 168 countries have submitted updated or new Nationally Determined Contributions to the UNFCCC. 90per cent of the latest NDCs address methane within the scope and coverage of their overall GHG reduction targets. However, only 9per cent explicitly identified methane focused measures to achieve their mitigation targets.



2. BASELINE ANTHROPOGENIC METHANE EMISSIONS

PROJECTION METHODOLOGY

The projections of methane emissions in the absence of additional policies, which we refer to as 'baseline' projections, that are analyzed in this report come from a variety of modeling approaches. We discuss results from Integrated Assessment Models, the IEA energy simulation model, and from 'bottom-up' inventory style models. The baseline scenarios do not include future policies but do include assumptions about those in place as of the date of development of the projections. We note, however, that there is a potential for current legislation and policies to fail to achieve their goals, making higher baselines possible.

2.1 ESTIMATES FROM INTEGRATED ASSESSMENT MODELS & SIMULATION MODELS

Integrated Assessment Models (IAMs) provide an internally consistent representation of the energy-land-economy system and are widely used in scientific and regulatory analyses, including the IPCC Sixth Assessment Reports. These models include all the major methane emitting sectors, though they tend to have much more detail for energy and agriculture than for the waste sector. The models typically project future emissions based on economic activities and are driven by external inputs of the future evolution of socio-economic factors such as population, GDP and consumption preferences and of technological factors such as emission factors.

We draw on the results of several recent multi-model intercomparison projects that include 'no climate policy' baseline scenarios. This allows us to characterize the uncertainty attributable to our representation of the energy-land-economy system by comparing across models for a given scenario, and that attributable to the projected changes in socio-economic drivers by comparing across scenarios. The baseline scenarios come from the ADVANCE, NAVIGATE, and ENGAGE projects (https://www.fp7-advance.eu; https://www.navigate-h2020.eu/; https://www.engage-climate.org/), as well as five distinct baseline scenarios from the Shared Socio-economic Pathways (SSPs) activity used in the IPCC Sixth Assessment Reports (Riahi et al. 2017)

The five SSPs envision futures with: sustainability as a focus, with lower resource and energy consumption (SSP1), a "middle-of-the-road" development pattern that largely follows historical trends (SSP2), regional rivalry and material-intensive consumption with a focus on regional energy and food security (SSP3), increasing inequality both across and within countries and highly uneven development (SSP4), and fossil fueled development with both high income growth and energy and resource consumption (SSP5). These SSP scenarios were created around 2015 and so include emissions changes beginning in 2016, but do not include policies or legislation implemented after 2015.

The NAVIGATE and ENGAGE scenarios are the most recent, and therefore include updates to actual trends in energy demand, costs, etc. and legislation through ~2020. The NAVIGATE scenario does not include any climate policies, to show the models' behavior without any policy assumptions (Harmsen et al. 2021).

The ENGAGE project, developed "no climate policy" baseline scenario as well as an alternate baseline following SSP2 but including currently implemented national climate, energy and land-use policies (through 1 July 2019) called NPi2100 (i.e. national policies extended till 2100). This scenario assumes that energy and climate policies that are currently implemented on the national level continue, but that there is no future strengthening of ambition. These policies include existing targets for the years 2020–2025 which are backed by legislation, with the models implementing these targets via emissions pricing, technology deployment, efficiency and shares of low-carbon energy, for example. This scenario therefore includes additional policies relative to the SSP2 baseline and would hence be expected to in general yield lower increases in methane emissions.

The IEA's Stated Policies Scenario (STEPS) provides projections for methane emissions from the energy sector (IEA 2021). This scenario is developed using the IEA's energy simulation model (rather than an integrated assessment model) and it reflects policy settings based on a sector-by-sector assessment of the policies in place and announced by governments around the world up to October 2021. The STEPS and NPi2100 scenarios differ from the 'no policy' scenarios and so results from these scenarios are not included within our primary analysis of projections below but we refer to results from these scenarios to provide further context.

We evaluate all available results from these 8 primary baseline scenarios for which regional data and at least some sectoral data was available (at minimum, total and Agriculture, Forestry and Other Land Use (AFOLU)). This dataset includes results from the following IAMs: AIM/CGE (versions 2.0 and 2.2), GCAM 4.2, IMAGE (versions 3.0.1, 3.0.2, 3.2), MESSAGE-GLOBIOM 1.0, MESSAGEix-GLOBIOM 1.1, POLES, REMIND 1.7, REMIND-MAgPIE (versions 1.5, 2.0-4.1, 2.1-4.2), WITCH 5.0, WITCH-GLOBIOM (versions 3.1 and 4.2), COFFEE 1.1. In general, the earlier model versions were used for the SSPs and ADVANCE with the latest model versions used for NAVIGATE and ENGAGE simulations. Not every model participated in every project or provided sufficient output to allow inclusion, so across the scenarios we include baseline projections from 42 separate IAM simulations.

2.2 ESTIMATES FROM "BOTTOM-UP" INVENTORY TYPE MODELS

IIASA's Greenhouse gas and Air pollution Interactions and Synergies (GAINS) model estimates global anthropogenic methane emissions using a method similar to "bottom-up" inventories. This means that quantification of human activities driving emissions in various source sectors are multiplied by emission factors that have been identified to represent the average emissions per unit of activity in a given technical- and physical- setting. The detailed methodology is outlined in Höglund-Isaksson et al. (2020) and follows the guidelines recommended by IPCC (2006, 2019a), i.e., for most source sectors a wealth of publicly available country-specific information is used to derive country-, sector- and technology- specific emission factors at an IPCC Tier 2 level. Baseline emission estimates reflect expected impacts on emissions from current legislation to control emissions. Because emission estimates are internally consistent and well comparable across geographic and temporal scales, they allow for the possibility to explore past emission trends.

Future methane emission pathways from 2015 to 2050 are developed in consistency with macroeconomic and energy sector activity drivers from the IEA World Energy Outlook 2018 New Policies Scenario (IEA-WEO 2018), agricultural sector activity drivers from FAO (Alexandratos and Bruisma 2012), and IIASA's own projections of solid waste and wastewater generation in consistency with the macroeconomic drivers. By incorporating policies projected forward in 2018 by the IEA in the energy scenario, these projections are more similar to the NAVIGATE and ENGAGE baselines than the earlier SSPs.

EPA's *Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation* report provides projections using a combination of country-reported inventory data supplemented with EPA-estimated calculations consistent with Inventory guidelines of the Intergovernmental Panel on Climate Change (IPCC). The full methodology is discussed in methodology documentation accompanying the report.

Historical emissions estimates are incorporated from country-reported data from 1990 through 2015. The projections that EPA make to year 2050 results reflect a "business-as-usual" (BAU) scenario with emission rates consistent with historical levels and do not include future effects of policy. To the extent that emissions reductions are reflected in country-reported base year data, those rates are used throughout the time series. Where country-reported data is not available, IPCC default Tier 1 emissions factors or other literature are used. Projected activity drivers are taken from a variety of globally available activity data sources depending on the source category. Trends in energy production and consumption are based on the EIA 2017 International Energy Outlook Reference Case scenario. Growth rates in crop and livestock production are from International Food Policy Research Institute's IMPACT model (International Model for Policy Analysis of Agricultural Commodities and Trade; Robinson et al. 2015). As with the GAINS model, the EPA's projections are more similar to the NAVIGATE and ENGAGE baselines than the earlier SSPs given their later starting year and including of later energy scenarios.

2.3 HARMONIZATION METHODOLOGY

To facilitate comparison of results across the 11 different models (9 IAMs and 2 bottom-up models), we have first harmonized all results so that the projections begin from a uniform starting point for 2020 anthropogenic emissions. We use results from the analysis by the Global Carbon Project (GCP) of methane (Saunois et al. 2020), which provides bottom-up and top-down estimates for 2017 as its latest data and estimates averaged over 2008-2017. We evaluate the growth rate of emissions between 2012, the mid-point of the latter range, and 2017 using the average of bottom-up and top-down estimates, and then extrapolate out three more years to obtain an estimate of 2020 anthropogenic emissions of 378 Mt. This value is only marginally higher than the 2017 estimate from GCP of 372 Mt, so results are not sensitive to the details of this short extrapolation. This value is also within one per cent of the average of the datasets shown in Table 1.1. The same normalization that is used for 2020 is applied to all future projected values (i.e. the harmonization is a constant fractional scaling over time).

Current data comes from the same inventories as analyzed in the 2020 GCP, but there have been updates to some of the datasets. For example, the 2021 version of the CEDS inventory (Hoesly et al. *in preparation)* has values for 2017 that are now 143, 132 and 81 Mt per year for agriculture, energy and waste, respectively, whereas they were 140, 176 and 67 in the earlier 2018 version, leading to totals for these three sectors differing by about 10per cent (356 vs. 383 Mt) and even larger differences for some individual sectors.

We did not normalize the results at either the regional nor sectoral level. This is because emissions at those levels are not as well constrained by observations as are global totals, as exemplified by the change in CEDS energy sector estimates over the past 3 years, and it is also difficult to ensure identical categorization at the sectoral level in all models. Such normalization might substantially affect the regional or sectoral results of some models and is worth revisiting as more observations become available. At present, the normalization to a single global value is a useful step that is well-supported by the available data, but in practice only marginally affects the results. See section 3.4 for further analysis of the sensitivity of the projected baseline methane emissions changes to this global harmonization process.

3. RESULTS FOR BASELINE EMISSIONS PROJECTIONS

3.1 GLOBAL TOTAL AND SECTORAL VALUES

We analyzed data for projected changes in anthropogenic methane emissions based on both Integrated Assessment Models (IAMs) and bottom-up inventory-type models, as described in Chapter 2. Figure 1 shows the global total projected increase in baseline anthropogenic methane emissions between 2020 and 2030 for the indicated sets of models. Based on the mean values across all scenarios and all models or the mean across all scenarios but giving equal weighting to the two types of models, annual anthropogenic methane emissions are projected to be about 25-40 Mt larger in 2030 than in 2020. This represents a growth of about 10per cent above the estimated 2020 level of ~380 Mt per year.

Depending on the socio-economic scenario used, the values can vary markedly. The mean 2030 anthropogenic emissions across the IAMs that simulated the 'sustainability' SSP1 was only 24 Mt higher than in 2020 whereas in the highest emission scenario, the 'fossil-fueled development' of SSP5 the change was 65 Mt (mean across models; full ranges are 6-33 Mt per year and 49-74 Mt, respectively). Recognizing that the world is not yet on a path toward sustainable development but that there has been movement away from fossil fuels at least in some parts of the world, we also examined the SSPs excluding those two most extreme scenarios. The average increase in annual emissions for the 10-year period 2020 to 2030 across all models over SSPs 2-4 is 44 Mt (standard deviation 13 Mt; range 22-69 Mt). The average annual increase over the so-called 'middle-of-the-road' SSP2 is quite similar at 41 Mt for this decade.

The two most recent IAM projects, NAVIGATE and ENGAGE, project growth at the low end of that seen in the SSPs, with annual 2030 emissions 28 and 22 Mt higher than in 2020, respectively (mean across models; full ranges are 13-44 Mt and 5-36 Mt, respectively). These values are in excellent agreement with the projections of the two 'bottom-up' models, which projected increases in annual emissions of 22 and 29 Mt for EPA and IIASA, respectively. Both the latest version of the IAMs and the bottom-up inventories internalize at least some effects of recent developments such as improved waste management in most OECD countries, levelling off of coal mining in China, etc.

We conclude that the most probable range of projected increases in annual emissions between 2020 and 2030 is ~20-50 Mt based on the combination of IAM and bottom-up estimates though a broader range of 5-75 Mt is plausible. In part, the larger projections are from scenarios developed earlier that did not account for increased political will to reduce methane emissions and increased availability of observations that have already begun to guide reduction practices, so that the lower projections can be thought of as indicative of recent progress towards achieving methane reductions, making the baseline projected in 2022 lower than the baseline projected in 2016 (the year the SSPs were published). To avoid subjectively choosing a particular subset of simulations to represent an ideal baseline, we hereafter rely upon the mean increase calculated with equal weighting of the average of all 42 IAM simulations and the average of the 2 bottom-up models (31 Mt per year; range 22-46; Figure 1). For the uncertainty range, we utilize the range that encompasses both the 25th-75th percentile from the IAMs and both the bottom-up projections (i.e. whichever is further from the mean is used to represent the range about the mean).

Contributions to the projected baseline increase are divided roughly equally among the three main emitting sectors, agriculture, waste and energy (Figure 2). In percentage terms, the mean values represent growth of about 14per cent in waste sector emissions, about 7per cent in the agricultural sector and about 8per cent in the energy sector (Figure 2). Note that there are substantial uncertainties, with the greatest consistency in the projected changes in the waste sector and the largest spread in the energy sector, with agriculture in between.

Projected trends attributable to specific sub-sectors are available mostly from the 'bottom-up' models with additional data for agricultural sub-sectors from 5 of the IAMs as well (from the ENGAGE simulations). Examining the main sub-sectors, we find that the growth in the agricultural sector is almost entirely or completely due to livestock, with a minimal change or perhaps even a decrease in the rice sector (Table 3.1). Across the IAMs, changes in livestock-related emissions have a very large spread, however, with the range of 2030 values relative to 2020 extending from +32 to -2 Mt per year. As these IAM results come from a single baseline scenario this indicates that projected emissions from this sector are highly sensitive to assumptions within the IAMs.

Projected trends across sub-sectors are similarly skewed within the energy sector, with virtually all the growth expected to occur within oil and gas whereas methane emissions associated with coal are expected to stay roughly constant or decrease slightly. The latter are highly sensitive to the development in future coal use in China as the world leading consumer of coal but may also be affected by shifts in production between regions with different emission intensities for coal mining. Within the waste sector, both emissions associated with solid waste and with wastewater are projected to grow, driven by growth in population and economic development, with those from solid waste increasing more rapidly in both tonnes per year and in per cent of current emissions. The two bottom-up estimates are in fairly good agreement on projected changes, with closest agreement in the waste subsectors. The models differ most strongly in the energy subsectors. These uncertainties in the sub-sectoral projections mirror the pattern in the sectoral projections in both these models and in the IAMs (Figure 2).

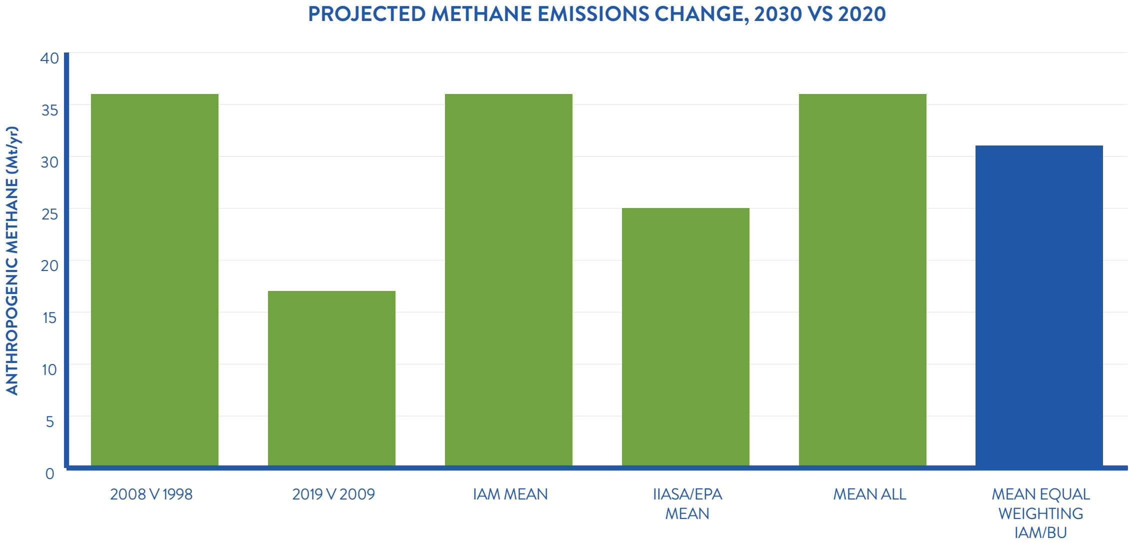


Figure 1. Global total projected increase in baseline anthropogenic methane emissions between 2020 and 2030 for the indicated sets of models (IAM mean from all 42 baseline scenarios; mean across all 44 projections; mean equal weighting of average of 42 IAMs and average of 2 bottom-up models) along with the two previous 11-yr periods for comparison (historical data from CEDS). The mean with equal weighting is highlighted as that analysis is used hereafter.

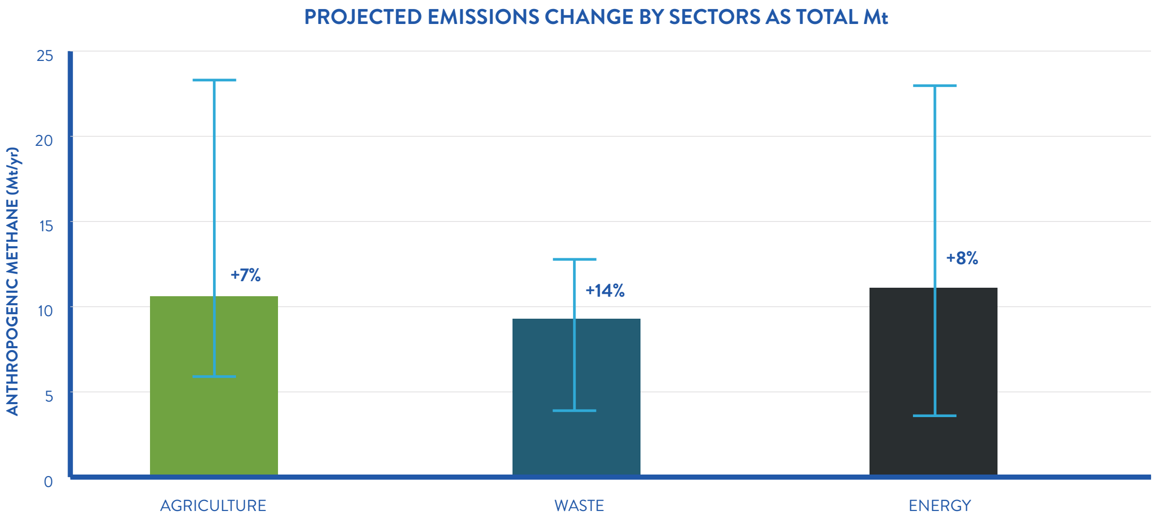


Figure 2. Global total projected increase in baseline anthropogenic methane emissions between 2020 and 2030 for the indicated sectors. The bar indicates the mean across estimates (equal weighting IAMs/BU) and the range is the combined 25th and 75th percentile results from the IAMs and the two BU results (whichever is further from the mean, so that the range encompasses both the 25th-75th IAM percentiles and both BU results). Values near each bar give the per cent of current sectoral emissions the mean increase represents.

Table 3.1. Sub-sector global projected change in methane emissions from 2020 to 2030.

SECTOR	IIASA	EPA	IAMS MEAN	IAM MAX	IAM MIN
Livestock	5.7	7.1	13.1	32.1	-2.0
Rice	0.0	-0.3	0.3	1.7	-1.5
Coal	0.2	-1.8			
Oil	2.0	0.5			
Gas	7.7	3.5			
Solid Waste	9.6	8.0			
Wastewater	3.0	1.7			

Values are Mt/yr in 2030 relative to Mt/yr in 2020.

3.2 REGIONAL VALUES: TOTALS AND SECTORAL

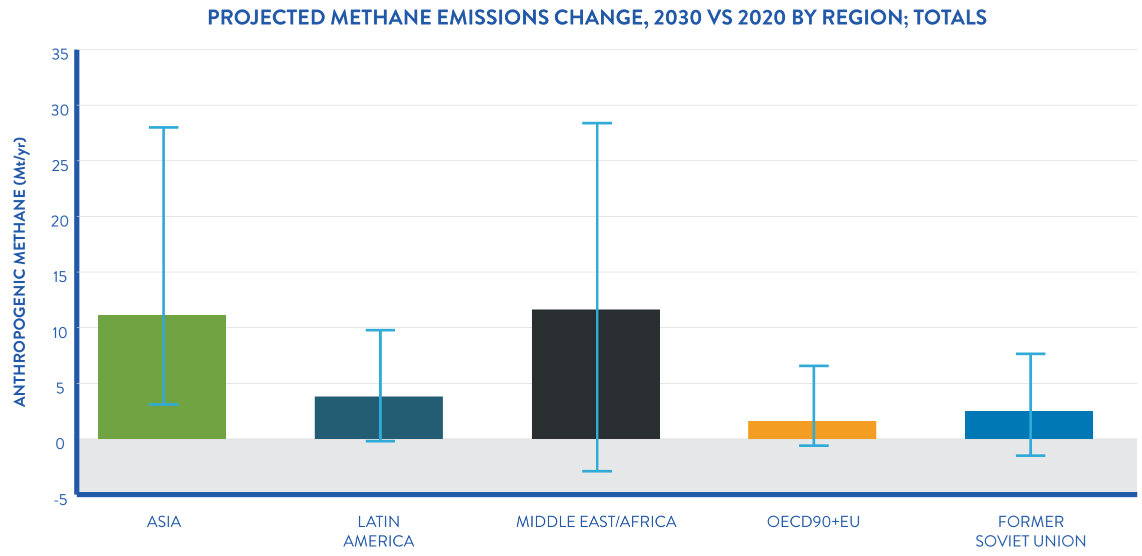
We examine regional values using 5 regions widely used by the IAM community and hence for which data is most readily available: Latin America (LAM), Middle East and Africa (MAF), Asia (countries in Asia that are not in another category), the former Soviet Union (FSU) and the advanced economies that are members of the EU or countries that joined the OECD by 1990 (OECD90+EU).

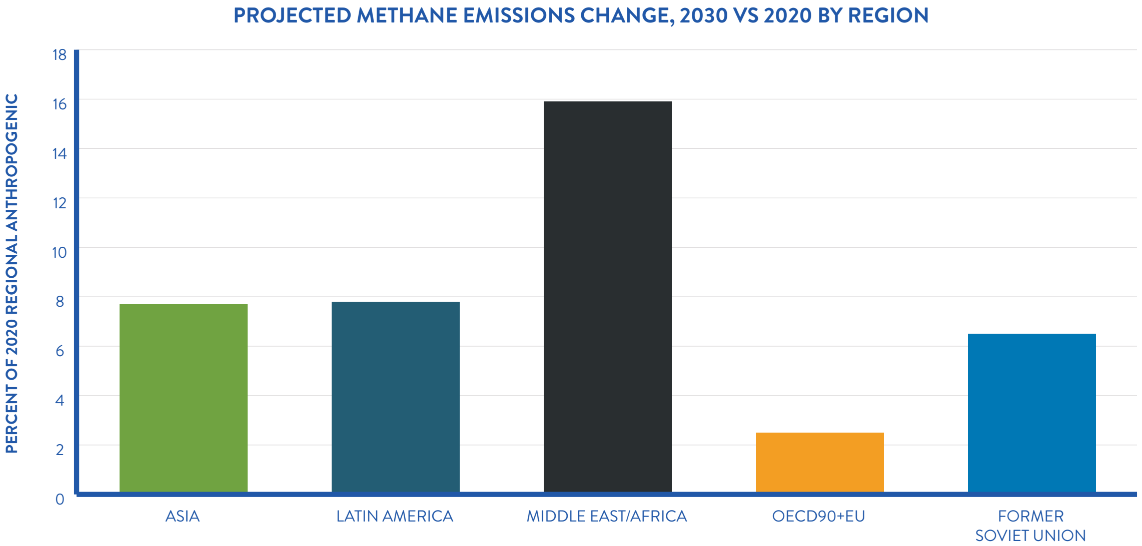
3.2.1 REGIONAL TOTALS

Examining the projected change between 2020 and 2030 in annual baseline methane emissions by region, the largest increase in tonnes per year are seen in Asia and Middle East/Africa (Figure 3, top). These two regions also showed the largest decadal increases over the past two decades (Table 3.2). Increases are markedly lower in the other three regions, and their probable range includes no increase or even a small decrease, especially in the OECD90+EU region (consistent with 2010s decrease, Stavert et al. 2021), though in all the other three regions a small increase is most commonly projected. Given the much larger emissions in Asia, the large change in absolute emissions there represents a percentage increase that is similar to that seen in Latin America and the former Soviet Union (Figure 3, middle). On a per capita basis, however, the increases are much larger in the former Soviet Union than in any other region (Figure 3, bottom), and these are almost entirely attributable to the fossil fuel sector (Harmsen et al. 2020). This result is driven in part by a projected level population or decreasing population in that region combined with increased emissions, whereas other regions show substantial increases in population (LAM, MAF, Asia) or fairly constant population but weak increases in emissions (OECD90+EU). Note that the very large increase in per capita emissions in the former Soviet Union is driven almost exclusively by the projected change in the energy sector as change in other sectors are <1.5 kg/person.

To convey the full range from the IAMs, we also show results from each individual simulation along with the central range used elsewhere in this analysis (Figure 4). The results reveal a very large range of possibilities. Though there are sometimes results that are significant outliers with respect to the group, the number of those is small ranging from 1 to 4 across the regions.

In comparison with historical trends, the projected growth in Asia is similar to that seen in the 2010s but much lower than that seen in the preceding decade (Table 3.2). In contrast, the growth foreseen in the Middle East/Africa is roughly double that of the 2010s, but similar to the value in the 2000s. For Latin America and the former Soviet Union, the growths represent an increase relative to the 2010s, although lower than the ones in the 2000s. Lastly, the projected growth in the OECD90+EU is a modest increase during the 2020s, which is still a clear departure from the prior two decades that showed a decrease in emissions from these countries. Note, however, that given the large ranges in the models (Figure 4) comparisons between one decade to another are often highly uncertain.





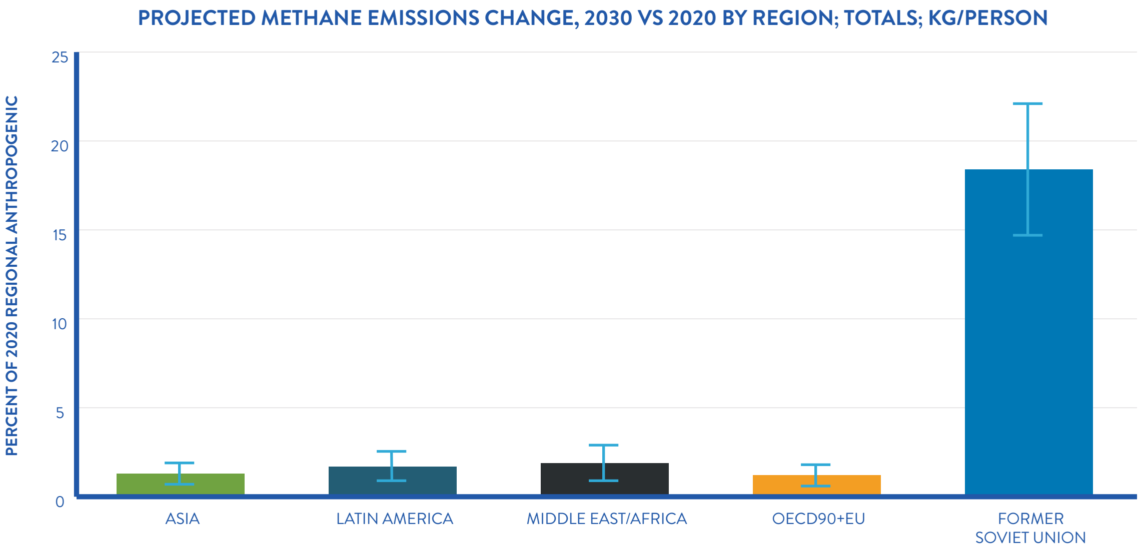


Figure 3. (top) Global total (all sectors) projected increase in baseline anthropogenic methane emissions between 2020 and 2030 for the indicated regions. The bar indicates the mean across estimates (equal weighting IAMs/BU) and the range is the combined 25th and 75th percentile results from the IAMs and the BU results (whichever is further from the mean). (middle) Same in per cent of current regional emissions (uncertainty ranges are similar to those in the upper panel). (bottom) Same in per capita emissions change.

Table 3.2. Estimated historical and projected total anthropogenic methane emissions by region in the IAMs (Mt/yr at end year relative to start year of 11-year period).

	2010 V 2000	2020 V 2010	2030 V 2020
ASIA	40	12	11
LATIN AMERICA	6	3	4
MIDDLE EAST/AFRICA	10	5	11
OECD90+EU	-5	-2	2
FORMER SOVIET UNION	5	-1	3

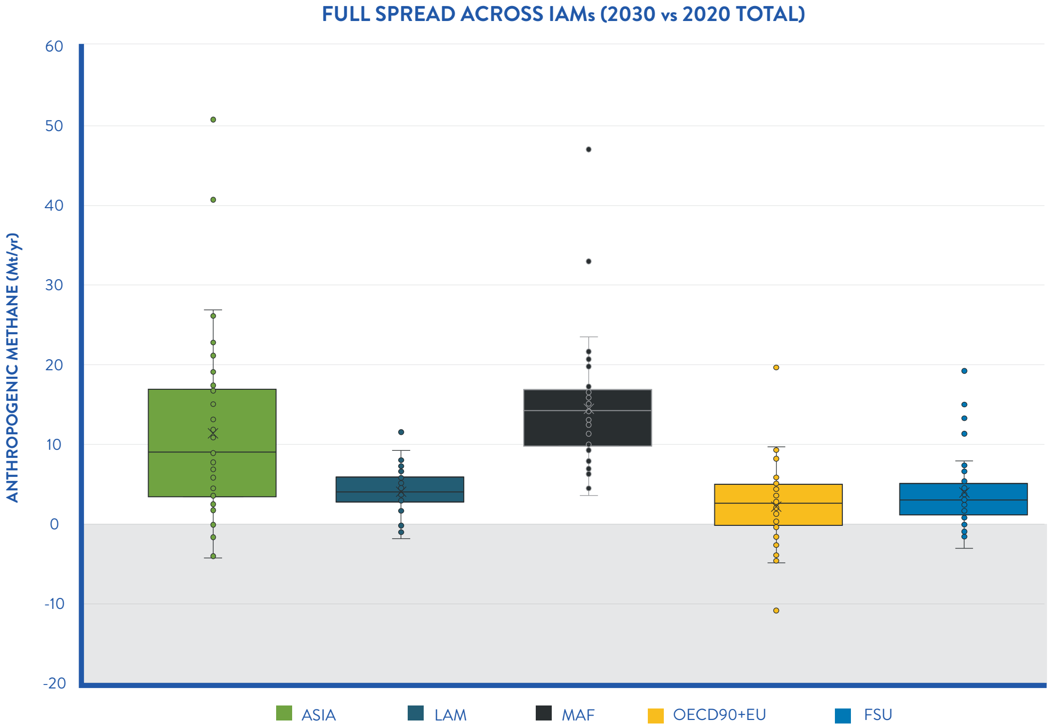


Figure 4. Regional emissions differences between 2020 and 2030 in the 42 IAM scenarios. The bar shows the 25th to 75th percentile of results, the horizontal line within the bar shows the mean result and the whiskers extend to 1 interquartile range above and below the central 50per cent to suggest which points might be considered outliers.

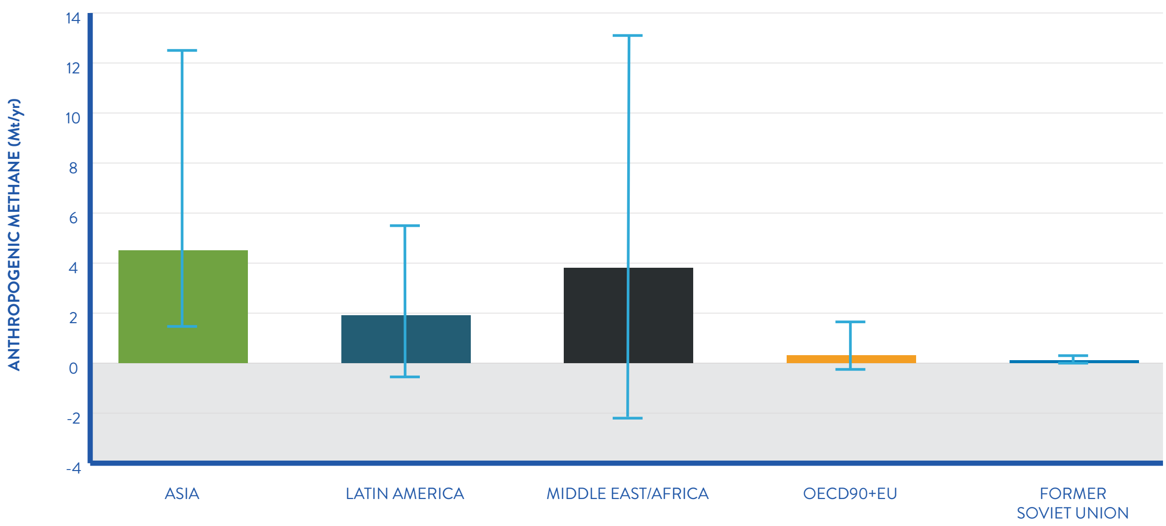
3.2.2 REGIONAL SECTORAL PROJECTIONS

Turning to the sectoral level within the analysis of regional results, we see that the projected increase in agricultural emissions between 2020 and 2030 is largest in Asia and the Middle East/Africa (~4 Mt per year), followed by Latin America (~2 Mt per year), with minimal growth in the OECD90+EU or the former Soviet Union (Figure 5). Within the energy sector, the increases projected in the Middle East/Africa region (~4 Mt per year) stand out from those in other regions which are ~1-2 Mt per year. The projections for the waste sector are fairly similar to those for the agriculture sector, with Asia and the Middle East/Africa again largest (~3-5 Mt per year). The range of model results is much broader for the agriculture and energy sectors than for the waste sector but is similar across regions for most sectors. One exception is the energy sector in Asia, which has a particularly large spread of model results ranging from large (>4 Mt per year decreases to large increases.

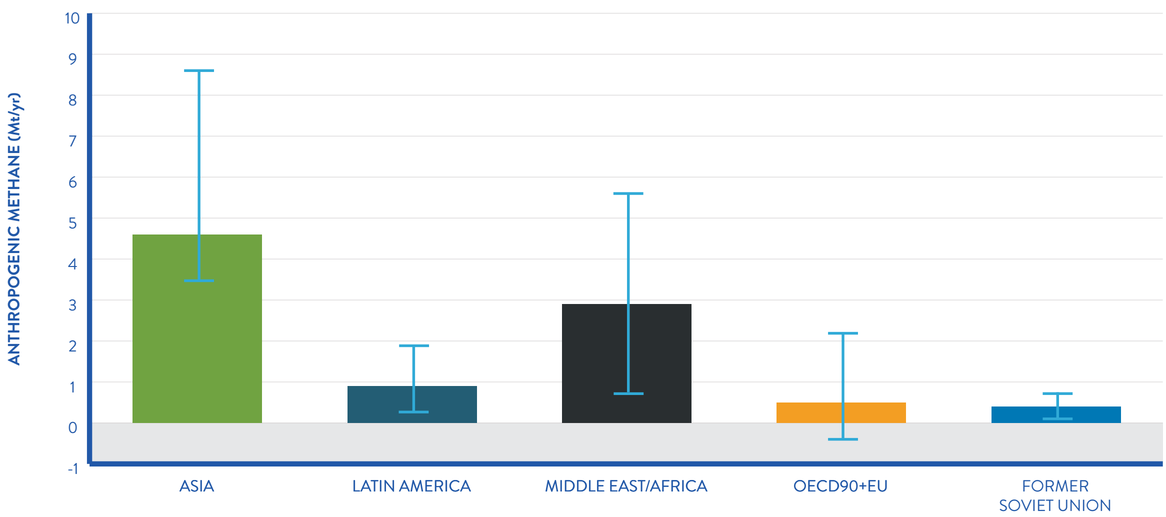
Examining the regional and sectoral projections on a per capita basis, increases are <1.5 kg per person in all sectors for all regions with the exception of energy in the former Soviet Union which increases by ~17 kg per person. As noted in section 3.2.1, this is driven in part by a projected level or decreasing population in that region combined with increased emissions, and this sector's change dominates the total regional per capita change (Figure 3). The next largest regional and sectoral emissions growth on a per capita basis is projected for waste in the former Soviet Union followed by agriculture in Latin America and the Middle East/Africa (all within 0.9-1.4 kg per person increase).

Comparing the inventory/bottom-up models with the range of results seen across the IAMs shows that for the regional totals, the bottom-up results fall within the 25th-75th percentile for the three regions other than the Middle East/Africa and former Soviet Union. For those two they fall within the 10th-90th percentile range across the IAMs (Table 3.3). Turning to sector specific regional values, the projected changes in the bottom-up models are generally consistent with those projected in the IAMs, falling within the 25th-75th percentiles in 8 of 10 and 7 of 10 cases for agriculture and energy, respectively (and within the 10th-90th percentile in 9 of 10 and 9 of 10 cases). There are larger discrepancies in the waste sector, however, with the two types of models showing agreement only in the OECD90+EU region whereas in the other regions both the bottom-up models project larger increases than those seen even in the 90th percentile of IAM results. As the IAMs having traditionally focused on the energy and agriculture sectors much more than on the waste sector, we expect that the larger values reported by the bottom-up studies may be more plausible. As such, we calculated the mean across the models using equal weighting of the IAMs and bottom up models for agriculture and energy but the bottom up models only for waste. This yields a growth of 34 Mt per year (range 25-49) rather than the 31 Mt per year using equal weighting for all sectors, and we adopt this value and range as the 'best estimate' for this report.

PROJECTED METHANE EMISSIONS CHANGE, 2030 VS 2020 BY REGION; AGRICULTURE



PROJECTED METHANE EMISSIONS CHANGE, 2030 VS 2020 BY REGION; WASTE



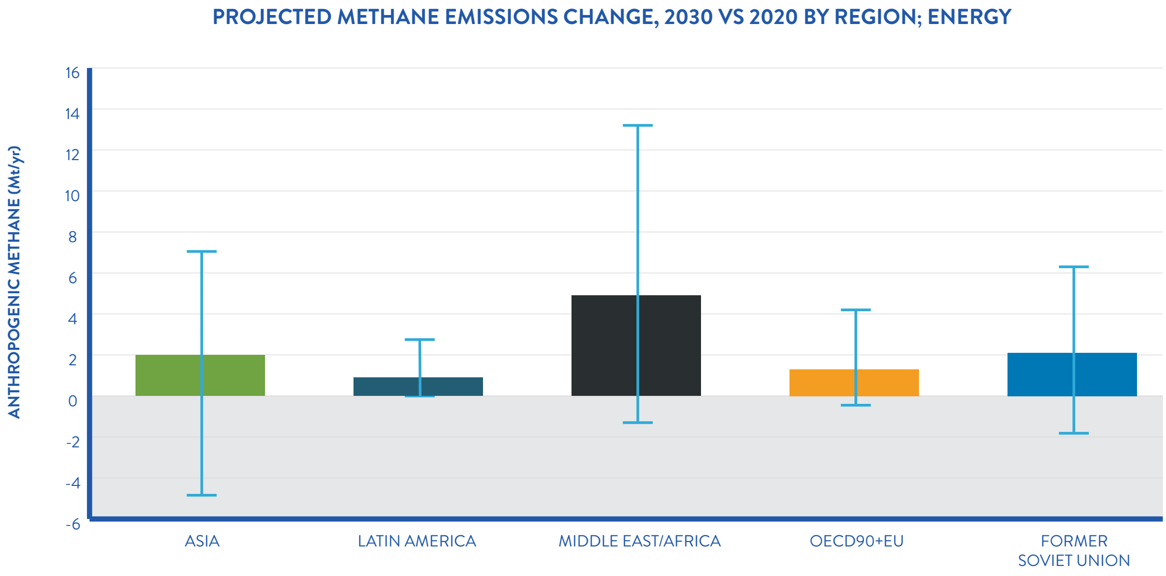


Figure 5. Regional and sectoral projected increase in baseline anthropogenic methane emissions between 2020 and 2030. The bar indicates the mean across estimates (equal weighting IAMs/BU) and the range is the combined 25th and 75th percentile results from the IAMs and the BU results (whichever is further from the mean). The population in the former Soviet Union is about 300 million, and the ratio for other regions is: FSU 1, LAM 2, OECD90+EU 4, MAF 5, Asia 13.

Table 3.3. IAM Means and ranges plus BU values by region and sector (annual emission changes for the decade 2020 to 2030 in Mt methane)

EMISSIONS	IAM MEAN	IAM 25TH	IAM 75TH	IIASA	EPA	IAM 10TH
ASIA	11.4	3.4	16.9	13.0	8.4	
LAM	4.0	2.7	5.9	4.2	2.9	
MAF	14.5	9.8	16.9	8.3	8.9	6.6
OECD90+EU	2.2	-0.2	5.0	1.6	0.6	
REF	4.0	1.1	5.1	1.0	0.9	-1.0
EMISSIONS|AGRICULTURE	**IAM MEAN**	**IAM 25TH**	**IAM 75TH**	**IIASA**	**EPA**	**IAM 10TH**
ASIA	5.5	2.4	8.0	3.5	3.5	
LAM	2.5	1.8	3.6	2.0	0.8	-1.1
MAF	6.0	1.3	9.3	0.0	3.1	0.7
OECD90+EU	0.5	0.0	1.4	0.2	0.0	
REF	0.1	-0.2	0.2	0.2	0.0	
EMISSIONS| ENERGY	**IAM MEAN**	**IAM 25TH**	**IAM 75TH**	**IIASA**	**EPA**	**IAM 10TH**
ASIA	2.8	-4.0	5.1	2.3	-0.1	
LAM	0.9	0.1	1.9	1.1	0.8	
MAF	6.2	3.6	8.3	4.6	2.5	2.0
OECD90+EU	1.8	-0.3	2.9	1.7	0.0	
REF	3.9	0.8	4.2	0.0	0.5	0.2
EMISSIONS| WASTE	**IAM MEAN**	**IAM 25TH**	**IAM 75TH**	**IIASA**	**EPA**	**IAM 90TH**
ASIA	3.0	1.9	4.0	7.2	5.0	4.8
LAM	0.6	0.2	1.0	1.1	1.3	1.0
MAF	2.2	1.6	2.7	3.7	3.3	3.2
OECD90+EU	0.9	-0.3	1.7	-0.3	0.5	
REF	0.3	-0.1	0.3	0.8	0.4	0.3

Bold italic font highlights when Bottom Up models are outside the IAMs 10th-90th percentile range.

3.3 SENSITIVITY OF RESULTS TO THE SOCIO-ECONOMIC SCENARIO AND THE MODEL USED

Figure 6 shows that for some IAMs, there is little sensitivity of the results to the variation in socio-economic baseline scenarios. Other models, however, including IMAGE, MESSAGE and WITCH, show large variations in baseline projected changes across the scenarios. Within the SSPs, increases are generally smallest in SSP1, rising gradually across SSP2 and SSP3 and greatest for SSP5. SSP4 is typically between the low SSP1 and high SSP5 as well (Figure 6).

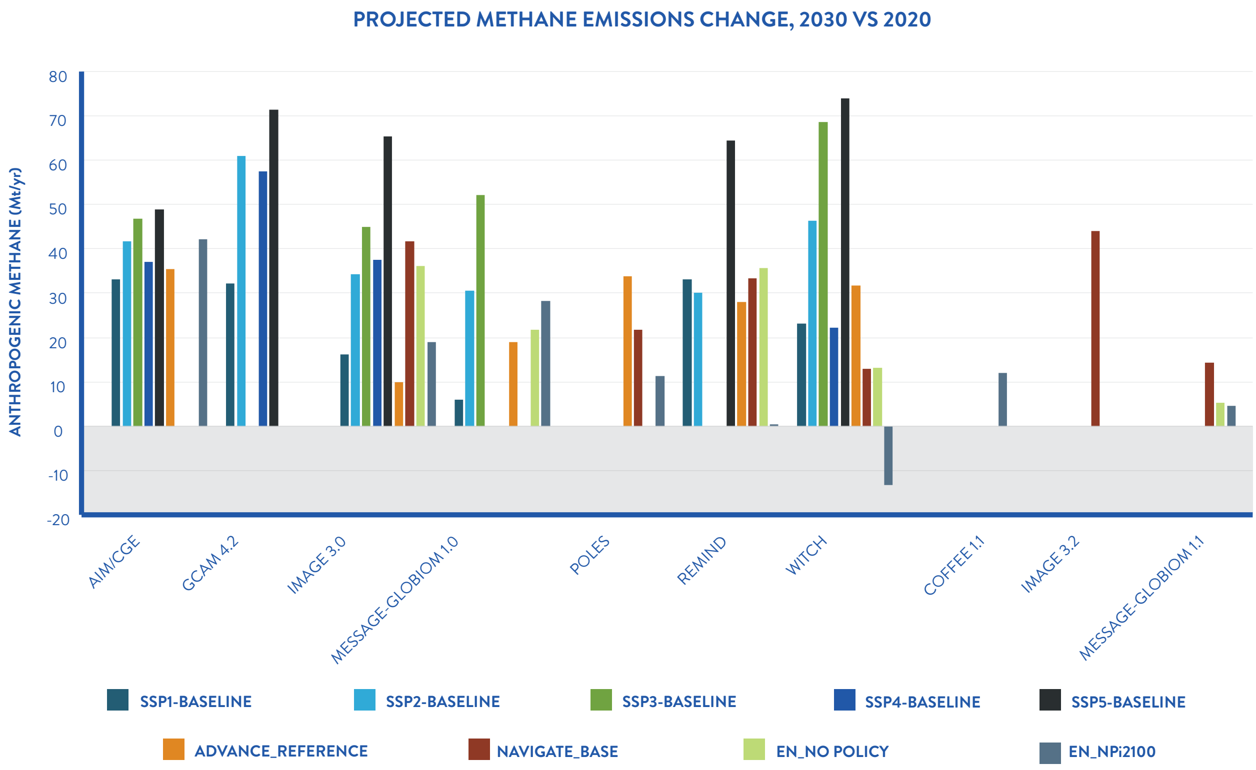
The standard deviation of projected increases in annual emissions between 2020 and 2030 is 10-14 Mt across all the available baselines. This variation across models represents a large fraction of the projected increase in estimated emissions in those scenarios that exhibit a relatively small growth in emissions, such as SSP1 for which it is 47per cent or ENGAGE for which it is 61per cent. In contrast, the variation across models is only 10-15per cent of the 2020 to 2030 increase projected under the high emissions SSP3 and SSP5.

As expected, baselines that include greater reliance on fossil fuels and high resource consumption such as SSP3 and SSP5 show the highest projected increases in annual emissions: 56 Mt and 65 Mt mean across the IAMs, respectively. In contrast, a scenario focused on sustainable development shows less than half of that (SSP1: 24 Mt mean across the IAMs), and similar values are found in the recent NAVIGATE and ENGAGE simulations (28 and 22 Mt, respectively). Hence the choice of scenario can alter the projection by around -15 to +30 Mt per year around the 36 Mt mean across all scenarios in the IAMs. Note also that the very low emissions in SSP1 include smaller increases in methane concentrations in the atmosphere from 2010 to 2020 than observed in half of the IAMs, suggesting that such a low trajectory may not be as realistic as other pathways.

The recent NAVIGATE and ENGAGE simulations also include updates to the underlying IAMs in several cases. These updates appear to have only a minor effect on the change in annual methane emissions in 2030 relative to 2020 in the IMAGE model. For IMAGE, model versions 3.2 and 3.0 (used for the SSPs) both performed the NAVIGATE baseline simulations and found global projected increases within 2 Mt both in the total and at the sectoral level. Differences can be larger at the regional level, however, with the newer version projecting annual energy sector increases that are 8 Mt in the former Soviet Union and decreasing by 5 Mt in Asia, for example. In contrast, the MESSAGE-GLOBIOM model version 1.0 (used for the SSPs) and 1.1 both performed the ENGAGE baseline simulations and found very large differences: global total annual increases of 22 and 5 Mt, respectively, in annual emissions between 2020 and 2030. In that model, the largest change in the projections across model versions was in agricultural emissions from the OECD90+EU which showed a growth of 1 Mt in version 1.0 but a decrease of 4 Mt in version 1.1. Overall, 13 Mt of the 17 Mt difference in annual emissions 2030 vs 2020 across the model versions came from decreases in projected emissions in the agricultural sector between the MESSAGE-GLOBIOM versions. Newer versions of the REMIND-MAgPIE model (2.0-4.1 and 2.1-4.2) appear to have similar projections as older versions based on a rough comparison between their NAVIGATE/ENGAGE results and the results from their REMIND-MAgPIE 1.5 version used for the SSPs, whereas a newer version of the WITCH model (5.0) has much smaller projected growth in energy sector emissions than in the WITCH-GLOBIOM 3.1 versions used for the SSPs and similar values for the other sectors. Given the difference in scenarios, however, it is impossible to compare the model version of these directly.

The ENGAGE scenario including national policies extrapolated to 2100 (NPi2100) shows both a much lower annual mean projected increase of just 13 Mt between 2020 and 2030 and a substantially larger standard deviation across models of 17 Mt. The annual range across the 8 models that performed simulations with this scenario extends from -13 to 42 Mt. Hence while this scenario suggests that current national policies might reduce projected emissions by around 9 Mt (NPi2100 vs ENGAGE baseline), this value is highly model dependent. As 7 of the 8 models find that current national policies still lead to increases in methane emissions over the 2020s, current policies, even if fully implemented, are very likely insufficient to transform the growth in methane into a decline in emissions.

At the sectoral level, the NPi2100 scenario shows continued increases in annual emissions between 2020 and 2030 in the agriculture and waste scenarios, with means of 6 and 7 Mt, respectively (ranges -2 to 25 and 5 to 11, respectively), along with a small decrease in the energy sector's emissions (mean -1 Mt, range +10 to -17 Mt). The low end of this range is consistent with the projections of the IEA's Stated Policies Scenario (STEPS) that projects a 10 Mt decrease in energy sector methane emissions between 2020 and 2030.



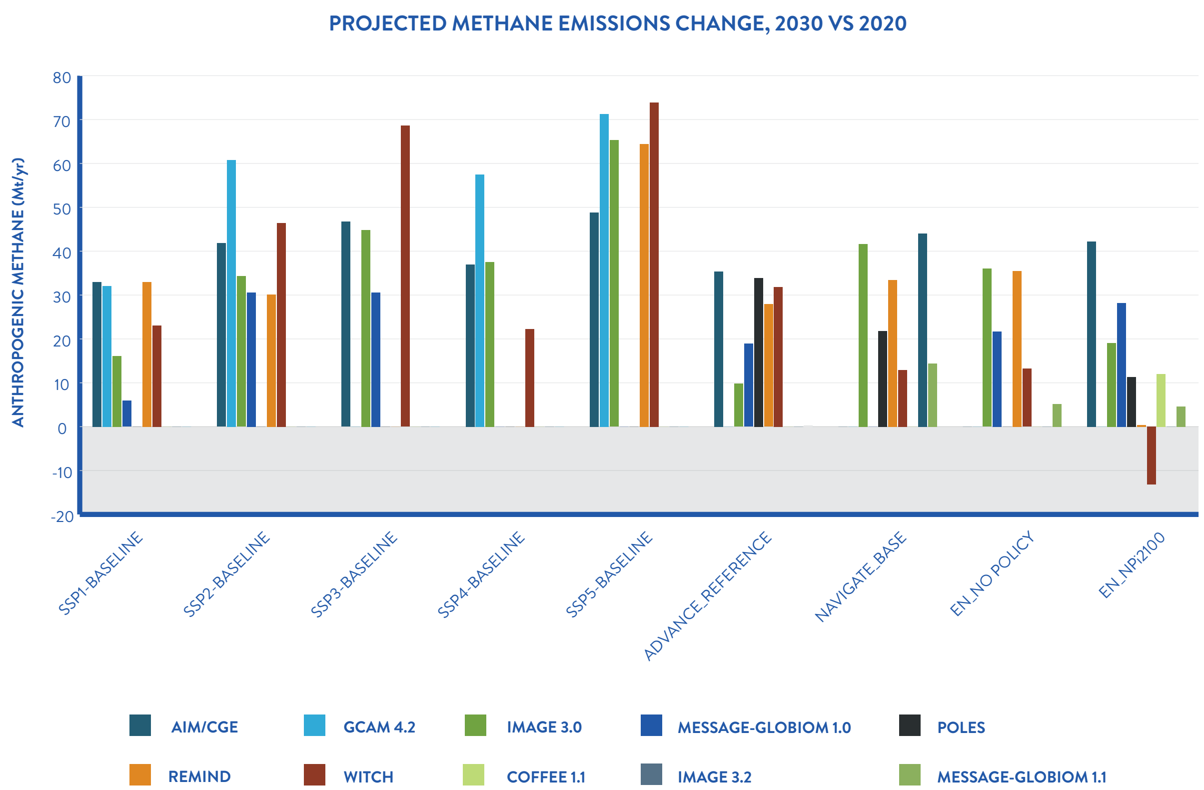


Figure 6. Global total projected increase in baseline anthropogenic methane emissions between 2020 and 2030 for the available IAM simulations grouped by model (top) and by scenario (bottom).

3.4 SENSITIVITY OF RESULTS TO THE HARMONIZATION PROCESS

The results presented in this report are only weakly sensitive to uncertainties in the global total anthropogenic emissions used to harmonize the projections. The global annual total anthropogenic emissions reported in Table 1.1 span a range of 350 to 390 Mt. Raising or lowering the global total to these levels changes the mean projected increase from 2020 to 2030 in anthropogenic methane emissions by +2per cent and -5per cent, respectively. With a slightly larger projected increase in tonnes per year from energy and agriculture, a similar sensitivity test shows a 2-6 per cent change in projected increases in those sectors whereas the impact is 1-3 per cent in waste.

To put these impacts in perspective, a change in the projected increase in total annual emissions of 5 per cent corresponds to a difference of less than 2 Mt in methane emissions. Such a change due to a differing global total harmonization is well within the uncertainty associated with the differing models (~15-20 Mt) or differing socio-economic projections (~20-25 Mt; see section 3.3). As noted, incorporating measurement-based estimates of anthropogenic emissions will be very valuable at national and sectoral levels (see Chapter 1 and Box 1). It could also have larger impacts via harmonization and will be important for future work examining national projections. Note that official national estimates for 2020 were not yet available for most countries at the time of development of this report. In addition, emissions in 2020 may be affected by the response to the COVID pandemic (see section 1.3). However, most of the results reported in Table 1.1 are based on projections that do not include that response or are from an earlier year in the case of CEDS, and so should provide a reasonable representation of longer-term emissions irrespective of any short-term potential pandemic effects on emissions.

IMPROVING CAPACITY TO MEASURE AND APPORTION METHANE EMISSIONS ACROSS DIVERSE EMISSIONS SOURCES

Over the past ten years significant progress has been made in characterizing the magnitude and location of methane emissions from different sources. This work has begun to significantly reduce the uncertainty of emissions, improve inventories, and provide insights into additional mitigation opportunities. While technically feasible mitigation options are readily available across sectors and their implementation need not wait for perfect data, improved empirical data is essential to further expanding mitigation efforts and assessing if targeted reductions are occurring.

Estimates of emissions based on atmospheric measurements at the regional and country scale can provide useful information that can help to quantify current emissions and track changes over time. Observations-based emission quantification (often called top-down approaches) at the regional scale have relied on ground-based networks (e.g. Bergamaschi et al. 2018), airborne-based measurements using mass balance and atmospheric transport models (Neininger et al. 2021; Gorchov-Negron et al. 2020) and more recently on satellite remote sensing (Turner et al. 2016; Schneising et al. 2020; Zhang et al. 2020; Pandey et al. 2021). Existing methodologies can provide accurate estimates of emissions if applied under the right conditions (e.g., sampling with enough frequency to capture potential variability in emissions), though such methods of course include uncertainties working from ambient concentrations back to inferred emissions.

One of the key challenges of creating regional and country-scale quantification of methane emissions using observational data is partitioning them between fossil (e.g., oil, gas, coal sources) and biogenic sources (e.g., agriculture, waste sector) as well as anthropogenic and natural sources. Analytical methods have been developed that allow emissions to be partitioned among sources through the use of stable isotopes (Neininger et al. 2021) as well as tracer/tracer ratios (i.e., methane to ethane ratio; ethane is only co-emitted by fossil sources) (Smith et al. 2015) at the regional scale.

According to international agreements, most countries have relied on emission factors to estimate bottom-up methane emissions and create emissions inventories (e.g., IPCC Tier 1 or the more sophisticated Tier 2 or 3). Recent studies have pointed out large discrepancies between national inventories and top-down emissions estimates—both underestimation and overestimation (Deng et al. 2022). Additionally, most existing global emission inventories or process models report methane emissions without uncertainties although these are sometimes included in national inventories (EPA 2021; IEA 2022). For bottom-up estimates a range of relevant results have been provided in some situations (Saunois et al. 2020). Emission estimates based on satellite observations as well as ground and airborne-based approaches can contribute to a clearer understanding of sources, especially in understudied regions such as Asia, Africa, and South America.

Bottom-up data provides insights useful for driving mitigation actions by allowing disaggregation into specific sources within each sector or industry. Top-down data based on direct methane concentration measurements at regional and country level can more effectively constrain the magnitude and location of emissions and how they are changing over time. Reconciling top-down and observation-derived facility-level data has been accomplished at regional and country scale for different geographies: US (Alvarez et a. 2018), Australia's Surat Basin (Neininger et al. 2021), and Mexico (Shen et al. 2021) and the use of top-down data to refine national emissions estimates by the UK and Switzerland have been included in the IPCC Task Force on Inventories Guideline refinements.

Ground-based and airborne-based observations have been widely used to characterize emissions among large populations of sites at the facility-level scale (Robertson et al. 2020; Tyner et al. 2021). Characterization of the distribution of emissions at the site/facility-level scale across a diversity of sites has significantly reduced the uncertainty of methane emissions from oil and gas infrastructure—where a common characteristic across the supply chain is the presence of a subset of high-emitting facilities with a disproportionate contribution to total emissions. The population of high emitters varies both in time and location. Therefore, to accurately estimate overall emissions requires understanding the frequency and magnitude of emissions across a wide range of sites, rather than monitoring emissions from a few sites. Effective approaches need to recognize the stochastic nature of the distribution of super-emitters. Thus, easily deployed ground and airborne-based measurement capabilities are needed to acquire the large sample sizes required to effectively characterize emissions distributions. Similar approaches have also been used to characterize other methane sources such as coal mines (Kostinek et al. 2021), waste (Mønster et al. 2015) and livestock (Arandt et al. 2018).

Satellite remote sensing observations are capable of characterizing methane emissions from individual locations, as well as regions and countries (Lauvaux et al. 2022), complementing local activity data. Remote sensing has the advantage of characterizing areas that might be challenging to access with ground-based or airborne-based methods.

METHANE REMOTE SENSING OBSERVATIONS CAN BE DIVIDED INTO THREE CATEGORIES:

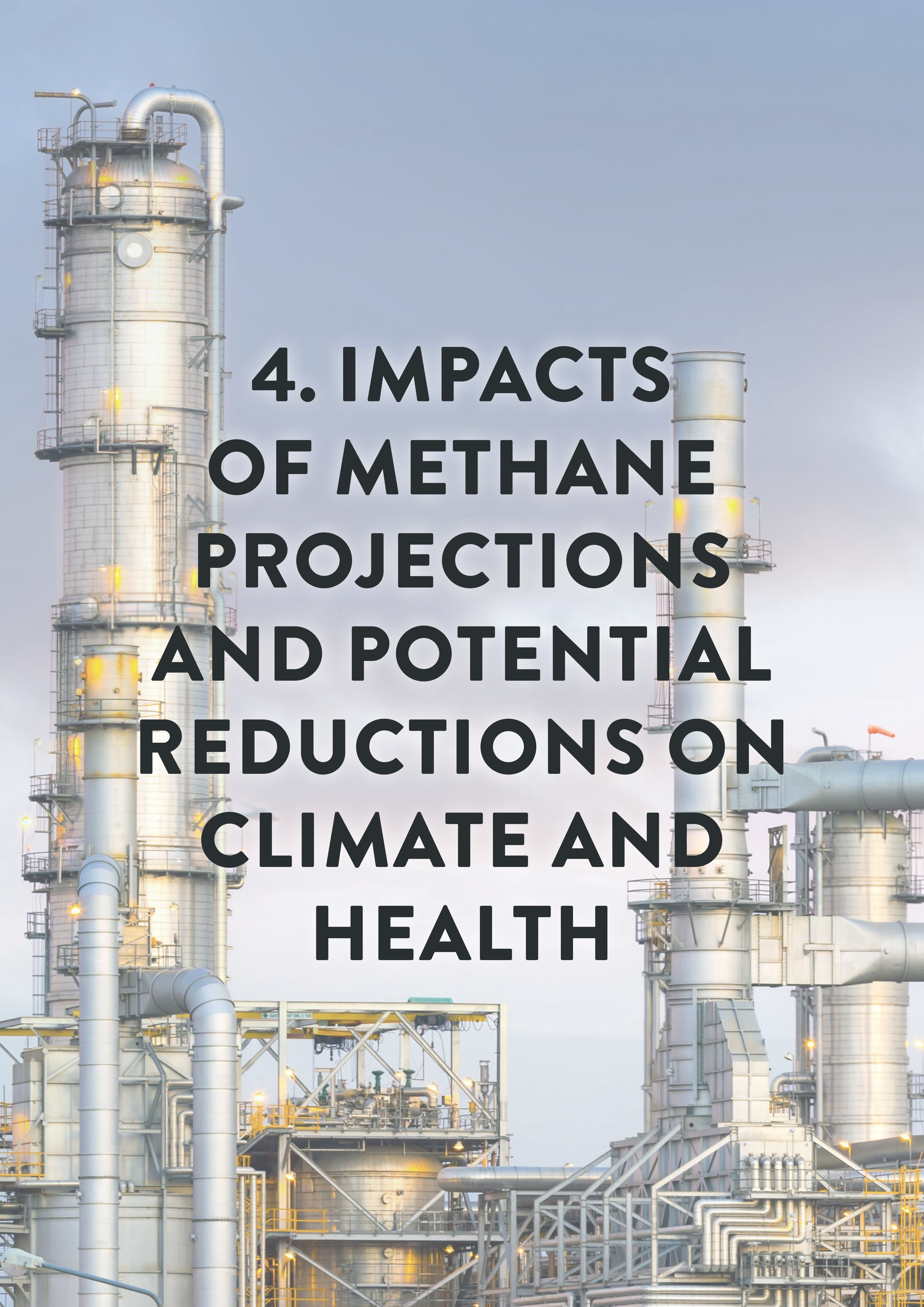
- *Global mapping*. This category includes satellite missions such as TROPOMI (launched in 2017). Other satellites such as GOSAT-GW, will also join this category in the near future. These satellites with quasi-daily global coverage have relatively coarse spatial resolution (7 km x 5.5 km for TROPOMI) and moderately high precision—they can be used for characterizing emissions at regional scale (e.g., Permian basin in the US; Zhang et al. 2020) and country scale (e.g., Mexico; Shen et al. 2021).

- *Point source imagers.* Systems designed to detect and quantify plumes from individual point sources. Operating satellites such as GHGSat, PRISMA and GF5-02, and upcoming missions such as CarbonMapper, EnMAP and Satlantis. These satellites have high spatial resolution (i.e., 25-50 m) and sufficient spectral sensitivity to detect emissions in the range 100-500 kg/h. Studies have already demonstrated how remote sensing can successfully characterize the largest of these point source emissions, so-called ultra-emitters, and how they can be tracked using both global mapping and point-source mapping instruments (e.g. Lavaux et al. 2022; Irakulis-Liotxate et al. 2021; Varon et al. 2018; Varon et al. 2019; Pandey et al. 2019; Sadavarte et al. 2021; Cusworth et al. 2021).

- *Hybrid area flux mappers and point source imagers*. Planned high precision satellite missions like MethaneSAT, to be launched in 2023 will bridge the first two categories, providing total emissions data from area or regional sources for targeted regions.

These remote sensing measurement illustrate a growing ecosystem of satellite-based methane monitoring instrument that can provide quantitative data on methane emissions and how they change over time across sources and geographies. The improved data will also facilitate greater reporting of uncertainties in methane emissions, which is key for demonstrating the robustness any quantification procedure. Emission characteristics may vary widely by geography given differences in industry standards and environmental policies. As a result, additional studies are needed at the country, regional, and local scale to produce accurate policy-relevant data that can effectively guide mitigation.

Multiple ongoing efforts will help policymakers optimize methane emissions. For example, the Integrated Global Greenhouse Gas Information System (IG3IS) that is being developed and promoted by the World Meteorological Organization with a number of partners provide a common framework for the observations-based emission estimates across different gases and scales. It was recommended for use by the UNFCCC SBSTA 50th session. The methodology is also included in the 2019 Refinement of IPCC Guidebook on the National Emission Reporting in Chapter 6 (emission verification). Similarly, the International Methane Emissions Observatory (IMEO)—hosted by the UN Environment Programme (UNEP)—is developing a public data platform to integrate methane emissions data across sources and estimation approaches (industry-reported, verified emissions data, empirically based regional and country scale estimates, national inventories, satellite remote sensing datasets). Using scientific insights, IMEO will integrate these multiple sources of heterogeneous emissions data into a coherent and transparent policy relevant dataset. These and other datasets will enable governments, industry players, and civil society to expand targeted mitigation opportunities beyond those already available and will further catalyze action and track emissions changes over time in line with the objectives of the Global Methane Pledge.



4. IMPACTS OF METHANE PROJECTIONS AND POTENTIAL REDUCTIONS ON CLIMATE AND HEALTH

The Global Methane Assessment's analysis of 1.5°C scenarios showed that least-cost pathways to achieving such a target required decreases in methane emissions by 2030. This report's finding that the projected change in methane emissions in the absence of climate policies is instead a continued growth in emissions emphasizes the need for strong, immediate actions if we are to realize the 1.5°C objective. This section analyzes the climate impacts of the Global Methane Pledge relative to the baseline projections of this Report and presents the climate response to both broad decarbonization efforts and to rapid and deep reductions in methane emissions to illustrate the differing and complementary influences of these strategies. It also discusses the portion of methane abatement achieved by decarbonization alone relative to that achievable by targeted measures.

4.1 METHODS TO EVALUATE SCENARIO CLIMATE IMPACTS

In our broader examination of the climate response to methane reductions, we examine the impact as a function of time assuming methane changes continue beyond 2030 and that they follow a 1.5°C pathway. We compare these impacts with those of a broad decarbonization consistent with a 1.5°C pathway. Decarbonization is achieved primarily by a shift away from fossil fuels, which is in part enabled by end-use electrification, efficiency increases and demand management, along with a contribution from changes in land-use (Rogelj et al. 2018). Emissions are based upon the SSPs as these have consistent scenarios that are available for SSPs 1, 2 and 5 for both baseline and 1.5°C pathways. Emissions of all pollutants other than methane (including cooling aerosol and aerosol precursors such as sulfur dioxide) are based on those three SSPs, with carbon dioxide emissions harmonized across the scenarios at 2020 (rather than the original 2015). The central estimate is the average of those 3 scenarios. For methane, the baseline in the central estimate is based upon the 2020 value of 380 Mt and the findings of this report that the central estimate of the projected increase from 2020 to 2030 is 34 Mt per year (range 25-49). The projected increase in 2050 relative to 2020 in the 3 SSPs is normalized to match the 2030 analysis in this report by multiplying by a factor of 0.9, (the ratio of the 34 Mt increase in 2030 relative to that projected in the SSPs for that year) to obtain a projected value of 470 Mt per year in 2050 for the central baseline case. The full methane mitigation scenario is based upon the percentage reductions in a 1.5°C scenario from the same 3 SSPs whereas the methane component of decarbonization (mostly reduced fossil fuel use) is based upon prior analyses showing that this accounts for roughly 30per cent of the total methane mitigation under a 1.5°C scenario (Shindell and Smith 2019; Harmsen et al. 2019) (Figure 7). Other decarbonization actions, such as reduced deforestation or afforestation, have little impact on methane emissions whereas other methane reduction actions in the scenarios such as changes in livestock or waste management are not considered part of decarbonization. Methane mitigation under the 3 individual SSPs is also examined to characterize uncertainty ranges. The Global Methane Assessment analyzed a much larger set of 1.5°C scenarios, many of which do not have associated baseline projections and so are not well-suited to the type of analysis carried out here. We note that under that larger set of scenarios, the mean methane decrease in 2030 relative to the uniform baseline increase used for all scenarios was slightly larger (45per cent) than that found in the analysis of SSPs 1, 2 and 5 (37per cent), but the latter value is well within the large range of scenarios examined in the Global Methane Assessment (GMA) (~30-60per cent).

The climate response is evaluated using absolute global temperature potentials (AGTPs), as in prior Assessments (UNEP 2017; UNEP and CCAC 2021), publications (e.g. Shindell et al. 2017a) and in the CCAC Scientific Advisory Panel's public Temperature Pathway Tool (https://sappathwaytool.shinyapps.io/CCAC_Pathway_Tool_V1/). Briefly, yearly AGTPs are used to represent the global mean temperature change per kilogram of emission each year subsequent to those emissions based on an impulse-response function for the climate system, as is used in IPCC for selected example years, for example, AGTP50 or AGTP100 (Myhre *et al. 2013).* In the calculations in this assessment, the transient climate response remains based on analysis of the previous generation of climate models (CMIP5) (Geoffroy *et al.* 2013) as the AR6 finds that this sensitivity range provides a good representation of current understanding. The AGTPs include the carbon-cycle response to the temperature change induced by the emitted species including the impact of ozone generated by methane on carbon uptake (Gasser *et al.* 2017; Collins et al. 2010) as described in Shindell *et al.* (2017). As in the Global Methane Assessment (UNEP and CCAC 2021), we use responses to methane that are calibrated to match the global climate impacts reported from the full composition-climate models used in that Assessment. In addition, the response to sulfur dioxide emissions have been updated to reflect the larger impact of current sulfur dioxide including cloud responses reported in AR6 compared to prior Assessments.

4.2 CLIMATE IMPACTS OF THE GLOBAL METHANE PLEDGE

Taking the 2020 emissions as 380 Mt, we can evaluate the climate impact of the methane reductions envisaged under the Global Methane Pledge. The GMP calls for a minimum reduction of 30per cent in comparison to 2020 emissions which translates to a decrease from 380 Mt to 270 Mt. In comparison with 2020 emissions, this lower level is a decrease of 113 Mt. In comparison with the projected value in 2030 based on the mean increase of 34 Mt from 2020 to 2030, however, this lower level represents a decrease of 150 Mt and a decrease of 36per cent compared to projected 2030 emissions levels.

As noted, this 36 per cent reduction relative to the 2030 baseline is within the rage of 1.5°C scenarios, which call for 30-60 per cent reductions from 2030 levels assess in the GMA, but is smaller than the mean 45 per cent reduction across the large set of 1.5°C scenarios.

Based on the climate modeling conducted for the Global Methane Assessment, the reduction in methane emissions relative to the baseline projected 2030 emissions would lead to a decrease in global mean warming of 0.22ºC over the 2040-2070 period. Evaluating the impact of methane reductions relative to 2020 emissions without accounting for the baseline projected growth would lead to a smaller decrease of 0.17ºC. Note that these results are based on methane changes through 2030 alone; additional post-2030 reductions would lead to larger benefits.

The Global Methane Pledge currently covers around half of the world's anthropogenic methane emissions. To achieve this scale of climate benefits would require not only achieving the goals of the Pledge within the signatory nations, but also either the expansion of the Global Methane Pledge to additional countries, comparable action by nations outside the Pledge, or greater action by the Pledge signatories.

THE MULTIPLE-BENEFITS OF THE GLOBAL METHANE PLEDGE

Based on the impact analyses developed using the comprehensive modeling in the Global Methane Assessment we also analyzed several societal effects of focused methane mitigation consistent with a 1.5ºC scenario. Based on the average mitigation across SSPs 1, 2 and 5 relative to their projected baselines, which leads to very similar 2030 emissions as would the achievement of the GMP (Figure 7), methane reductions would provide the following cumulative benefits worldwide through 2050:

- prevent roughly 5.6 million premature deaths due to ozone exposure (3.6-8.0 million range)
- avoid 580 million tons of yield losses to wheat, maize (corn), rice and soybeans (360-1,000 million range)
- avoid $520 billion (2018 US$) in losses due to non-mortality health impacts, forestry and agriculture (360-700 billion range)
- avoid 1,600 billion lost work hours due to heat exposure (480-2,700 billion range)

These benefits include only a portion of the avoided climate damages (those that form part of the crop impacts and the labor losses). For example, though the impacts of heat exposure on premature death have not been characterized in all countries the Global Methane Assessment reported an approximate value of 390 additional deaths per million tons methane emissions (UNEP and CCAC 2021). Using those results, the average mitigation across SSPs 1, 2 and 5, methane reductions would prevent roughly 50,000 premature deaths due to heat exposure by 2050, with much larger values later in the century.

4.3 CLIMATE IMPACTS OF BROAD DECARBONIZATION AND FOCUSED METHANE ABATEMENT

To assess the relative roles of broad decarbonization and focused methane action on near-term climate we perform two analyses: in one case comparing with constant 2020 emissions (Figure 8) and in the second comparing with the projected changes in the baseline emissions (Figure 9). This reveals the important role of projected changes in several non-methane pollutant emissions under the baseline, including both carbon dioxide and sulfur dioxide (SO_2).

Methane mitigation is able to generate greater temperature reductions than decarbonization alone in the near term. In comparison with constant 2020 emissions, the climate impact of focused methane mitigation is greater than that from decarbonization throughout the entire first half of the century (Figure 8). When the impacts are assessed relative to baseline projections, the climate impact of focused methane mitigation is greater than that from decarbonization through 2046 (Figure 9; considering systematic differences between scenarios as described in the caption). We reiterate that decarbonization includes substantial methane reductions in the energy sector. If we were to instead compare methane reductions against all pollutants other than methane under decarbonization, the impacts of focused methane mitigation would be greater through 2050. Evaluating the effects of decarbonization on climate against either the constant 2020 emissions case or the projected baseline emissions case, decarbonization activities become important in the 2040s and would grow further in importance during later decades, but they provide minimal climate benefits over the next 20 years (though they provide large air quality benefits). Benefits are of course greatest when both decarbonization and targeted methane reductions are pursued simultaneously (Figure 8).

Decarbonization due to fossil fuel phaseout alone does not mitigate warming in the near term due to associated removal of co-emitted cooling pollutants, primarily SO_2. As a result, while CO_2 reductions do lead to cooling in the longer term, modest warming will be seen for the first 1 ½ to 2 ½ decades following decarbonization absent additional targeted measures to reduce methane and other non-CO_2 greenhouse gases.

This is consistent with prior analyses showing that a realistic phaseout of fossil fuels avoids the large increase in warming seen in idealized instantaneous removal scenarios but can lead to minimal warming (Shindell and Smith 2019). When compared with the baseline projections in the SSPs rather than constant 2020 emissions, decarbonization leads to almost no near-term warming and greater cooling from 2040-2050, however. This is due to the assumptions in the baseline scenarios, which are that CO_2 emissions will increase (either weakly or strongly, depending upon the scenario) whereas sulfur dioxide emissions decline due to increased application of air pollution controls in all three SSP scenarios. This leads to a smaller warming from SO_2 reductions under decarbonization relative to the constant 2020 case since SO_2 is assumed to be declining anyway under the baseline scenario. It also leads to a greater impact of CO_2 reductions since they are declining from a higher baseline. Both these changes shift the effects of decarbonization towards more cooling. Note that this report has not exhaustively explored the projections of CO_2 and SO_2 but relies only upon the SSP scenarios, and as such the impact of decarbonization relative to the baseline projections do not necessarily encompass the full range of possibilities.

This analysis supports the conclusions of the GMA and other studies (e.g. Dreyfus et al. 2022; Allen et al. 2022; Shindell et al. 2017b; Jackson 2009; Daniel et al. 2012) that have both highlighted the distinct and complementary roles of actions targeting carbon dioxide/fossil fuel usage and those targeting short-lived climate pollutants such as methane and called for separate mitigation strategies and/or reporting.

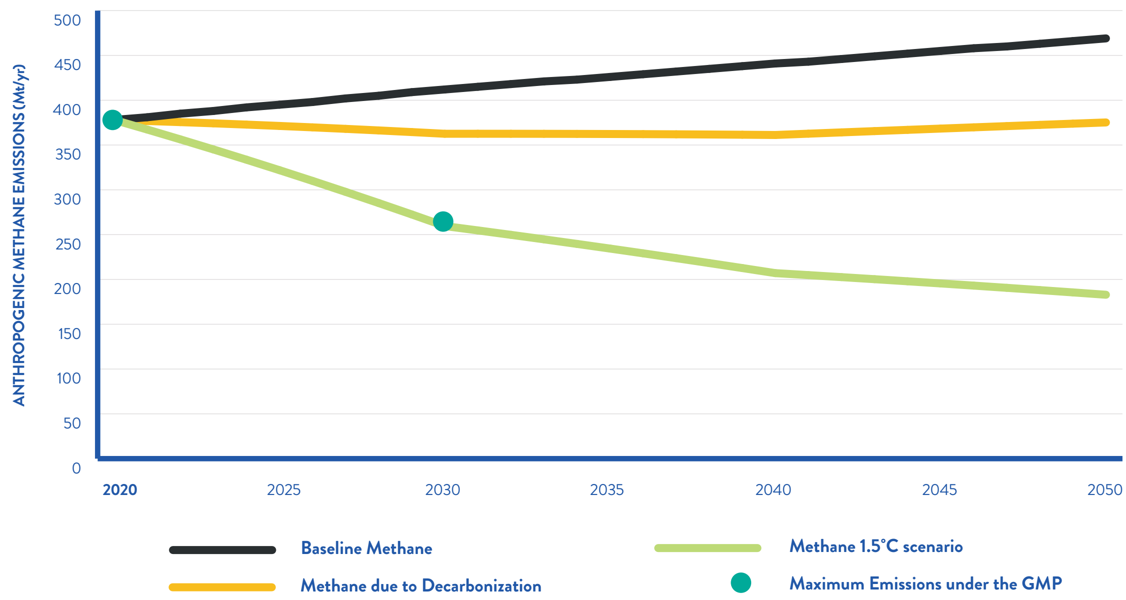


Figure 7. Methane emissions under the best estimate baseline projections (Section 3.2.2), under a deep decarbonization scenario phasing out fossil fuels, and under a full 1.5°C scenario. The turquoise dot shows an emission reduction of 30 per cent in 2030 relative to the 2020 value, the minimum target of the Global Methane Pledge.

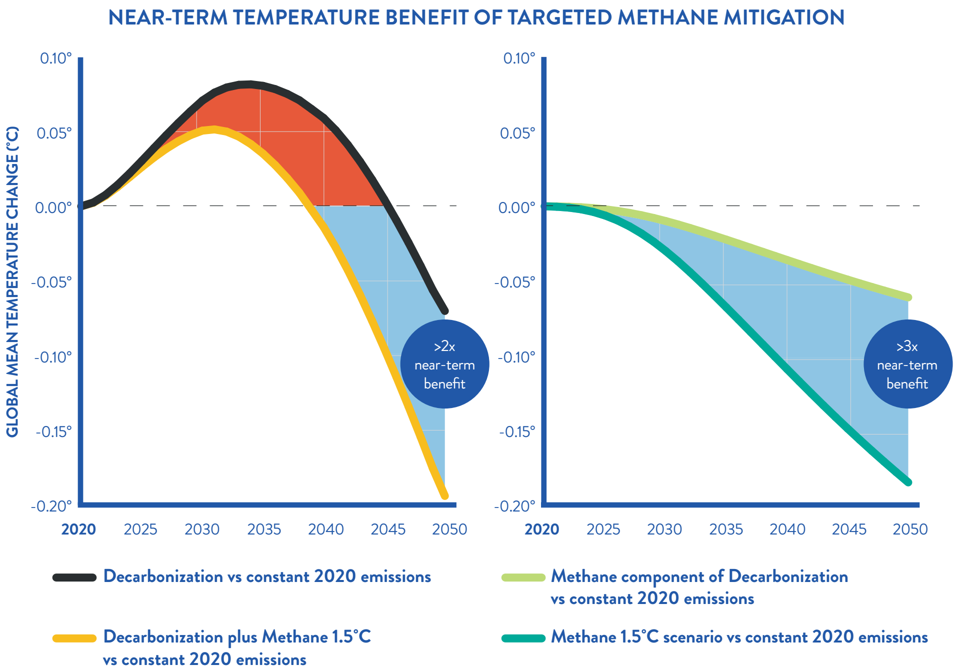


Figure 8. (Left) The climate response under a decarbonization scenario that phases out unabated fossil fuel use (black) compared to a decarbonization scenario plus targeted methane measures consistent with a 1.5°C scenario (orange). Note that the decarbonization scenario reduces all pollutants including some methane. (Right) The climate response to only the change in methane emissions under a decarbonization scenario (light green) compared to decarbonization plus targeted methane reductions consistent with 1.5°C (turquoise), all relative to constant 2020 emissions. Values are averages across IPCC Shared Socioeconomic Pathways (SSP) scenarios 1, 2 and 5.

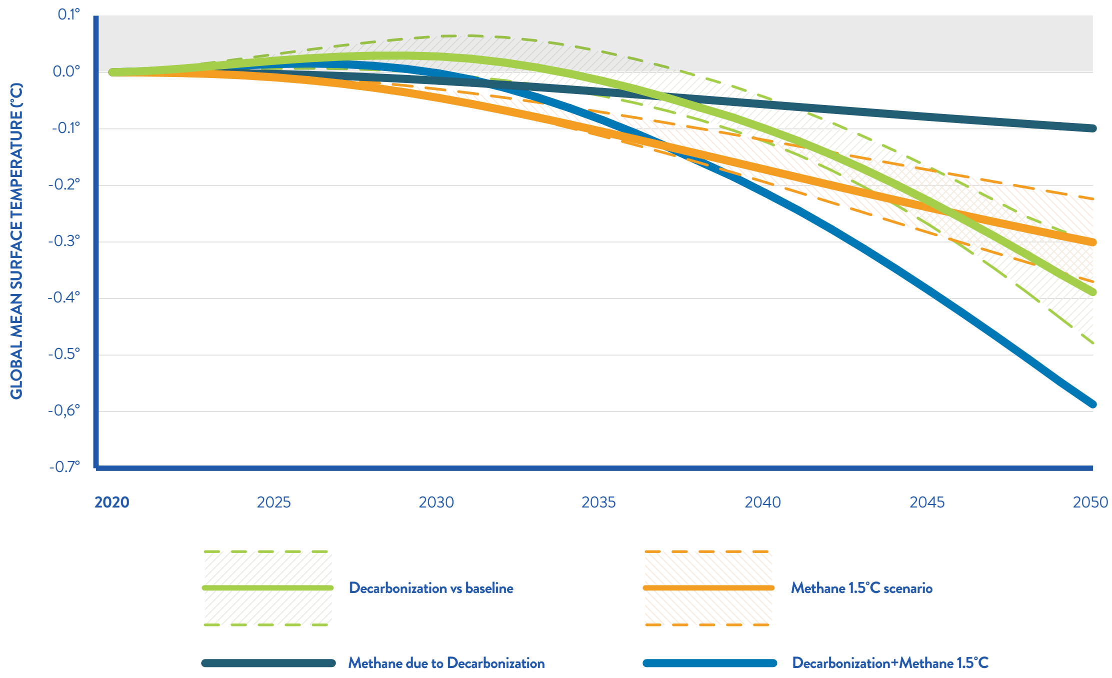


Figure 9. The climate response to all pollutants (including methane) under a decarbonization scenario (green), to methane alone under both decarbonization (blue) and a 1.5°C scenario, and to both decarbonization and methane under a 1.5°C scenario (orange) relative to the projected baseline changes. Solid lines show the averages across SSPs 1, 2 and 5 with dashed lines portraying the range across those three scenarios. Note that although the maximum effect of decarbonization exceeds the minimum effect of methane in the late 2030s such a comparison is unrealistic as the effects of both sets of pollutants vary systematically across these scenarios (i.e. the maximum should be compared with the maximum, the average with the average, and the minimum with the corresponding minimum).

DEFINITIONS/MODELS

EDGAR – Emissions Database for Global Atmospheric Research (EDGAR) is a global database of anthropogenic emissions of greenhouse gases and air pollution. https://edgar.jrc.ec.europa.eu/

CEDS – Community Emissions Data System (CEDS) inventory is a public open-source framework that produces annual historical emission estimates for anthropogenic aerosols, aerosol precursor and reactive compounds. http://www.globalchange.umd.edu/ceds/

ADVANCE – The Advanced Model Development and Validation for the Improved Analysis of Costs and Impacts of Mitigation Policies (ADVANCE) project. Available at: https://www.fp7-advance.eu/

NAVIGATE - Next Generation of Advanced Integrated Assessment Modelling to Support Climate Policy Making (NAVIGATE) project. Available at: https://www.navigate-h2020.eu/

ENGAGE - ENGAGE project. Available at: https://www.engage-climate.org/.

SSP Database (Shared Socioeconomic Pathways). Available at: https://iiasa.ac.at/models-and-data/iamc-15degc-scenario-explorer

GAINS – Greenhouse gas and Air pollutant INteractions and Synergies model. Available at: https://iiasa.ac.at/models-and-data/greenhouse-gas-and-air-pollution-interactions-and-synergies

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