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Trends of methane emissions and their impact on ozone concentrations at the European and Global levels

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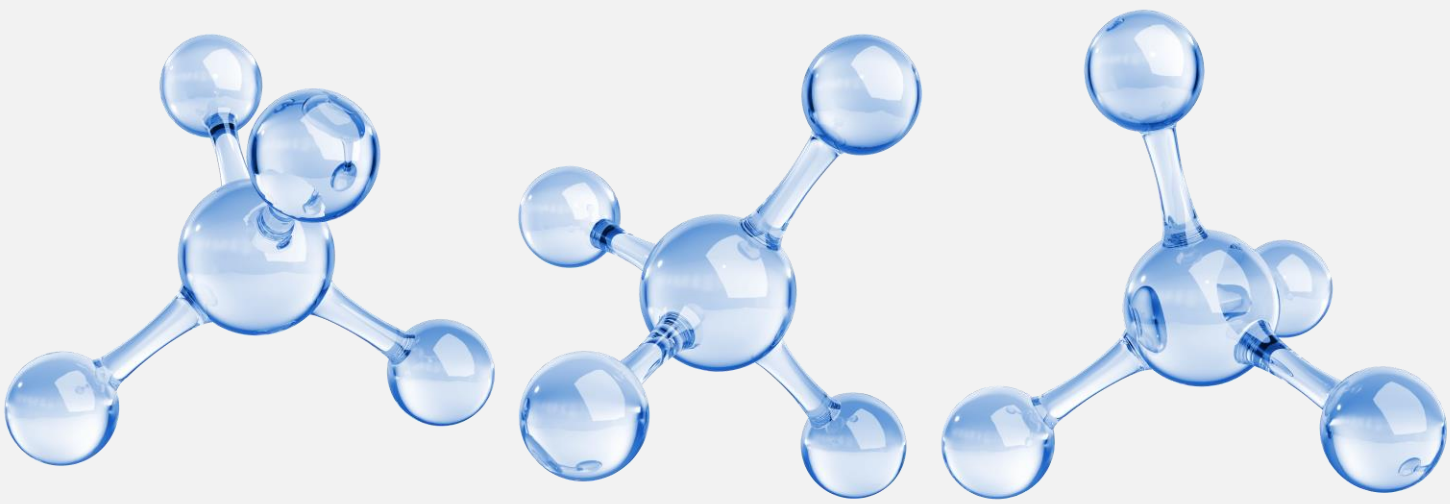

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Contents

Abstract

Methane is a potent greenhouse gas and as an air pollutant it contributes to tropospheric ozone formation, which is detrimental to health. About 60% of total global methane emissions stems from anthropogenic emissions, and about 40% from natural sources. In 2022, Europe contributed to 5.2% of the global anthropogenic methane emissions.

Satellites are now commonly used to track methane leakages from fossil fuel production sites, transmission systems, ships and distribution systems, which remain the largest source of uncertainties regarding emissions. Based on the U.S. National Oceanic and Atmospheric Administration (NOAA) global surface observation network, the concentration in 2017-2023, is close to the value of 1925 ppb and, by 2030, is projected to reach 1796 to 2099 ppb depending on which scenario is considered.

A significant proportion of European population is still exposed to concentrations of ozone that are near or above the target values set by the EU legislation and the WHO guidelines. Compared to 2015, the number of premature deaths associated to methane related background ozone in Europe in 2050 is projected to increase by 7000 to 8000 (68% to 78%) compared to 2015 for the high emission scenarios and decrease by 700 to 1700 (-7% to -16%) for the high mitigation scenarios.

Regarding impacts on agriculture and major crops, our results for the high emission scenarios, show global crop yield losses increasing by 13% to 16% in 2030 compared to 2015 and decreasing by 32% to 37% for the high mitigation scenarios.

The Global Methane Pledge (GMP) is a collectively voluntary commitment to reduce global anthropogenic methane emissions across all sectors by at least 30 percent below 2020 levels by 2030 that was launched at COP26 by the European Union and the United States. If all actions were implemented globally to their maximum technical mitigation potential, the emission reduction would be beyond the GMP goal. International cooperation engaging public and private bodies will be key to curb methane emissions and their impact on air quality. This report is intended to inform the implementation and monitoring of the EU strategy to reduce methane emissions (COM/2020/663), although it is not formally linked to the process.

Foreword

This study provides invaluable insights and actionable recommendations to guide efforts in combating climate change and improving air quality. Methane is a significant greenhouse gas with a global warming potential far exceeding that of carbon dioxide. It plays a pivotal role in both climate dynamics and air quality. As the second largest contributor to global warming after carbon dioxide (CO_2), methane has 80 times the climate-warming power of CO2 in the short term. Despite being responsible for over 40% of recent global warming, methane's shorter atmospheric lifespan of about 12 years makes it a prime target for rapid emission reduction, offering significant potential to quickly lower global temperatures.

Methane could be the emergency brake on global warming. This report leverages advanced models and recent emissions data to provide a comprehensive overview of global methane emissions, emphasizing their impact on health and crop yields through ozone formation.

Recent international developments have shown promising progress. The United States has introduced regulations to cut methane emissions by nearly 80% by 2038, while the European Union has enacted similar legislation targeting the fossil fuel industry. These steps are crucial as methane emissions from human activities are projected to rise by up to 13% between 2020 and 2030 if current trajectories continue. Methane emissions primarily stem from agriculture (42%), fossil fuel extraction (36%), and organic waste (18%). Notably, the energy sector has seen the most significant mitigation advances, particularly in regulating methane leaks from oil and gas extraction.

In Latin America, countries like Argentina, Colombia, and Ecuador are proactively regulating methane emissions from the energy sector. Collaborative efforts within the Latin American Energy Organization (OLADE) are addressing methane mitigation by state-owned oil companies. Technological advancements, such as satellite systems, are enhancing our ability to track and manage methane emissions, marking a new era of accountability.

This report highlights the continued exposure of populations to high ozone levels despite existing abatement measures, underscoring the importance of global cooperation and ambitious mitigation strategies. It critically evaluates current legislative frameworks and discusses the potential benefits of including methane in these regulations. The findings are clear: reducing methane emissions is essential not only for mitigating climate change but also for improving air quality and public health.

The Global Methane Pledge is a testament to the collective commitment required to tackle this issue. By reducing methane emissions, we can achieve substantial benefits for both climate and public health, demonstrating the dual benefits of these efforts. It is with great pride and a sense of urgency that we present this comprehensive study. We hope it serves as a catalyst for informed decision-making and inspires continued research and action in this vital field. Together, we can build a sustainable future for generations to come.

Sincerely,

Marcelo Mena

Head of Global Methane Hub

Former Environment Minister of Chile

Professor, Pontificia Universidad Católica de Valparaíso

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Executive summary

This report is an update of the first edition (Van Dingenen, et al., 2018) aimed to synthesizing the most recent advances on methane (CH_4) and its impact on ozone (O_3), based on JRC and external organisations' studies. It also reviews international developments concerning CH_4. Recent bibliography discussing the links between methane and ozone is reviewed and synthetized. EDGARv8 emissions are used to provide an overview of global scale emissions with a zoom on the main macro-regions. The TM5-FASST model has been run with the ECLIPSE V6b scenarios to obtain up-to-date impacts of methane-induced ozone on mortalities and crop yields.

Policy context

A proportion between 20% and 90% of the European population is still exposed to concentrations of O_3 that are near or above both the target values set by the Ambient Air Quality directive (2008) and the guidance levels provided by the World Health Organisation (World Health Organization, 2021; EEA, 2020). Air pollution abatement measures adopted to achieve the emission reduction commitments set in the European Union (EU) National Emission reduction Commitments Directive (NECD) and in the Gothenburg Protocol under the United Nations Economic Commission for Europe (UNECE) Air Convention, have achieved significant success, but risks to human health, agriculture and ecosystems due to O_3 and other pollutants continue to exist.

The main legislative instrument in the EU to achieve the 2030 objectives of the Clean Air Programme and the EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil is Directive 2016/2284/EU (EU, 2016) on the reduction of national emissions of certain atmospheric pollutants, which entered into force on 31 December 2016. It sets emission reduction commitments for five air pollutants with significant impacts on human health and the environment. However, methane, one of the key precursors to O_3 formation, is not amongst the regulated pollutants[1]. The Commission will evaluate the Directive by the end of 2025 and assess in this context to what extent not including methane has hampered reducing methane emissions (from agriculture, waste and energy) at EU and international level[2].

Methane is an important greenhouse gas (GHG) that has a 100-year global warming potential about 29 times larger than carbon dioxide (CO_2). Anthropogenic sources are mostly derived from the agriculture, energy and waste treatment activity sectors. Globally, concentrations of CH_4 continue to increase and enhance the greenhouse effect, by retaining infrared radiation (heat) within the lower atmosphere and therefore contributing to climate change. According to the sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC, 2021), in 2019 global temperature increased by 1.1°C. CH_4 has contributed by about 1/3 to the 1.5 warming by long lived GHGs, and other human drivers cooled the planet by 0.4°C. In comparison, natural (solar and volcanic) drivers changed global surface temperatures by -0.1°C to +0.1°C.

The Global Methane Pledge (GMP), launched at COP26 by the European Union and the United States[3], is a collective voluntary commitment to reduce global anthropogenic methane emissions across all sectors by at least 30 % below 2020 levels by 2030. At the COP27 in 2022, the EU confirmed (and reaffirmed at COP28) its commitment to reduce methane emissions by endorsing a 'Joint declaration on reducing greenhouse gas emissions from fossil fuels', together with the United States, Japan, Canada, Norway, Singapore, and the United Kingdom. At COP28, the EU became member of the newly launched Lowering Organic Waste Methane (LOW-Methane), a new initiative to jumpstart a scale-up of global action to cut methane emissions from the waste sector. The objective of the initiative is to contribute to the GMP by delivering at least 1 million metric tons of annual waste sector methane reductions well before 2030 working with 40 subnational jurisdictions and their national government counterparts. In 2020, the European Commission put forward a Methane strategy to reduce emissions focused on the energy, agriculture, waste and wastewater sectors. The European Parliament and Council have reached a provisional agreement in 2023 on a new EU Regulation to reduce methane emissions in the energy sector and in its supply chains[4]. Climate policies such as the Paris Agreement, are also an important means to reduce CH_4 emissions. Internationally, in the late 2000s the UNFCCC promoted Clean Development Mechanisms and Joint Implementation plans to reduce CH_4 emissions from venting and flaring in

[1] It was part of the Commission's legislative proposal but not retained in the final text agreed by the European Parliament and the Council.
[2] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13968-National-Emission-Reduction-Commitments-Directive-evaluation_en
[3] https://www.globalmethanepledge.org
[4] https://ec.europa.eu/commission/presscorner/detail/en/IP_23_5776

natural gas production, to promote the recovery of CH_4 from coalmines, and to control emissions from waste disposals.

Key conclusions

About 60% of the current global anthropogenic methane is emitted by sources like agriculture, landfills and wastewater, and the production and pipeline transport of fossil fuels, while ca. 40% is from natural sources. Wetlands are also an important source of methane particularly in a warming climate. Asia represents more than 50% of world methane emissions in 2022. Globally, CH_4 emissions and concentrations continue to increase, raising concerns for air quality and climate change.

A recent attribution work showed that methane currently contributes to 35% globally and to 41% of the Northern Hemisphere (about 37% in Europe) tropospheric ozone burden. This is more than any other source of reactive carbon. While ozone peaks have shaved off, baseline ozone levels are increasing, caused by the reduction of the NOx emissions and the increasing role of CH_4.

Methane exemplifies the role of Short-lived Climate forcers (SLCF) on both climate and air quality issues. Acting on the reduction of primary SLCF will be beneficial for both climate and air quality. At COP28, Global Methane Pledge (GMP) actors recommitted to cut methane emissions by at least 30 percent by 2030. In 2022, global anthropogenic methane emissions were about 400 Tg yr^{-1}. According to their associated ambition levels, methane scenarios would lead to emissions ranging between 100 and 900 Tg yr^{-1} by the end of the century with intermediate values between 150 to 650 Tg yr^{-1} by 2050. As methane has a shorter atmospheric lifetime than CO_2 (around 12 years), mitigation benefits will quickly materialize and slow the rate of atmospheric warming. This would help limiting dangerous climate feedback loops, such as the melting of the polar ice caps and sea level rise, while simultaneously delivering important health, environmental, and economic benefits by reducing ground-level ozone.

This report, building on evidence from observations and modelling, suggests that CH_4 emission reductions can play a key-role in further reducing O_3 in Europe and in the world. Since Europe's contribution to global CH_4 emissions is currently only about 5%, global cooperation to reduce CH_4 in countries and regions in- and outside of the EU, will also be essential to reduce related O_3 effects in Europe and the world.

The objective of the Lowering Organic Waste Methane (LOW-Methane) initiative to reduce 1 million tons of CH_4 emissions by 2030 (ca. 1% of the global CH_4 emissions from this sector) corresponds to approximately one thousand avoided premature deaths attributable to ozone exposure per year between 2025 and 2030.

Main findings

After a period of stagnation in the 1990s, CH_4 air concentrations increased during the last decades and may reach the pessimistic climate scenarios estimates for 2030 as presented in the IPCC AR6 report.

Waste related emissions could potentially increase by 70% to 130% in 2050 for the pessimistic scenarios and decrease by up to 80% for optimistic ones (relative to 2010). Alignment with sustainable development goals in developing countries may help to realise the most ambitious emission reductions.

In 2022, agriculture, fuel exploitation and waste represented 41%, 33% and 23% of the global anthropogenic CH_4 emissions, respectively, while in the EU the shares for the same sectors are 51%, 11% and 32%, respectively. According to IEA (IEA, 2023), almost 50% of the methane emissions from the energy sector could be mitigated at negative marginal costs. Compared to 2010, energy related emissions in 2050 could potentially increase by up to 70% (pessimistic scenarios) or decrease by 30-80% (optimistic scenarios). Lower energy consumption, fuel substitution, but also upgrading old gas and oil production and gas distribution infrastructure are important factors to consider.

Worldwide, an increase of at least 7% in the ozone related mortalities due to CH_4 emission would take place by 2050 even if the most stringent reduction scenarios are implemented while such increase is above 100% in the high emission scenarios. At the European scale, CH_4 -related O_3 mortalities would decrease by at least 7% in 2050 in the low emission scenarios and increase by at least 68% in the high emission ones.

Reduction of methane emissions also means less damage to crops (via ozone). By 2050, the crop yield loss (RYL) is expected to decrease by at least 27% (relative to 2015) at the global scale for the most optimistic scenarios, while an increase of at least 40% would be observed for the most pessimistic scenarios either in Europe or at global scale. While other vegetation types such as forests can likewise be affected by ozone, this was not analysed in this study. Since the benefits of CH_4 of emission reductions are globally distributed, global mitigation strategies are most effective in reaching substantial benefits within and outside individual world regions.

More work is needed to reduce the uncertainty of fugitive CH_4 emissions from fossil fuels extraction and use.

Related and future JRC work

JRC provides support to the Convention on Long-Range Transboundary Air Pollution and its Task Force on Hemispheric Transport of Air Pollution under the EMEP programme. JRC further keeps collaborating with and contributing to international organisations and initiatives (e.g. CLRTAP, AMAP, CCAC, IPCC, OECD, UN Environment, WHO, WMO[5]), to assess the benefits of reducing air pollutants and GHG emissions.

Quick guide

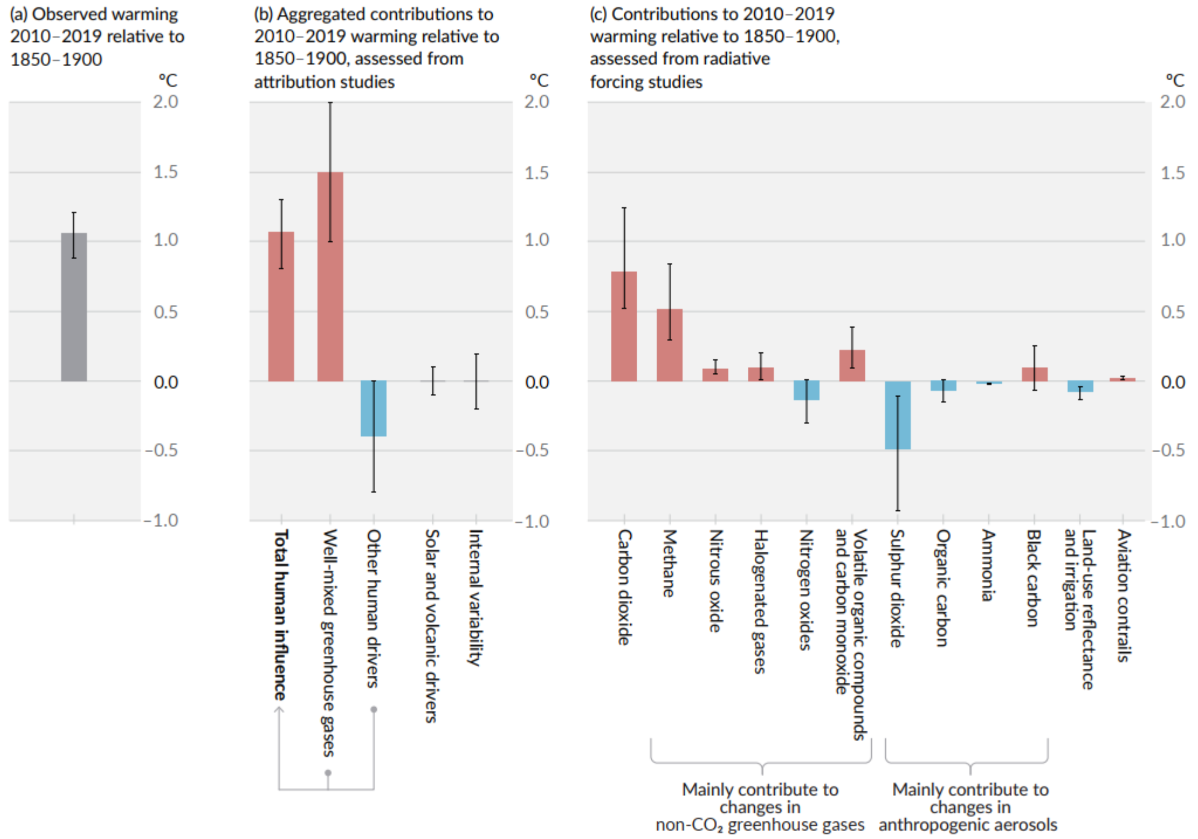
The report presents an overview of current knowledge on atmospheric methane and ozone concentration trends, anthropogenic emissions and emissions scenarios, with a focus on Europe. CH_4 emissions' influence on ozone concentrations and related impacts on health and crops are derived using the JRC's FAst Scenario Screening Tool (FASST).

[5] Check list of abbreviations and definitions

1 Introduction

Methane (CH_4) is a greenhouse gas as well as a precursor pollutant to tropospheric ozone (O_3). As a greenhouse gas (Figure 1) it is included in the basket of emissions under the Kyoto protocol and likewise in the Paris Agreement (UN, 2015).

Figure 1: Assessed contributions to observed warming in 2010–2019 relative to 1850–1900, Panel (a) Observed global warming (increase in global surface temperature). Whiskers show the very likely range. Panel (b) Evidence from attribution studies, which synthesize information from climate models and observations. The panel shows temperature change attributed to: total human influence; changes in well-mixed greenhouse gas concentrations; other human drivers due to aerosols, ozone and land-use change (land-use reflectance); solar and volcanic drivers; and internal climate variability. Whiskers show likely ranges. Panel (c) Evidence from the assessment of radiative forcing and climate sensitivity. The panel shows temperature changes from individual components of human influence: emissions of greenhouse gases, aerosols and their precursors; land-use changes (land-use reflectance and irrigation); and aviation contrails. Whiskers show very likely ranges. Estimates account for both direct emissions into the atmosphere and their effect, if any, on other climate drivers. For aerosols, both direct effects (through radiation) and indirect effects (through interactions with clouds) are considered.



Source: IPCC-WG1-Figure SP.2 (IPCC, 2021).

Regarding global warming potential, methane is about 28 and 82.5 times more efficient than carbon dioxide on a 100 and 20 year timescales, respectively (IPCC, 2021). In the atmosphere, CH_4 has a turnover time of about 10 years, resulting in a relatively homogeneous distribution around the globe. In November 2021, the United States, the European Union, and partners formally launched the Global Methane Pledge[6], an initiative to reduce global methane emissions to reach the 1.5°C climate target. Over 100 countries representing 70% of the global economy and nearly half of anthropogenic methane emissions now signed the pledge. While 60% of methane emissions are of anthropogenic origin, about one third of the methane in the atmosphere originates from wetlands.

[6] https://www.ccacoalition.org/resources/global-methane-pledge

CH_4 is the dominant anthropogenic volatile organic compound (VOC) contributing to O_3 formation in the global troposphere (Fiore et al., 2002). In the lowest part of the atmosphere, in regions where NO_x concentrations are sufficiently high, reactions of OH radicals with CH_4 and other substances lead to the production of O_3. Ozone is a strong oxidant and air pollutant damaging human health (Brunekreef and Holgate, 2002; Jerrett et al., 2009; Malley et al., 2017; Turner et al., 2016), ecosystems and agricultural crops (Fowler et al., 2009; Maas and Grennfelt, 2016; Mills et al., 2011; Pleijel et al., 2018), whilst also affecting climate (Myhre et al., 2017; Stevenson et al., 2013; Stevenson et al., 2006). Roughly 1 million people die prematurely every year because of exposure to tropospheric ozone, 24 thousands of which in the EU (UNEP and CCAC, 2021; EEA, 2020). According to the Global Methane Assessment[7], implementing solutions to reduce waste methane could avoid 45,000 deaths from ozone worldwide, 135,000 emergency room visits for asthma symptoms, 5 mega tonnes of crop losses, and 13 billion work hours lost per year. This is why the World Health Organization proposed more ambitious Air Quality Guideline (AQG) for O_3 with a 8-hourly averaged target of 100 µg m^{-3} (ca. 50 ppb) not to be exceeded by more than 3 times per year (World Health Organization, 2021). In contrast to short-lived precursors for tropospheric O_3 (NO_x, carbon monoxide, and non-methane VOCs), methane is fairly well-mixed in the atmosphere, and primarily affects global *background*[8] concentrations of O_3 (Dentener et al., 2005; Forster et al., 2007).

Managing methane emissions, through their impact on background surface O_3 concentrations, can therefore have a significant impact on air quality, human health and crop productivity. Its role as a surface O_3 precursor has been the topic of a host of studies, including the HTAP (Dentener, Keating, and Akimoto, 2010) report and (Wild et al., 2012). The concluded special issue of the scientific journal Atmospheric Chemistry and Physics[9] addressed various relevant aspects of hemispheric transport. These studies pointed to the increasingly important role of CH_4 in determining future O_3 concentrations. Adeleye and Tiwari (2024) recently highlighted the role of methane on infant mortality, through consistent findings from static and dynamic panel data techniques revealing that: methane emissions were correlated with higher mortality in EU.

This report updates a previous assessment (Van Dingenen et al., 2018) on the potential role for CH_4 emission reductions to further reduce O_3 in Europe. Given the hemispheric nature of O_3, CH_4 reduction in EU27 should be considered in the context of a broader hemispheric approach to cost-effective reduction of background concentrations.

Policy-relevant questions are:

- What is our current understanding of observed changes of CH_4 concentrations and background O_3, and modelling capacity to understand these changes?
- What is the current knowledge on the geographical distribution of CH_4 emissions and on the contributing sources?
- What are policy-relevant CH_4 emission scenarios until 2050 and how are they expected to contribute to O_3 concentrations in Europe and other parts of the world?
- What are the benefits to human health, crops and vegetation of CH_4 emission reductions in the EU alone, and through collaboration with other parties?

Which are the most promising economic sectors to effectively achieve CH_4 emission reductions?

[7] https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions
[8] Ozone concentrations in the absence of anthropogenic emissions, as determined by models. For instance global background ozone would be estimated assuming no global anthropogenic emissions. European background means the situation without European anthropogenic emissions.
[9] https://www.atmos-chem-phys.net/special_issue390.html

2 The global methane budget, trends, and changing background ozone

2.1 The global methane (CH_4) budget

Atmospheric methane (CH_4) is the second largest contributor, after CO_2, to the greenhouse effect. It globally contributes to about 19% of the direct anthropogenic radiative forcing of all long-lived greenhouse gases (IPCC, 2021). Currently, the UNFCCC GHG reporting system uses the GWP-100[10] value of 25, derived from the IPCC AR4 report (Forster et al., 2007). Using the most recent IPCC AR6 (IPCC, 2021) GWP-100 value of 29.8 for methane issued from fossil fuel and 27 when issued from the bio-gas industry would further increase the relative importance of CH_4 as a greenhouse gas. We use the latter values in this report.

Due to the intermediate atmospheric residence time of about 10 years, actions to reduce CH_4 emissions are considered to be an important tool to mitigate global warming in the short-term (Shindell et al., 2012; Shindell, Fuglestvedt, and Collins, 2017; Holmes, 2018). Furthermore, reductions in global CH_4 would have significant co-benefits for air quality, the topic of this report.

Simulations performed in a recent study (He et al., 2020) with optimized global emissions were used to capture the observed trend, variability, seasonal cycle, and other spatial pattern of methane emissions. The total global amount of CH_4 emissions, from both natural and anthropogenic sources, can be accurately determined from the combination of information on observed atmospheric CH_4 concentrations and on chemical destruction in the troposphere. It amounts to 580 ±34 Tg CH_4 yr^{-1} over the period 1980-2017. These simulations with different emission adjustments suggest that increasing methane emissions (mainly from agriculture, energy, and waste sectors) are compensated by increased sinks (mainly due to increases in OH levels[11]), leading to methane stabilization (with an imbalance of 5 Tg yr^{-1}) over the period 1999–2006. During the period 2007–2012, increased emissions were combined with stable sinks leading to increasing methane concentrations (with an imbalance of 14 Tg yr^{-1} for 2007–2017). Compared to 1999–2006, both the methane emissions and the sinks were larger during the period 2007–2017 (by 31 and 22 Tg yr^{-1}, respectively). In that study, the authors indicate that anthropogenic sources were likely the major contributors to the increasing methane after 2006.

Nisbet et al., (2023) discuss the unusualness of the recent CH_4 growth rates compared to the sudden changes during glacial-interglacial changes. The rapid growth observed since 2006 is unprecedented in observational records, and may be an early sign of a rapid transition to a new climate state. They suggest that natural biogenic processes, in particular wetland emissions play an important but poorly quantified role. Larger wetland emissions may impede on the Paris Agreement objective to limit climate change to 1.5 C above pre-industrial. From the IPCC AR6 Cross Chapter Box 5.2 (IPCC, 2021), overall scientific evidence based on surface concentration, carbon-isotope measurements, satellite and inverse modelling, shows that multi-decadal trends in CH_4 concentrations are dominated by multi-decadal trends in fossil fuel anthropogenic emissions and agriculture (livestock), whereas inter-annual variability is dominated by the El Niño-Southern Oscillation (ENSO) and variations in OH levels.

The complex interplay of processes involved in the methane chemistry has been highlighted in a recent study that explains the large CH_4 increase in 2020 during the COVID period (Peng et al., 2022). They attribute this methane growth rate anomaly to lower OH sinks (53 ± 10 %) caused by lower NOx emissions and higher natural methane emissions (47 ± 16 %), mostly from wetlands. In line with previous findings, the results imply that wetland methane emissions are sensitive to a warmer and wetter climate and could further exacerbate methane emissions and hence global warming. Overall, the methane growth rate remains subject of research, with sometimes contrasting conclusions. Recently the dual role of wetland has been highlighted (Li et al., 2024), showing that the radiative forcing of methane emissions from wetlands could completely offset the net carbon dioxide uptake in a temperate freshwater marsh.

Anthropogenic sources contribute around 60% of the total CH_4 concentration (section 3). While inverse models, that combine information derived from observations, emissions, and atmospheric transport, can determine total emissions, they cannot separate the natural from the anthropogenic fractions on a regional basis. Uncertainties

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[10] GWP is the Global Warming Potential used to describe the relative per molecule potency of a greenhouse gas, taking account how long it remains active in the atmosphere (here on 100 years basis)

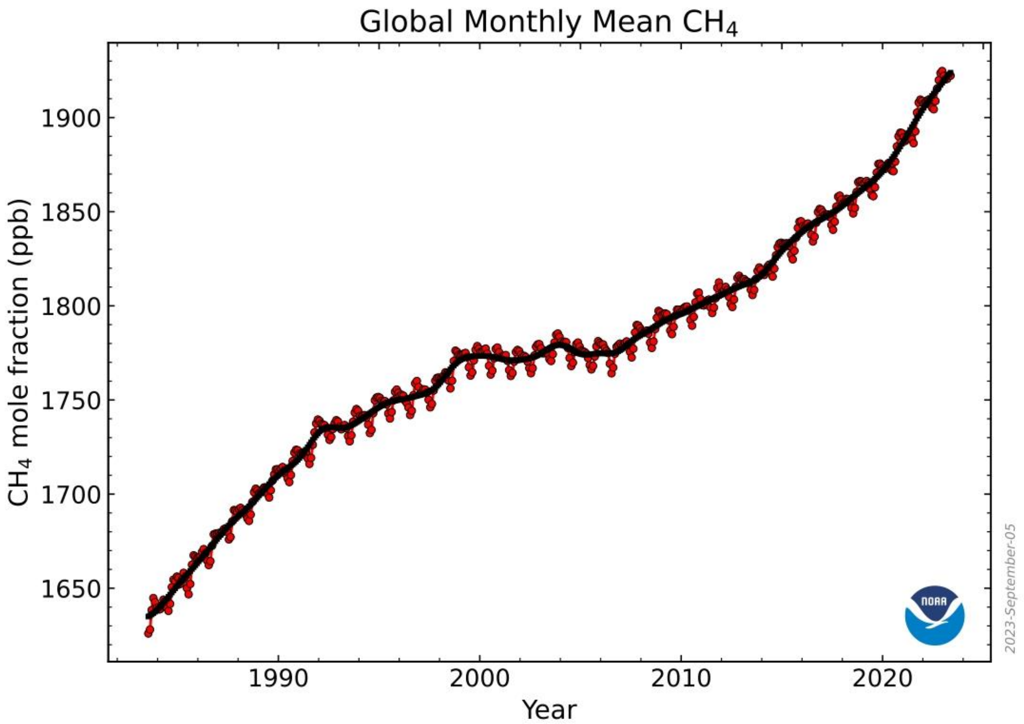
[11] The OH radical is produced by reactions linked with the chemistry of nitrogen oxides in the presence of light. The oxidation of CH_4 by the OH radical involves several steps which ultimately lead to the production of CO_2 and other pollutants (e.g. aldehydes, peroxides and/or ozone).

therefore remain regarding the estimate of this regional anthropogenic fraction.

2.2 Observationally derived CH_4 trends

Global CH_4 concentrations have increased, with varying rates, from 722 ppb in pre-industrial period to 1850 ppb by the end of 2017, corresponding to an average rate of increase of 4.3 ppb yr^{-1}. Direct measurements of atmospheric CH_4 showed a large increase during the 1980s of almost 12 ppb yr^{-1}, a slower increase during the 1990s of about 6 ppb yr^{-1} and a stabilisation between 1999 and 2006. Since 2007, CH_4 concentrations have risen again significantly with a growth rate of about 6 ppb yr^{-1} in 2007-2013 (Dlugokencky et al., 2009) and accelerating to 10 ppb yr^{-1} during 2014-2018 as shown in Figure 2. According to NOAA, the concentration in 2017-2023 is close to 1925 ppb, a value that most of the scenarios projected for 2030 (scenario values range from 1796 to 2099 ppb). The main explanation for the increase in the recent years is still not fully understood.

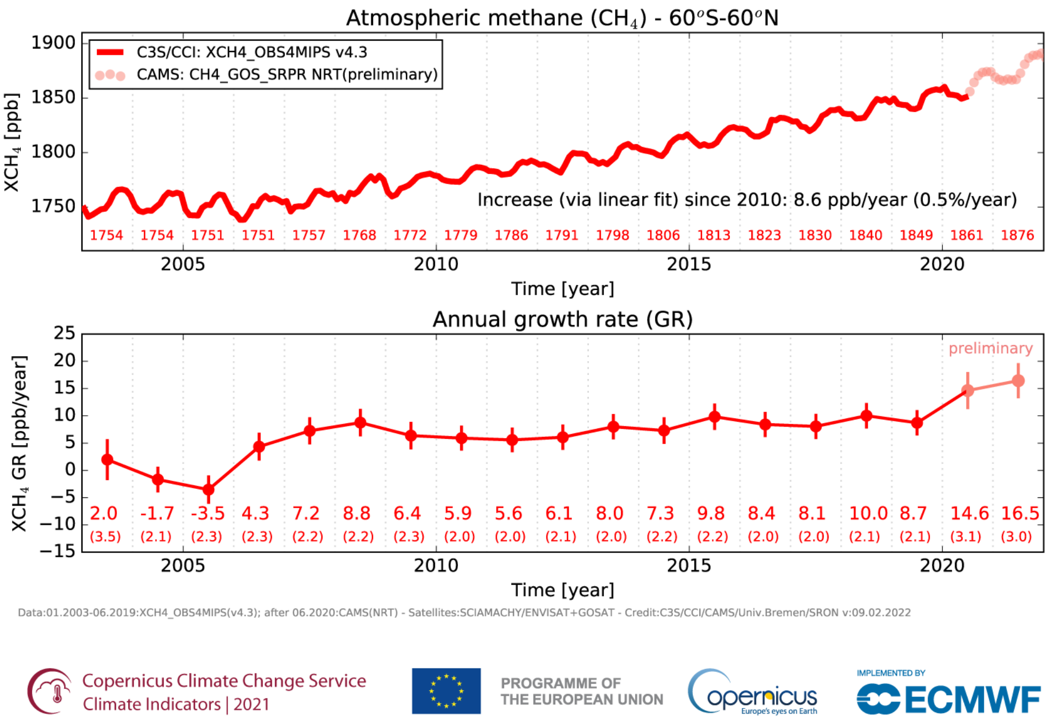
Figure 2: Atmospheric methane measured as"dry air mole fraction" in ppb. The red dots are globally averaged monthly mean values, whereas the black line shows the long-term trend through a 12-month running mean (removing the average seasonal cycle).



Source: https://gml.noaa.gov/ccgg/trends_ch4 downloaded in November 2023.

As a complementary source of data, the Copernicus Atmospheric Monitoring Services (CAMS) provides satellites measures of methane throughout the entire depth of the atmosphere and cover the whole globe (Figure 3); however, their data are currently less accurate than in situ measurements even though the global trend is similar to NOAA.

Figure 3: Global trends of methane mixing ratio. *Monthly global column-averaged methane (XCH4) concentration from satellites (top panel) and derived annual mean growth rate (bottom panel) for 2003 2021. Bottom: The listed numerical values correspond to the growth rate including an uncertainty estimate in parentheses.*



Source: CAMS service (https://atmosphere.copernicus.eu).

There are multiple observation-based evidences that suggest the important role of the increasing anthropogenic fossil fuels emissions, as well as the agriculture, waste, or natural tropical wetland emissions to explain the recent methane trend. Studies using isotope signatures (Schwietzke et al., 2016) and ethane to propane ratios (Dalsøren et al., 2018) suggest that fossil fuel related emissions, e.g. from coal, oil and gas production and distribution may contribute substantially to recent increases in methane concentrations. However, the ethane-to-methane ratios vary greatly among different oil and gas sources, rendering these estimates uncertain. The high uncertainties associated to fossil-fuel related CH_4 emissions were highlighted in the US. Based on aircraft measurements, Alvarez et al., (2018) estimated the emissions of oil and natural gas supply to 13±2 Tg CH_4 yr^{-1} , i.e. to 60% more than US EPA estimates.

In contrast, Nisbet et al. (2016), Schaefer et al. (2016) and Saunois et al. (2017) point to the role of the increased biogenic CH_4 emissions (tropical wetlands, and agriculture). Worden et al., (2017). Bottom-up emission inventories are highly uncertain, in particular for fugitive emissions from fossil fuels. It is therefore imperative that the current observational capacity for CH_4 concentrations is maintained (Houweling et al., 2012) to explain the recent CH_4 trends and inform both climate and air pollution policies.

The role of methane in relation to Hydrogen (H_2) production and use, is expected to be a key instrument to meet climate neutrality by 2050. Renewable hydrogen deployment is expected to significantly reduce EU greenhouse gas (GHG) emissions by displacing carbon-intensive sources of energy. Concerns have, however, been raised regarding the potential indirect global warming impact of hydrogen emissions. Although hydrogen is neither intentionally emitted to the atmosphere during usage, nor a direct greenhouse gas, hydrogen losses indirectly affect atmospheric chemistry and contribute to global warming. A renewable hydrogen economy would significantly reduce the global warming impact compared to a fossil fuel economy. However, hydrogen losses to the atmosphere will impact the lifetime of other greenhouse gases, like methane, ozone, and water vapour, indirectly contributing to the increase of the Earth's temperature in the near-term (Arrigoni and Dravo Diaz, 2022; Hauglustaine et al., 2022; Bauer et al., 2022; Turner et al., 2017; Howarth and Jacobson, 2021).

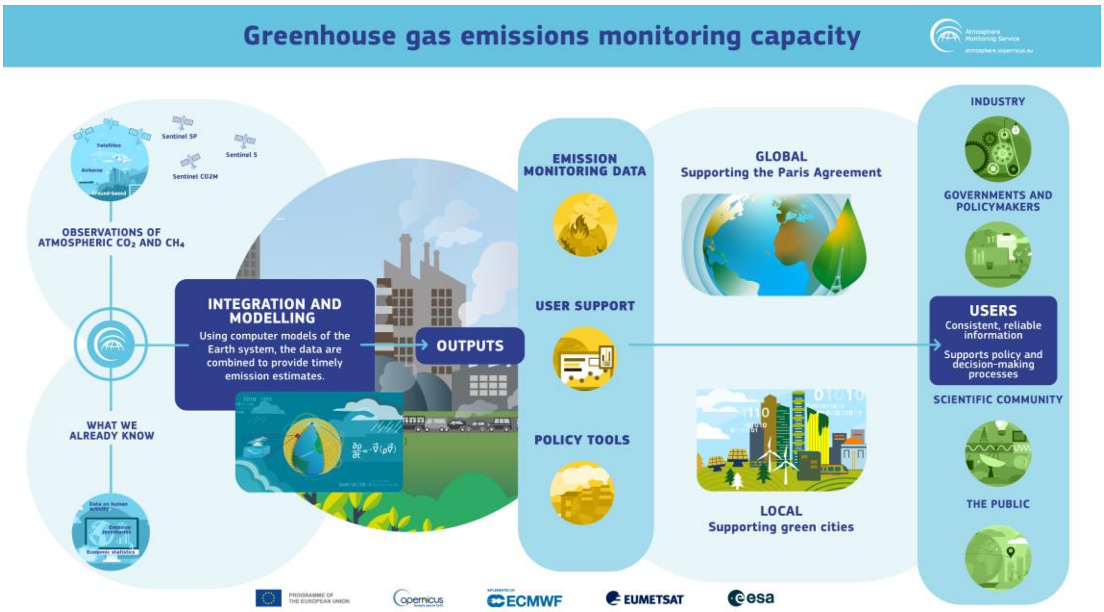
2.3 Policy framework and initiatives at the global and EU level

This section provides an overview of several initiatives launched or invigorated from the COP26 including those at the EU level. At the end of the 28th UN Climate Change Conference (COP28), the European Union and world leaders recommitted to delivering the Paris Agreement goals to limit the global average temperature increase to 1.5 °C. They agreed to accelerate emission reductions towards net zero by 2050, with urgent actions in this critical decade. This includes transitioning away from fossil fuels and reducing global GHGs emissions by 43% with an objective of 30% methane emission reductions, by 2030. One of the key commitments announced by the EU and its member states at COP28 was to propose €175 Million of financial support to reduce methane emissions.

Moreover, in December 2023[12], in the frame of UNECE (United Nations Economic Commission for Europe), the Air Convention parties adopted new guidance on co-mitigation of methane and ammonia emissions from agricultural sources (accounting for around half of anthropogenic methane emissions) and technical measures for reducing methane emissions from landfill, from natural gas grid and from biogas facilities. They highlighted the co-benefit of agriculture measures targeting methane and ammonia, beneficial to both climate and air quality.

The Global Methane Pledge[13] (GMP) was launched at COP26 by the European Union and the United States. Participants joining the Pledge agreed to take voluntary actions to contribute to a collective effort to reduce global methane emissions at least by 30 % by 2030 (from 2020 levels). With currently 158 parties, representing more than 50% of the global anthropogenic methane emissions, expectations are high to reach the Pledge goals. Following the Paris Agreement, CAMS, supported by the European Commission, proposed a transparent system to monitor and report emissions. This system is now being extended towards a global monitoring and verification support capacity for anthropogenic CO_2 and CH_4 emissions (CO_2MVS), using the complementarity between observations and models (Figure 4).

Figure 4: The GHG emissions monitoring chain developed by CAMS.



Source: https://atmosphere.copernicus.eu/ghg-services#expanding-cams-services-portofolio.

Meeting the GMP would reduce methane emissions to a level consistent with the 1.5°C pathway while delivering significant benefits to human and ecosystem health, food security and to our economies. It has the potential to reduce global warming by at least 0.2 °C by 2050 and prevent, annually, 26 million tons of crop losses, 255,000

[12] https://unece.org/media/press/386648
[13] https://www.globalmethanepledge.org

premature deaths, 775 thousand asthma-related hospitalizations and 73 billion hours of lost labour due to extreme heat.

The Lowering Organic Waste Methane ("LOW-Methane") initiative was launched at COP28, by a coalition of international partners, including the EU, to cut methane emissions from the waste sector and contribute to the achievement of the Global Methane Pledge[14]. LOW-Methane aims at supporting action across the waste value chain, from reducing food loss and waste, to diverting, treating and valorising organic waste, in line with the waste hierarchy. Initial LOW-Methane jurisdictions intending to participate include Lagos, Rio de Janeiro, and Santiago, with the intention to extend the initiative in a first stage to Chile, Dominican Republic and Indonesia. The purpose of LOW-Methane is also to boost equity and create healthier communities.

The Global Methane Hub[15] is a philanthropic organization dedicated to reducing methane emissions. Last year, the Hub was a donor to the Climate and Clean Air Coalition (CCAC) in an effort to financially assist 30 countries with developing plans to reduce their methane emissions. These plans include technical support to estimate emissions, identify mitigation options, and design policies to meet these goals. In addition, through this initiative, the Hub supports and funds technical experts on methane to be embedded in ministries to increase capacity in the long term. Since its launching, the organization has raised over $300 million, including $200 million that is managed as part of a pooled fund for more than 20 of the largest climate philanthropic organizations to reduce methane emissions. As connectors, funders, and educators in the methane space, the Hub's commitment to the Global Methane Pledge aligns with the CCAC's approach to achieve the pledge's goals.

Another initiative, the Global Methane Initiative[16] (GMI) is an international public-private partnership focused on reducing barriers to the recovery and use of methane as a valuable energy source. GMI provides technical support to deploy methane-to-energy projects around the world that enable Partner Countries to launch methane recovery and use projects. GMI focuses on three key sectors: Oil and Gas, Biogas, and Coal Mines. The GMI missions are among others to: identify opportunities for emissions reductions, foster best practices and effective policies, share technical resources and strategies, increase capacity and skills to address methane and host webinars and events.

The UNEP initiative International Methane Emissions Observatory (IMEO) aims to deliver a step-change improvement across research, reporting and regulation and to convey this information to individuals who see urgency to reduce methane emissions. IMEO provides open reliable actionable data to individuals who act to reduce methane emissions (150 Mt by 2030). OGMP2.0, launched managed by IMEO, is a voluntary methane emissions reporting partnership for oil and gas companies that has gained a lot of traction globally.

According to a recent report of the Climate Policy Initiative[17], the annual financing dedicated to abate methane emissions has moved in the right direction since the launch of the Global Methane Pledge, with an increase of 18% in 2021/2022 compared to 2019/2020. The new funding scheme from the Methane Finance Sprint catalyses this progress by providing technical assistance to national methane planning and policy actions.

EU Methane Strategy

In October 2020 the EU adopted a strategy[18] to reduce methane emissions (Methane Strategy) focused on actions within the EU and internationally in the energy, agricultural, waste and wastewater sectors. The energy sector is the only one for which new legislation is foreseen deriving directly from this strategy while it promotes the creation of an expert group to analyse life-cycle methane emissions metrics in the agricultural sector. The EU regulation on methane emissions reduction in the energy sector was adopted on 27 May 2024. The Methane Strategy also supports the production of biogas in the waste sector and the use of the digestate as fertiliser, in line with the 2017 Communication on *The role of waste-to-energy in the circular economy*. This approach is further supported in the Biomethane Action Plan under REPowerEU, to also address the energy autonomy issue. To improve the reliability of estimations the strategy promotes the establishment of an independent international methane emissions observatory. Moreover, the strategy envisages an enhanced international

[14] https://www.globalmethanepledge.org/news/lowering-organic-waste-methane-initiative-low-methane
[15] https://www.globalmethanehub.org/
[16] https://www.globalmethane.org/
[17] https://www.climatepolicyinitiative.org/publication/landscape-of-methane-abatement-finance-2023/#:~:text=The%20average%20annual%20methane%20abatement,48%20billion%20annually%20by%202030
[18] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0663

cooperation through the EU participation in the Climate and Clean Air Coalition (CCAC), the Arctic Council and the Association of Southeast Asian Nations (ASEAN).

In November 2023, a deal was achieved on a new EU regulation to reduce methane emissions from the energy sector both in Europe and its global supply chains. The EU aims to reduce avoidable methane releases and minimise methane leaks by fossil energy companies[19] by: (i) controlling and quantifying methane emissions, (ii) obliging stakeholders to carry out regular surveys of their equipment to detect and repair methane leaks, (iii) banning routine venting and flaring by the oil and gas sectors and restricts non-routine venting and flaring, (iv) limiting venting from thermal coal mines from 2027, with stricter conditions kicking in after 2031, (v) asking to companies in the oil, gas and coal sectors to carry out an inventory of closed, inactive, plugged and abandoned assets. This regulation establishes a methane transparency database where data on methane emissions, reported by importers and EU operators, will be made available to the public. The European Commission should establish methane performance profiles for countries and companies to allow importers to make informed choices on their energy imports. The Commission will also put in place a global methane emitters monitoring tool and a rapid alert mechanism for super-emitting events, with information on the magnitude, recurrence and location of high methane-emitting sources both within and outside the EU. As part of this tool, the Commission will be able to request prompt information on action to address these leaks by the countries concerned. As of January 2027, the Regulation requires that new import contracts for oil, gas and coal be only concluded when similar monitoring, reporting and verification obligations are in place for exporters or EU producers. The Regulation will set out a methane intensity methodology and maximum levels to be met for new contracts for oil, gas and coal.

The Biomethane Action Plan, that was launched in May 2022 as part of the REPowerEU plan[20], is another pillar of the EU action to curb methane emissions. The strategy aims at expanding the production of biomethane (mainly from waste and residues) to reach 35 billion cubic meters in 2030 by promoting industrial partnerships, accelerating investments and reducing production costs.

2.4 Ozone trends and links to methane

CH_4 and O_3 are connected through large-scale atmospheric chemistry and transport processes. In Section 2.4.1 we present the observational evidence for worldwide and European O_3 trends. Increasing CH_4 concentrations may partly contribute to these increasing trends or, in regions where O_3 declines due to local-to-regional air pollutant emission reductions, counteract these efforts. Models (section 2.4.2) are used to attribute trends in O_3 to specific sources. Concepts often used in this context are background O_3 - a hypothetical O_3 concentration calculated by models, where the absence of anthropogenic sources is assumed. Baseline O_3 refers to observed O_3 concentrations not directly influenced by recently emitted or produced pollution, but including further away influences. Once a long-lived substance is emitted in the atmosphere, it takes about one month to be mixed across the Northern Hemisphere, and about 1 year between the Northern and Southern Hemisphere. Therefore, ozone with a turn-over time of about 22 days, is subject to intercontinental transport, and CH_4 (10 years) is globally mixed.

2.4.1 O_3 observations and trends

Comparison of O_3 observations at the end of the 20th century with earlier data indicates that over the last century, surface O_3 in Europe increased by more than a factor of 2 (IPCC AR5; Hartmann et al., 2013). Only nineteen predominantly rural surface global datasets have long-term records that stretch back to the 1970s. 11 out of 13 Northern Hemispheric observation sites had statistically significant positive trends of 1 to 5 ppb per decade, equivalent to a more than doubling of the O_3 concentration since the 1950s (IPCC AR5 WG1:Myhre et al., 2013). Between 1960 and 2000, O_3 increases amounted to 14 ppb, 10 ppb between 1970-2000 and 5 ppb for 1990-2000.

Recently, the Tropospheric Ozone Assessment Report (IPCC, 2021) identified and evaluated 60 records of surface ozone observations collected at rural locations worldwide between 1896 and 1975, which were based on a range of measurement techniques with potentially large uncertainties (Tarasick et al., 2019). They found that from the mid-20th century (1930s to the early 1970s) to 1990–2014, rural surface ozone annual averages increased by 30–70% across the northern extra-tropics (above 30°N). This is smaller than the 100% increase

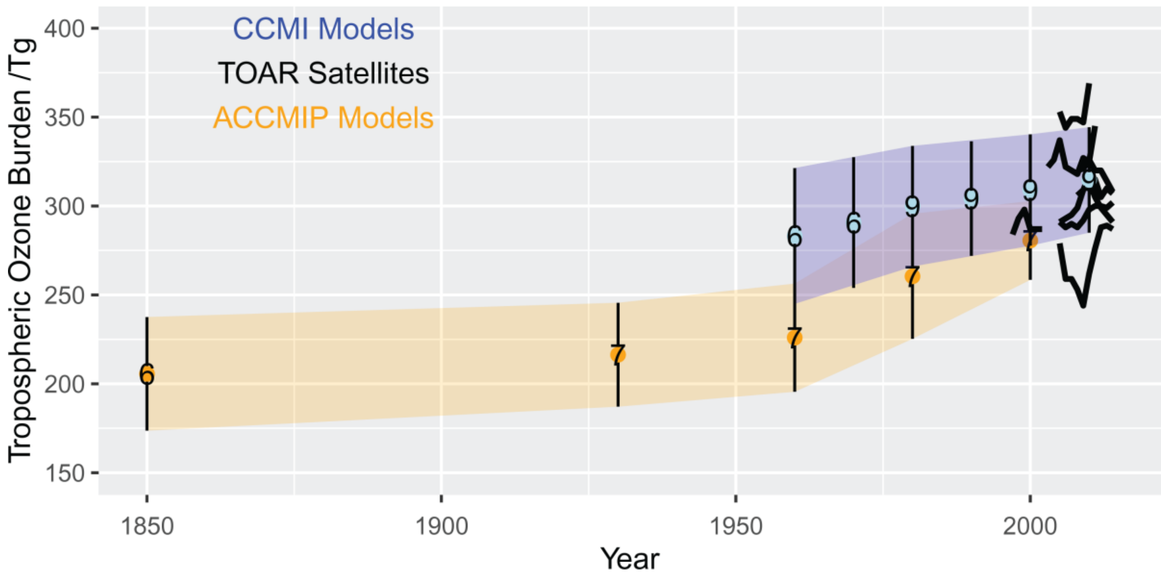
[19] https://ec.europa.eu/commission/presscorner/detail/en/IP_23_5776
[20] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022SC0230&from=EN

reported over the 20th-century in AR5, which relied on far fewer measurement sites, all in Europe. In the northern tropics limited low-elevation historical data (1954–1975) provide no clear indication of surface ozone increases (Tarasick et al., 2019). However, similar to the northern mid-latitude increases, lower-free tropospheric ozone at Mauna Loa, Hawaii increased by approximately 50% from the late 1950s to present (Cooper et al., 2020).

Overall the picture emerges that in Europe and Northern America, declining surface O_3 trends in summer are largely compensated by increasing trends in winter (Gaudel et al., 2018). According to Paoletti et al., (2014), ground-level ozone levels are usually lower in urban centres than nearby rural sites. Comparing trends in O_3 levels during the period 1990–2010, they obtained monitoring data from paired urban and rural sites from the European Environment Agency and the US Environmental Protection Agency. Ozone peaks decreased at both station types, with no significant differences between urban and rural stations whereas annual averages increased at both urban and rural sites, with a faster rate of increase for urban centres. Ozone levels exceeded the criteria established for the protection of human and vegetation health at both urban and rural sites.

In Southeast Asia, significant increases in local NOx emissions are the reason for the increase in tropospheric ozone, especially those from ground transportation and international shipping. Indeed, increasing NOx emissions enhance the efficiency of ozone production by interacting with VOCs (Li, Yang, et al., 2023).

Figure 5: Comparison of modelled (orange and blue envelopes) and satellite-observed (gray envelope) trends in the tropospheric ozone burden between 60°N and 60°S. Means of the model data are shown as circles with the vertical lines reflecting ±1 standard deviation of the mean. The number of models used in calculating the means are displayed in the circles. TOAR Satellites i the range of satellite tropospheric ozone burden estimates.



Source: Archibald et al., 2020.

The Tropospheric Ozone Assessment Report (TOAR) satellite data and model simulations from the IGAC and Climate Model Intercomparison Project and Chemistry Climate Modelling Initiative were analysed (Archibald et al., 2020) to assess the changes in the tropospheric ozone burden and its budget from 1850 to 2010. Analysis of these data indicates that there has been significant growth in the ozone burden from 1850 to 2000 (approximately 43 ± 9%) but smaller growth between 1960 and 2000 (approximately 16 ± 10%) and that the models simulate burdens of ozone well within recent satellite estimates (Figure 5).

2.4.2 Model attribution of O_3 trends to CH_4 emissions

To what extent can models be used to understand ozone trends and the contribution of CH_4 to them?

Global atmospheric chemistry transport models (ACTMs) are used to simulate past, current and future ozone concentrations. Regional model over limited areas can also be used but they require an adequate management of boundary conditions provided by global models. These models ingest spatially resolved emission information, and typically include coarse spatial resolutions up to 1°x1° longitude-latitude, parameterised descriptions of meteorology and atmospheric transport, oxidation chemistry, and removal processes by wet and dry deposition.

Of particular importance for the ozone budget and concentration variability, is the stratosphere-troposphere exchange of ozone, which is subject to large variability and is yet highly uncertain.

A modelling analysis of the evolution of tropospheric ozone through the 21st century by Archibald et al. (2020), in the context of the Climate Model Intercomparison Project Phase 5 reveals large uncertainty associated to the way models simulate the chemical and physical processes that control tropospheric ozone. This processes uncertainty dominates in the short-term (two to three decades) whereas uncertainties related to emission scenarios dominate in the longer-term (2050–2100).

Using the best available information on air pollutant and CH_4 emission trends, the changes in annual O_3 calculated by a set of HTAP1 global models (Wild et al., 2012), can only explain 30-50% of the observed surface ozone trends from the 1960s to the 2000s (compare to Cooper et al., 2014). However, differences in trends tend to get less in the more recent decades. Indeed regional and global models and observations (supported by an expanded network and better spatial coverage) all indicate relatively constant annual ozone concentrations since the 2000s (Colette et al., 2017).

To what extent can the O_3 trends be attributed to CH_4 emissions?

Ozone is produced by the interaction of sunlight with emissions of nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC) and CH_4. In addition, a substantial part (15-20%) of tropospheric ozone is transported from the stratosphere. Our knowledge of the degradation chemistry of CH_4 and resulting ozone production is based on many decennia of laboratory, field studies and modelling of a rather uncomplicated chemistry of which the mechanisms are well understood. Nevertheless, the interactions with NO_x and VOC degradation chemistry, and the resulting radical levels, lead to an uncertainty of ca. 50% on CH_4 induced O_3 changes over 40 years as calculated by multiple models (Wild et al., 2012). The atmospheric chemistry of ozone is a strongly buffered system: increases in ozone production from rising NO_x, VOC, or CH_4 emissions, are counteracted by enhanced ozone destruction and shortened ozone lifetimes. The amount of buffering varies among models, and is subject to uncertainty. Model studies indicated that ca. 55% of the ozone budget increase since the pre-industrial era can be attributed to NO_x, ca. 25% to CH_4, and 19% to CO and VOCs (Wang and Jacob, 1998). Attribution of ozone changes to sources is useful to understand past changes and assess the potential to reduce concentrations. The most frequently used technique to assess the potential of emission reductions to control tropospheric O_3 is to use moderate perturbations (10%-20%) of precursor emissions across different emission sectors.

Using this method, the HTAP1 multi-model analysis (Fiore et al., 2009) showed an annual mean O_3 reduction of 1.1 to 1.3 ppb averaged over the regions of North America, Europe, South Asia and East Asia, for a 20% decrease in global CH_4 concentrations. These O_3 reductions can be compared to regionally and seasonally highly variable surface O_3 observations- ranging from monthly average of 20-35 ppb in winter, and 40-55 ppb in summer (Fiore et al., 2009). Based on these results, and consistent with earlier estimates, they also estimated that currently all anthropogenic CH_4 emissions have contributed to 5.5 – 6.5 ppb or 20% of the overall ozone concentration increase[21] since the pre-industrial era. Wild et al., (2012) attributed ca. 1.8 ppb of O_3 increase in Europe to global CH_4 emissions trends from 1960-2000. This is about 35% of the overall *modelled* annual O_3 trend in this period and less than 15% of the long-term annual trends *observed* at several surface sites (see above). About 20-40% of the O_3 trends derived from long-term night-time[22] mountain top observations (Gaudel et al., 2018), representative for changes in the free-troposphere. Therefore, although observations do not provide strong indications on the contribution of CH_4 to O_3 trends, they also do not contradict the model-estimated contributions from CH_4 to O_3 trends.

A recent contribution (Butler, Lupascu, and Nalam, 2020) using a novel attribution tagging technique, showed that NOx emissions from international shipping over the high seas play a disproportionately large role in the model system regarding the hemispheric-scale response of surface ozone to changes in methane. In all regions, they also found that local precursor emissions have a smaller impact on annual average ozone than the combined effect of precursor emissions from the rest of the world. According to these authors, methane

[21] Early observations are difficult to interpret and provide not enough coverage to provide a tropospheric average. Northern mid-latitude surface ozone increases from pre-industrial to the 2000s computed by models are about 20 ppb.

[22] Night-time trends at mountain tops are determined by downward flows from the free troposphere, and are therefore more representative for large scale O_3 changes. CH_4 is expected to exert its influence mostly on these large scales. Of the 8 sites analysed in (Gaudel et al., 2018), 6 sites have time-series starting in the 70s-90s. Of these 6 sites, 5 display positive trends, and 1 negative. Trends differ over seasons.

contributes to 35% of the tropospheric ozone burden (integrated mass over the vertical and horizontal spatial scales) and to 41 % of the Northern Hemisphere annual average surface mixing ratio.

Given the expected increases of CH_4 (Turner, Frankenberg, and Kort, 2019), Derwent et al. (2023) concludes that background ozone concentrations in the northern hemisphere would be increasingly influenced by interactions between CH4 and NOx emissions from international shipping that are is expected to decrease only at a low pace. Future work should investigate the ozone production via the interaction of these two sources in more detail.

What is the impact of CH_4 on O_3 policy responses?

Fiore et al., (2002) estimated that reducing global CH_4 emissions by 50% would almost halve the occurrence of high ozone events in the US. Such measure is therefore highly relevant for attaining air quality standards. By combining modelled ozone concentrations with health-impact relationships, West et al. (2006) demonstrated that about 30,000 premature deaths per year would be saved globally from a 20% reduction in anthropogenic CH_4 emissions. Methane emission reductions have also been identified as an efficient method to reduce crop yield losses that occur with ozone concentrations above 30-40 ppb (West and Fiore, 2005). In Chapter 4 of this report, we use the most recent epidemiological evidence to provide updated information compared to the previous version of this report (Van Dingenen, et al., 2018).

While methane-related damages to climate and human health, measured as the Social Cost of Methane (Shindell, Fuglestvedt, and Collins, 2017), have been analysed by different studies and considered by government rulemaking in the last decades, methane-related damages to crop revenues associated to ozone have not been incorporated to the policy agenda. Using a combination of the Global Change Analysis Model and the TM5-FASST Scenario Screening Tool, Sampedro et al. (2023) estimate that global marginal agricultural damages range between ~ 423 and 556 \$2010/t-CH4, of which 98 \$2010/t-CH_4 occur in the USA, followed by China, EU-15, and India. These damages would represent 39–59% of the climate damages and 28–64% of the human health damages associated with methane emissions, according to this study. The marginal damages to crop revenues calculated in this study complement the damages from methane to climate and human health, and provides valuable information to be considered in future cost-benefits analyses.

In conclusion, policy actions addressing methane within Europe but also in North America and Asia are required to reduce future exceedances of the O_3 air quality standards and guidelines because of the important contributions from intercontinental O_3 transport (Derwent et al., 2021; Parrish, Derwent, and Staehelin, 2021; Derwent et al., 2023; Derwent and Parrish, 2022). Derwent et al. (2023) found that in addition to reactive VOCs already targeted by emission reductions, other VOCs play an important role in intercontinental O_3 transport.

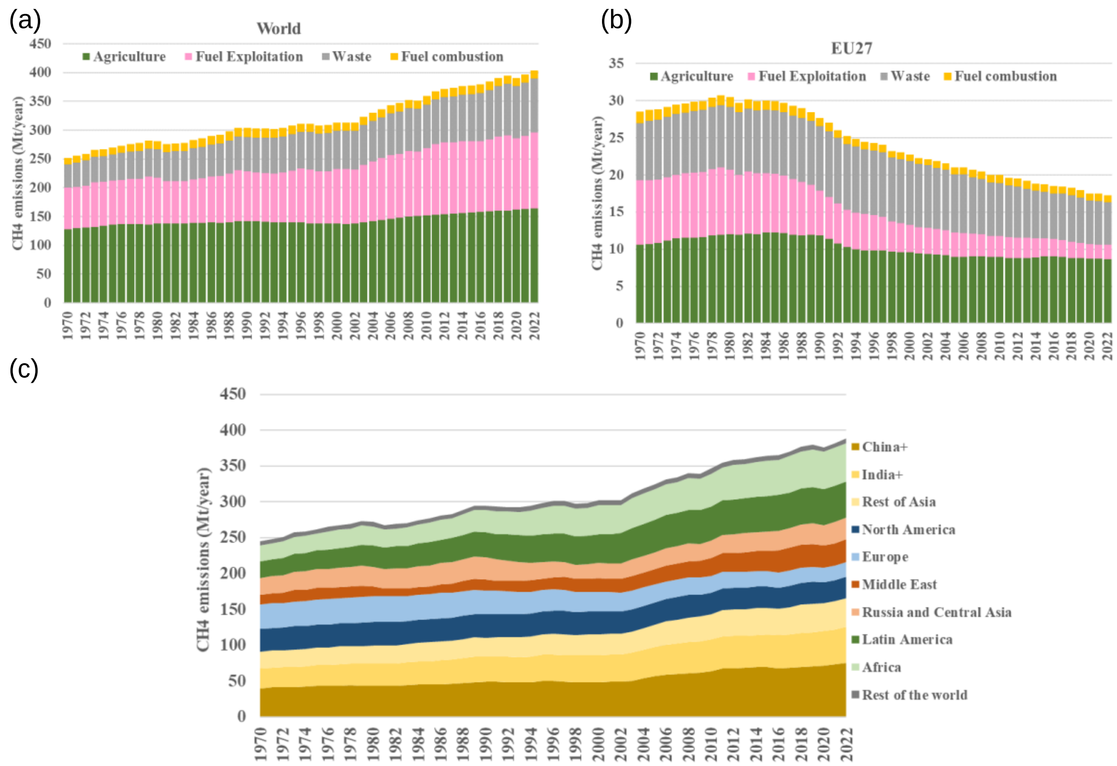
3 Trends of anthropogenic CH_4 emissions

In section 3.1, we use the European Commission's EDGAR (https://edgar.jrc.ec.europa.eu/) global air pollution and greenhouse gas emission database to show the changes of regional and global anthropogenic CH_4 emissions over the last five decades, and the growing contribution from new economies to global methane emissions (Figure 6). In Annex 2 , we discuss the sectoral break-down of CH_4 emissions and in Annex 3 are described the RCPs scenarios (Representative Concentration Pathway) used in the IPCC AR5 (Fifth Assessment Report of the Intergovernmental Panel on Climate Change) assessment, as well as 3 marker scenarios (Shared Socioeconomic Pathways as SSPs) that support the IPCC AR6 (Sixth Assessment Report of the Intergovernmental Panel on Climate Change) assessment and scenarios from the European Commissions' Global Energy and Climate Outlook 2022 (Keramidas et al., 2022).

3.1 Past CH_4 emissions

In our analysis, we use EDGARv8.0[23][24] (Crippa et al., 2023) CH_4 emission time series covering the years 1970-2022 (Figure 6) that provide consistent emission estimates for all countries worldwide. Based on international statistics and a consistent IPCC methodology, EDGAR provides emission estimates that are independent from emissions reported by European Member States or by Parties under the United Nations Framework Convention on Climate Change (UNFCCC). Details on the emission methodologies in EDGAR are provided in Annex 1.

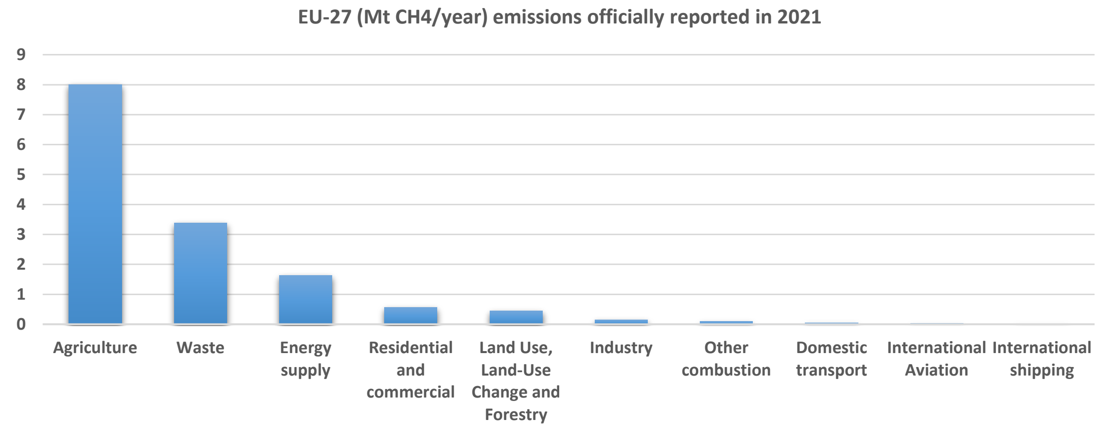
Figure 6: Methane emissions (Mt CH_4 yr^{-1}): (a) global, (b) EU27, (c) by world region.



Source EDGAR V8.0.

[23] ©European Union 2023, European Commission, Joint Research Centre (JRC), EDGAR (Emissions Database for Global Atmospheric Research) Community GHG database, comprising IEA-EDGAR CO2, EDGAR CH4, EDGAR N2O and EDGAR F-gases version 8.0 (2023). Unless otherwise noted, all material owned by the European Union is licensed under the Creative Commons Attribution 4.0 International (CC BY 4.0) licence. This means that reuse is allowed, provided that appropriate credit is given and any changes are indicated.
[24] https://edgar.jrc.ec.europa.eu/ . Full documentation of this database is summarised in Annex 1.

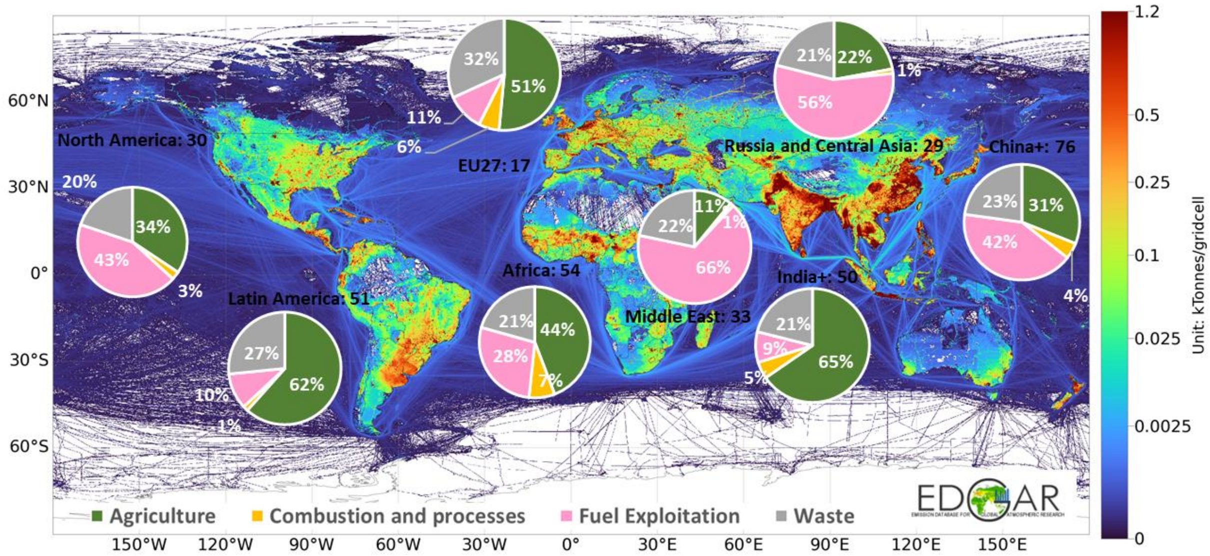
Figure 7: EU27 methane emissions (Mt CH_4 $year^{-1}$) in 2021 officially reported.



Source: JRC elaboration based on EEA data.

For EU27, the official (EEA[25]) CH_4 emissions from agriculture, energy and waste sum up to 13 Mt $year^{-1}$ (Figure 7) while EDGAR estimates it to around 17 Mt $year^{-1}$.

Figure 8: Global CH_4 emissions in 2022 with sector specific shares and regional total emissions (Mt=Tg) for major world regions. Definition of EDGAR sectors is given in Annex 1



Source: EDGARv8.0.

Global emission shares in 2022 for agriculture, fuel exploitation and waste (Figure 8) are 41%, 33% and 23%, respectively, with large regional differences, as discussed below.

Table 1 provides an overview of the global share of methane emissions by macro-regions in 2022, with Asia representing more than 50% of them.

[25] https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer

Table 1: CH_4 emissions (Tg CH_4 yr^{-1}) and shares (%) by region for EDGAR8.0 in 2022.

	CH_4 emission	Share of the global total
China + (Eastern Asia)	75.9	19.5%
Africa	53.5	13.8%
Latin America	50.9	13.1%
India + (Southern Asia)	49.7	12.8%
Rest of Asia	40.3	10.4%
Middle East	32.7	8.4%
North America	29.7	7.6%
Russia and Central Asia	29.3	7.5%
Europe	20.2	5.2%
Oceania	5.7	1.5%
Int. Shipping	0.5	0.1%
Int. Aviation	0.003	<0.1%

Source: EDGARv8.0.

Anthropogenic CH_4 (Figure 6) is mainly released from the agricultural sector (enteric fermentation, manure management, waste burning and rice paddies); from the fuel exploitation sector (venting of CH_4 during oil and gas production, and diffusive processes such as coal mine leakage, and gas distribution losses), and landfills and wastewater (Annex 1). According to EDGAR, global anthropogenic CH_4 emissions increased by 32% between 1990-2022, compared to a 71% increase in fossil CO_2 emissions. CH_4 emissions showed increasing trends over the past decades although with different yearly rates. CH_4 emissions increased by 11% (or 1.02% yr^{-1}) from 252 to 280 Tg CH_4 yr^{-1} between 1970 and 1980, by 8.6% (or 0.78% yr^{-1}) from 280 to 304 Tg yr^{-1} over the period 1980-1990, by 2.9% (or 0.26% yr^{-1}) from 304 to 313 Tg CH_4 yr^{-1} between 1990-2000, by 15% (or 1.33% yr^{-1}) from 313 to 359 Tg CH_4 yr^{-1} between 2000-2010 and by 12% (or 0.95% yr^{-1}) from 359 to 403 Tg CH_4 yr^{-1} between 2010 and 2022. The latter numbers are consistent with the global estimates provided by Saunois et al. (2020) (see synthesis in section 3).

3.1.1 Europe, USA and other OECD countries

At EU27 level, the CH_4 emission shares in EDGAR in 2022 for agriculture, fossil fuel exploitation (including production and transmission) and waste (including solid waste wastewater treatment) were 51%, 11% and 32%, respectively (Figure 8). CH_4 emissions decreased in average by 0.7% yr^{-1} between 1970-2022. The largest reduction is for the fuel exploitation sector, which fugitive emissions decreased by 68% over the 1990-2022 period. In particular, CH_4 fugitive emissions from coal extraction decreased by 83% over that period, while the gas component reduced only by 26%, given the increase of the gas distribution sector emissions (+25%). CH_4 emissions from the oil exploitation sector also decreased by 45%. In particular, Germany considerably reduced its coal mining activities, leading to an estimated 90% reduction in its fugitive emissions in 2022 compared to 1990. The waste sector emissions reduced by 34%, in particular landfill (49%). This is in part a direct effect of the more stringent operation of landfills and separation of waste due to the implementation of the EU's landfill directive since the 1990s. CH_4 agricultural emissions reduced by 27%.

In contrast, in the USA, CH_4 emissions decreased by just 0.4% yr^{-1}, over the same period 1990-2022. As in Europe, landfill emissions also substantially declined in the USA, but emissions from fossil fuel production did not. Despite declining coal mining activities, increasing emissions from shale oil and gas exploration, in particular since 2007, have more than compensated for the emission reductions from the coal sector. Note that emissions from abandoned coal mines and oil and gas wells could represent significant levels of emissions. Kholod et al. (2020) estimated that abandoned mines could account for almost one fifth of the worldwide coal production methane emissions. These emissions are not included in the Global Methane Tracker since existing measurements cover a limited number of facilities and regions, and reliable data on abandoned mines and wells is not available for most countries.

Unlike the USA and EU27, CH_4 emissions in the remaining OECD countries increased by 0.5% yr^{-1} over the period 1990-2022. The three dominant sectors for the 24 industrialised countries of the OECD[26] were in 1990 enteric fermentation (29%), fossil fuel production (27%) and waste (30%).

3.1.2 Russia, China and India and other countries in transition

In 2022, China+ dominates the global share of CH_4 emissions whereas International Shipping and Aviation represents less than 0.1% (Table 1). Russia's CH_4 emissions are dominated by fossil fuel production and distribution (61%), followed by waste (26%) and agriculture (12%). Due to the 3.7-fold increase of the natural gas production activity and two-fold increase in oil production, Russian CH_4 emissions showed a strong increase in the period 1970-1989, followed by a decrease during 1989-1998 but picking up again from 1998 onwards. Expansion of the pipeline network led to increasing fugitive emissions from the gas transmission pipelines (about 20% of the total gas emissions) and from gas distribution networks (about 30%). Since the 1990s, natural gas production increased, but investments were made to improve the pipeline infrastructure. Russian CH_4 emission trends were further influenced by the reduction of the enteric fermentation emissions due to a halving of the cattle stock between 1990 and 2000 and a 1.5-fold CH_4 emission increase from landfills between 2000 and 2012.

China+ is the largest and yet growing emitter of CH_4 in the world. In 2022, emissions are dominated by fuel exploitation (42%), agriculture (31%) and waste (22%). The single most important agricultural sector is rice cultivation, with 19% of the total emissions or 14 Tg CH_4 yr^{-1}. This is almost three times more than in India (4 Tg CH_4 yr^{-1} or 14%), despite 40% more land being used. This difference is explained by different management practices and production systems. While India typically has one harvest per year from around one-third rain-fed fields and two-thirds irrigated fields, China+'s production is more intensive with two harvests per year from irrigated rice fields and an overall 30% higher production. Note that continuously irrigated rice fields emit almost twice as much CH_4 as rain-fed fields. CH_4 China+ emissions doubled from 1970 to 2022, predominantly due to a 7-fold increase of the coal production emissions, partially compensated by a reduction of the rice cultivation emissions by 32% (introduction of higher yielding and lower emitting rice varieties). Xu, Zheng, and Wu (2024) confirm the major role of rice cultivation as the primary contributor to the overall increase in national CH_4 emissions, particularly after 2014, while CH_4 emissions from other sources have decreased. Economic activity is the key driver of rising methane emissions, although emission intensity tends to decrease as a result of improved farm management practices.

India + is a CH_4 emitter of growing world importance with emissions dominated by agriculture (65%), waste (21%) and fuel exploitation (9%). Agricultural emissions are dominated by enteric fermentation (44% of the Indian total), and rice cultivation (14%). A moderate increase in total CH_4 emissions from 1970 to 2022 is predominantly due to the 68% increase of the enteric fermentation emissions, partially compensated by a 16% reduction of the rice cultivation emissions, similarly to China+.

Other developing countries show as largest share the enteric fermentation and fuel exploitation sectors, with relevant contributions from rice cultivation and domestic wastewater treatment. Emissions from enteric fermentation from African (21 Tg CH_4 yr^{-1}) and Latin-American (29 Tg CH_4 yr^{-1}) countries contribute each by around 19% and 26% to the global enteric fermentation emissions of 112 Tg CH_4 yr^{-1}. Remarkably, enteric fermentation emissions in Brazil more than tripled during the period 1970-2022. In contrast to Latin America, fuel exploitation in Africa is also a significant contributor to the total emissions (28%). Interestingly, both continents show significant emissions from charcoal production in the transformation industry sector with 24% (Africa) and 12% (Latin America) of their total gas and oil production emissions. These emissions have large reduction potentials.

3.2 Sectoral break-down of anthropogenic CH_4 emissions.

The main sectors contributing to CH_4 emissions globally are: a) agriculture, fugitive emissions from fuel production, b) transport by pipelines and other energy industries and c) solid waste and waste water emissions. In this section we summarize the emission of the main sectors. A more exhaustive description is provided in Annex 2.

[26]OECD countries in 1990: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.

Global CH_4 emissions from the agricultural sector as a whole were 164 Tg CH_4 yr^{-1} (or 42% of the global anthropogenic total) in 2022, with contributions from agricultural soils (primarily rice production) amounting to 37 Tg CH_4 yr^{-1} or 9% of the global total, and livestock (including both enteric fermentation and manure management) to 125 Tg CH_4 yr^{-1} or 32%. Livestock is a dominant source of GHG emissions. In the EU27, enteric fermentation is responsible for about 74% of the agricultural CH_4 emissions.

Global fugitive methane emissions from fossil fuel production and transmission amounted to 132 Tg CH_4 yr^{-1} in 2022, representing 33% of the estimated global total anthropogenic CH_4 emissions. An increase from charcoal production in the transformation industry (1.3% of global CH_4 emissions) is seen in particular in African countries and China, where emissions more than doubled (factor 2.3) over the period 1970-2022. Methane can be trapped underground when organic strata are converted over time into coal. Fugitive emissions may therefore occur during mining operations and venting as part of normal safety operations. Flaring is widely used by the fossil fuel industry to dispose of natural gas but this practice is considered inefficient.

Solid waste and waste water CH_4 emissions globally amount to 93 Tg CH_4 yr^1 (or 23% of the global total) in 2022. Landfills emissions decreased by 40% in EU27 from 1970 to 2022, in particular in Germany, Great Britain and the Netherlands. Over the same time period, they reduced similarly in the USA, while they strongly increased in China, India, Middle East, Russia and Turkey.

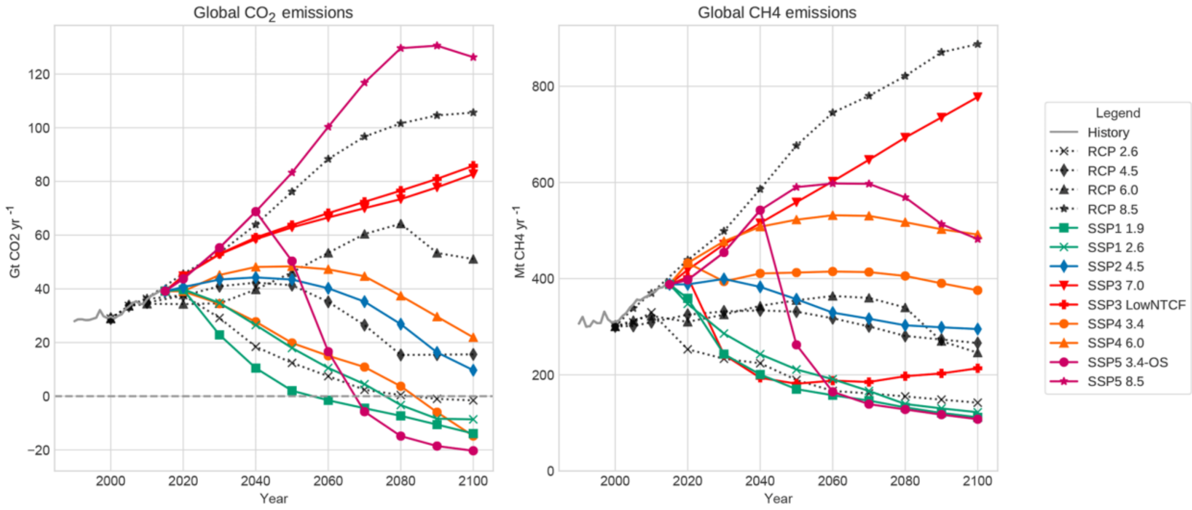
Other sources of CH_4 are production processes of chemicals, iron and steel, the manufacturing industry, fossil fuel fires (*e.g.* Kuwait fires), transformation industry and ground transport (road, inland shipping, and rail) residential and other sectors. In 2022, these sectors amount to 21 Tg CH_4 yr^{-1} (or 5% of the global total of which 3% from the residential sector).

3.3 Future CH_4 emissions

Future methane emissions will depend on a range of economic, technological, societal and political developments. Gidden et al. (2019) provide an overview of various pathways (Figure 9) where methane and CO_2 emissions by the end of the century, show a large span across scenarios. These can be grouped in (1): those showing a consistent downward trajectory (SSP1, SSP4-3.4), (2) those that peak in a given year and then decrease in magnitude (SSP2-4.5 in 2040 and SSP4-6.0 in 2050), and those that show a consistent growth (SSP3). The SSP5 scenarios, mimicking a fossil-fuel-driven world bound the scenario set, with the highest emissions for SSP5-8.5 that peak in 2080. Trajectories differ between CO_2 and CH_4 emissions. For instance, SSP4 3.4 shows an increase of the emissions until 2050 whereas a decrease is observed for CO_2 emissions starting from 2020.

Although we focus here on anthropogenic sources of methane, we must keep in mind that 40% of methane emissions remain natural and these emissions could also increase in the future due to climate change. The main non-anthropogenic sources of methane emissions are associated with bacterial activity in oxygen deficit environments like freshwater bodies and wetlands. A recent study shows that methane emissions from the biosphere, rise strongly as a reaction to climate warming, thus leading to atmospheric methane concentrations substantially higher than assumed in the scenarios used for CMIP6 Climate Model Intercomparison Project 6 in support to the UNFCCC negotiations.

Figure 9: Trajectories of CH_4 and CO_2 emissions for various scenarios in the frame of the modelling exercise CMIP6.



Source: Gidden et al., 2019.

Natural emissions could become larger than anthropogenic ones in many scenarios (Kleinen et al., 2021; Peng et al., 2022). In a warming climate, methane stored in permafrost, peatlands, lakes, shallow seas and sediments could be an additional emission flux in the atmosphere (Glikson, 2018; Fewster et al., 2022).

We provide in section 3.3.1 an overview of available mitigation options in several key-sectors. In section 3.3.2, we select and discuss a range of scenarios to explore possible methane trajectories.

3.3.1 Mitigation potentials

Table 2 provides an overview of technological control measures in a number of key-sectors, based on the recent assessment of sectoral CH_4 emission reduction potentials provided by the Arctic Monitoring and Assessment (AMAP) Report (AMAP, 2015), and EDGAR data. Mitigation options can be separated into two broad sets: reduced production/consumption characterised by less energy, less waste, and less animal/crops, and improved efficiency via technological control measures.

The 476 methane-focussed mitigation actions within the 168 NDCs (Nationally Determined Contributions) have been analysed by a recent study, targeted to countries and sectors emitting approximately 40% of the global methane (Malley et al., 2023). If all mitigation actions were implemented to their maximum technical potential, global emissions would reduce by ~31%. Behavioural measures, such as dietary shifts and reduction in waste generation would come with additional benefits. In Annex 2, all NDC measures are reported.

Table 2: Technically feasible control measures for CH_4 emissions in a number of key-sectors.

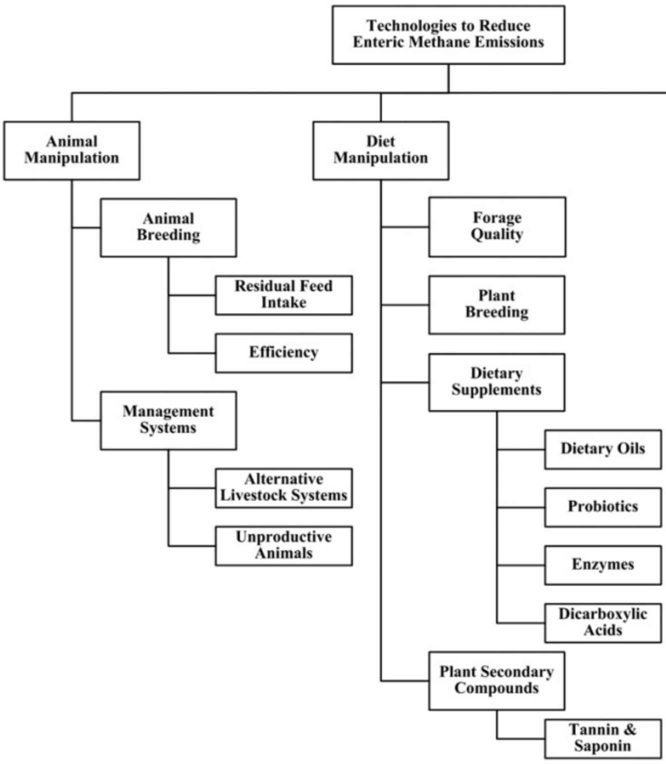
Sector	Control measure
Livestock	Enteric fermentation: diet changes, vaccination
	Improving animal health and productivity: genetic improvement, diet changes
	Manure management: anaerobic digestion, direct injection in soils of liquid manure.
Rice cultivation	Mixed: interrupted flooding and alternate wetting and drying, alternative hybrids, sulfate amendments
Agricultural waste burning	Ban on burning.
Solid waste	Maximum separation, treatment and valorisation; no landfill of biodegradable waste
Wastewater	Extended treatment with gas recovery and utilization
Coal mining	Pre-mining degasification
	Ventilation air oxidizer with improved ventilation systems
Conventional natural gas production	Recovery and utilization of vented associated gas
	Good practice: reduced unintended leakage
Unconventional natural gas production	Good practice: reduced unintended leakage
Long-distance gas transmission in pipelines	Leakage control, especially at the pumping units
Gas distribution networks	Leakage control and replacement of grey cast iron networks
Oil production and refinery	Recovery and utilization of vented associated gas
	Good practice: reduced unintended leakage

Source: Höglund-Isaksson, 2017; Höglund-Isaksson, 2012.

Agricultural sector

Measures to reduce emissions in agricultural production target different methods and changes in consumer's food preferences. As discussed in section 3.3.1, global emissions from rice have declined by 22% in the period 1970-2022, while production increased by a factor of 2.3. For rice, management practices for cultivation as well as changes in varieties can further reduce emissions (Yan et al., 2009; Peng et al., 2016). Ruminant enteric fermentation can be reduced *e.g.* through adjustment of animal's diets and vaccination (Hristov et al., 2013; Eckard, Grainger, and De Klein, 2010; Soder and Brito, 2023; Smith et al., 2008), see Figure 10. Manure management, *e.g.* using anaerobic digesters, provides a further opportunity to reduce methane emissions.

Figure 10: Source: Literature review) for Control measures for enteric CH_4 in ruminants.



Source: Eckard, Grainger, and De Klein, 2010.

There are relatively few studies that provide a quantitative evaluation of the global mitigation potential. Höglund-Isaksson (2012) finds a modest mitigation potential for technological options amounting to 13 Tg CH_4 yr^{-1} (or 9% of the agricultural total) by 2030 for rice and livestock production together, which can be split between 3% for livestock and 31% for rice.

For the EU28, the JRC EcAMPA2 study (Pérez Domínguez et al., 2016) performed an economic evaluation of 12 agricultural GHG mitigation technologies, including methane farm-scale and community-based anaerobic digestion methods, vaccination, and changes in the composition of animals diets (feed). EcAMPA2 shows that subsidies to support GHG reduction targets, can reduce production losses, as well as emission leakages.

Among the technologies affecting CH_4 emissions, anaerobic digestion, feed additives and vaccination, account for around 30% of the overall emission GHG reductions (ECAMPA2) but these results highly depend on implementation and are uncertain[27]. A recent review showed that vaccines can mitigate CH_4 emissions from enteric fermentation but it is complicated to evaluate the real effectiveness of this strategy. Few studies have directly assessed the complete approach, i.e., from vaccination to emissions from enteric fermentation. Furthermore, the great variety of methods prevents a meaningful comparison of the results. However, the strategy has been considered promising by many authors, and more research is needed to reach a rigorous conclusion on its feasibility, practical implementation, and sustainability (Baca-González et al., 2020). Increasing animal health and productivity (in terms of protein produced) are identified by FAO as successful strategies to mitigate GHG emissions (Hristov et al., 2013; Gerber, Seinfeld, and Henderson, 2013). Increases in productivity, especially in Eastern Europe, are indeed projected in Europe to contribute to declining CH_4 emissions (EU, 2017).

[27] Follow-up work will address in more detail the effects of emission leakage, cost, benefits and uptake barriers for mitigation measures. The assumed GWP100 for CH_4 in ECAMPA2 was 21, while for policy negotiations a value of 25 is used. Using the more recent IPCC AR5 (Myhre et al., 2013) GWP-100 value of 28 would increase the relevance of CH_4 by 33 %. See section2.

Another option to reduce CH_4 emissions from the agricultural sector is through change in consumers' food preferences towards reducing consumption of meat and milk products (Hedenus, Wirsenius, and Johansson, 2014; Westhoek et al., 2016). Life-cycle analysis indicate large differences in terms of GHG emissions for the same product, depending on mitigation choices along the whole supply chain (Poore and Nemecek, 2018). Vegetable substitutes always cause less GHG emissions than the lowest impact animal product. In Europe, a shift by 50% in meat and dairy consumption would reduce emissions by 45% and overall GHG agricultural emissions by ca. 20-40%. While worldwide animal product's protein consumption increased from 22 g capita^{-1} day^{-1} in 1970 to 32 g capita^{-1} day^{-1} in 2012 (FAO data of 2014[28]), it is plateauing in EU28 around 60 g capita^{-1} day^{-1} since 2000. This is about 60% of the total protein consumption, and substantially above the recommended daily protein intake[29]. In this context, large efforts are needed to achieve substantial reductions in meat and dairy consumption.

The technical abatement potential is considerably limited for agricultural sources, especially for extensive livestock rearing in developing countries, where keeping large herds of robust but relatively unproductive animals often fills a vital function. Overall, Höglund-Isaksson et al. (2020) find it technically feasible to remove 54 % of the anthropogenic CH_4 emissions by 2050, thereby leaving 5.7 Pg CO_2eq. This is a concern, considering the IPCC estimates that GHG overall emissions should not exceed 10 Pg CO_2eq by 2050 to remain below a 1.5 °C warming threshold in 2100. In addition to technical solutions, this calls for widespread implementation 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.

Waste and wastewater

Large regional differences are observed in terms of emissions between developed and developing countries for wastewater (EDGARv8.0, Table 3). While in large parts of Europe, domestic wastewater sanitation is common practice, sewage and industrial wastewater are treated in dedicated plants, this is not the case in developing countries where public or open pit latrines are emitting much more CH_4.

The US-EPA identified several abatement measures to control landfill emissions. The global abatement potential for that sector is estimated to be approximately 61% by 2030, compared to the baseline emissions, of which 12% at low costs and 49% at increasingly higher costs[30].

The ambition of LOW-Methane is to deliver at least 1 million metric tons of annual waste sector methane reductions well before 2030 for which is expected to unlock over $10 billion in public and private investments. The Inter-American Development Bank aims to reduce by 30% methane emissions from solid waste operations in Latin America and the Caribbean. At the 2023 North American Leaders Summit Canada, USA and Mexico committed to reducing methane emissions from the waste sector by at least 15% by 2030. The CH_4 emission reduction target of the LOW-Methane represents a 1% of the total CH_4 emissions from this sector in 2022, corresponding to approximately one thousand avoided premature deaths attributable to ozone exposure per year between 2025 and 2030.

In the EU, the Waste Framework Directive [31]and the Landfill Directive [32] as well as circular economy policies and actions, significantly contributed to reducing methane emissions from the waste management sector. However, the basic obligations of these Directives (closure of illegal landfills, rehabilitation, and treatment of waste before landfilling) are not completely implemented in many Member states[33]. Also the Circular Economy Action Plan[34] and the "From Farm to Fork" strategy are expected to contribute to reduce emissions by abating the amount of organic waste to be disposed.

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[28] https://www.fao.org/faostat/en/#data/QCL

[29] Recommended daily protein intake range from 0.80 to 0.83 g per kilogram of body weight for both men and women with modest levels of physical activity. An adult of 70 kg would need ca. 56-58 g protein https://knowledge4policy.ec.europa.eu/health-promotion-knowledge-gateway/dietary-protein_en . Accessed November 2023.

[30] https://19january2017snapshot.epa.gov/global-mitigation-non-co2-greenhouse-gases/global-mitigation-non-co2-greenhouse-gases-landfills_.html

[31] Directive 2008/98/EC, at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098

[32] Directive (EU) 2018/850, at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018L0850

[33] https://eur-lex.europa.eu/resource.html?uri=cellar:784da925-2f5e-11ed-975d-01aa75ed71a1.0005.02/DOC_1&format=PDF

[34] COM(2020) 98 final (see: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A98%3AFIN)

Table 3: Implied waste water emission factors in ton CH4/kton organic degradable material by world regions (BOD).

	Waste Water
Africa	331
India + (Southern Asia)	322
Latin America	288
Middle East	288
China + (Eastern Asia)	284
Rest of Asia	284
Russia and Central Asia	109
Oceania	74
North America	46
Europe	45

Source: EDGARv8.0.

Biogas production is one of the solutions to limit GHG emissions, as it reduces CO_2 emissions from organic waste that otherwise could go to landfill. The remaining digestate can be used as fertiliser, replacing fertilisers from fossil resources. Another option is to capture methane from landfills, however, this solution is sub-optimal according to the waste hierarchy. While biogas production from waste is a major step towards cleaner fuels, room for improvement remains (e.g. on techniques to increase usage of biogas). One major hurdle for biogas is cost. Despite biogas is not the perfect solution, its place in the context of waste management will continue to grow in the coming years (Adnan et al., 2019).

Fossil fuel production

Globally, there is considerable technical abatement potential for methane emissions from fossil fuel production in several sectors, with various technologies. Table 4 details the regional production-related emission factors (EDGARv8.0). For coal production, emission factors vary by up to a factor of 7 among regions. Depending on its quality, coal extraction is assumed to be more efficient in Europe and USA than in China and Russia (Janssens-Maenhout et al., 2019). While the recovery of CH_4 from underground mining before starting up the operation is nowadays implemented by most of the main producer countries, large-scale recovery/oxidation of ventilation air during operation is not routinely installed, nor is it applied to surface open-cast mining.

CH_4 emissions from venting of oil/gas extraction sites (expressed in energy content of the oil/gas) vary by up to a factor of 9 with the largest values in Africa and Middle East, while the lowest values are in the range of 0.01-0.04 ton of CH_4 TJ^{-1} for North America, Europe, China and Russia.

Differences reflect the assumptions made on the type and age of infrastructures, leak detections and maintenance. Measurements around gas fields in the Netherlands, indicate that production volume alone – used as activity data in most inventories - is not necessarily a good indicator for methane emissions (Yacovitch et al., 2018), as sites that are shut down may still be emitting. As mentioned in chapter 2, similar uncertainties pertain to the United States (Alvarez et al., 2018). Unfortunately, in many cases published emission factors are not available, rendering these numbers highly uncertain. More studies are needed to link local measurements to emission inventories.

Table 4: Fuel exploitation metrics in 2022 ranked from high-to-low. Coal, combined oil and gas production, gas transmission and distribution.

Coal production ton CH_4 TJ^{-1}		Venting from oil and gas production ton CH_4 TJ^{-1}		Gas transmission ton CH_4 $km^{-1}yr^{-1}$		Gas distribution ton CH_4 $km^{-1}yr^{-1}$	
Rest of Asia	0.50	Africa	0.23	Russia and Central Asia	4.5	Russia and Central Asia	1.9
Russia and Central Asia	0.35	Middle East	0.11	North America	2.6	Oceania	1.3
China + (Eastern Asia)	0.28	Rest of Asia	0.07	Africa	2.5	India	0.5
Africa	0.26	India	0.06	India	2.5	Latin America	0.5
Middle East	0.24	North America	0.04	China	2.5	China	0.5
Europe	0.18	Latin America	0.03	Latin America	2.3	Africa	0.5
India + (Southern Asia)	0.16	China	0.03	Middle East	2.3	Middle East	0.5
Latin America	0.14	Russia and Central Asia	0.02	Rest of Asia	2.2	North America	0.5
North America	0.12	Oceania	0.01	Oceania	1.3	Rest of Asia	0.3
Oceania	0.07	Europe	0.01	Europe	1.1	Europe	0.2

Source: EDGARv8.0.

Very little data is available on emissions from gas transportation in pipelines (transmission). In EDGAR annual emissions range between 1.1-4.5 ton km^{-1}, with lowest values assigned to OECD countries with the newest and best maintained infrastructure. CH_4 losses from gas distribution differ by a factor of 8 among countries. Old pipeline systems, which were leak-tight for wet gas, become leaky with a shift to dry gas. Altogether the largest mitigation potential is found in countries where production and distribution infrastructures and technologies are old, prone to gas leakages.

The IEA (IEA, 2023) estimates that around 70% of methane emissions from fossil fuel operations could be reduced with existing technology. In the oil and gas sector, emissions can be reduced by over 75% by implementing well-known measures such as leak detection and repair programmes and upgrading leaky equipment. In the coal sector, more than half of methane emissions could be cut by making the most of coal mine methane utilisation, or by flaring or oxidation technologies when energy recovery is not viable.

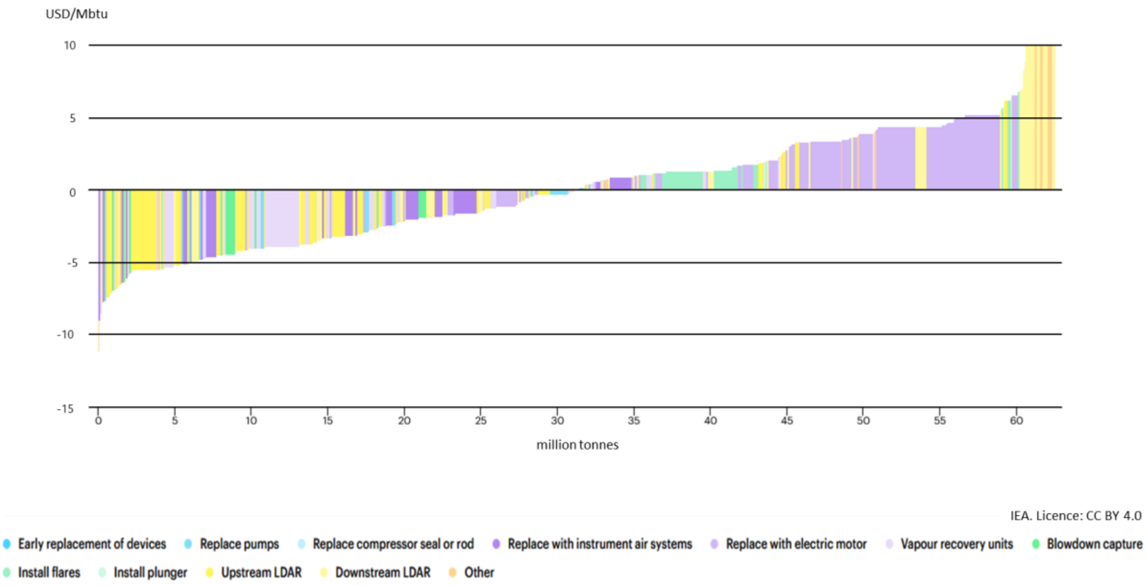
Shirizadeh et al. (2023) showed that the adoption of best available methane abatement technologies would reduce by up to 80% methane emissions from leakage, limiting the additional environmental burden to 8% of direct CO_2 emissions (vs. 35% today). They show that, while renewable energy sources are key drivers of climate neutrality, the role of natural gas strongly depends on actions to abate both associated CO_2 and methane emissions.

Cost of measures

Höglund-Isaksson et al. (2020) found that extensive technical opportunities exist at low costs to control fugitive emissions from fossil fuel production and use. In Russia and in the Middle East, this would lead to remove more than 10 % of the emissions by 2050. An almost as large reduction is expected by implementing infrastructures to separate the treatment of solid waste and proper wastewater treatment in China, India and the rest of South-East Asia.

Almost 50% of methane emissions from the energy sector can be mitigated at negative marginal costs (Figure 11).

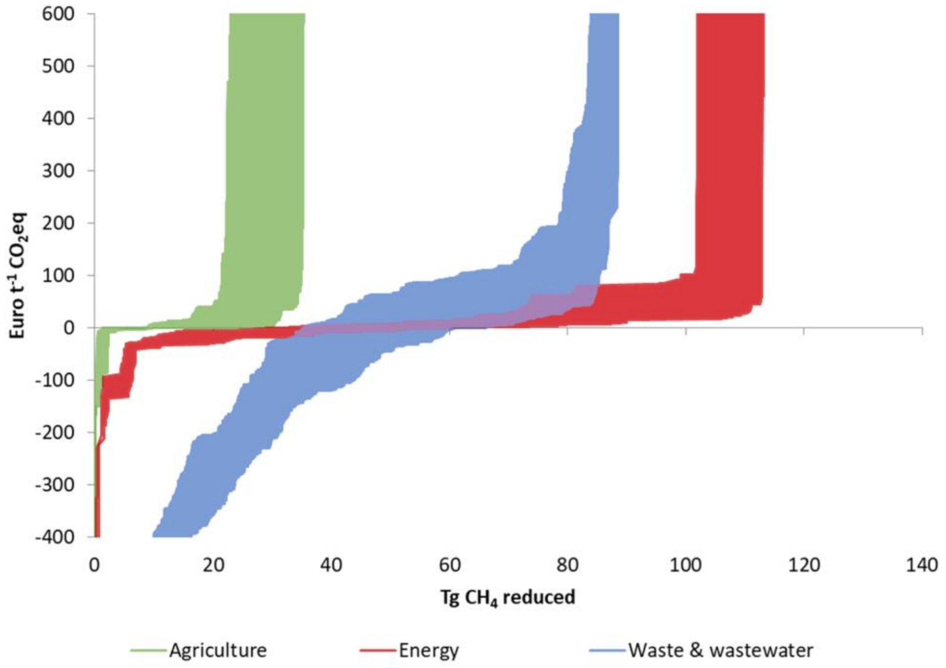
Figure 11: Marginal abatement cost curve for oil and gas methane emissions by mitigation measure, 2022.



Source: IEA, 2023.

The marginal abatement costs for methane (as shown in Figure 12) is highly sensitive to the time and opportunity 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 carbon price level higher than the one found optimal from a social planner's perspective will be needed to stimulate private investors. More than 85% of the global maximum feasible reduction potential is attainable at a marginal cost below 20 €/t CO_2eq for the three major sectors: energy, agriculture and waste.

Figure 12: Ranges for global marginal abatement cost curves for reducing CH_4 emissions in 2050 by major source sector.



Source Höglund-Isaksson et al., 2020.

The timeline to act is also important. If climate policies continue to focus on long-term horizons, the powerful climate benefits of short-term actions can be overlooked. A major opportunity to limit warming and its damages over the next few decades would be missed. Ocko et al. (2021) show that short-term methane action can considerably limit climate damages.

3.3.2 Emission scenarios

Projected CH_4 emissions for the coming decades strongly depend on the socio-economic narrative adopted, including assumptions on economic development, technological development and regional disparity as well as the political and societal willingness to abate greenhouse gas and air pollutant emissions. Depending on assumptions on the driving parameters, methane emissions would range from about 100 to 900 Tg yr^{-1} by the end of the century, and from 150 to 650 Tg yr^{-1} by 2050. In this section, we focus on global scenarios, and discuss four sets of commonly used families, developed by the climate and air quality communities. In this section, a short description of the main scenarios and their associated emissions is presented. A full description is provided in Annex 3.

While it is beyond the scope of this report to assess all factors driving the scenarios, we give some examples for the well-documented four families:

a. The ECLIPSE V6b[35] emission set (Amann et al., 2018)[36], was created with the GAINS model. It was used in a number of scientific studies and at the basis of the analysis performed by the Task Force Hemispheric Transport of the UNECE CLRTAP. The V6b scenarios are used to analyse the impact of CH_4 on O_3 concentrations with TM5-FASST in section 4.

b. The Representative Concentration Pathways scenarios (RCPs) were developed for the IPCC's fifth Assessment Report (AR5, van Vuuren et al., 2011) and widely used in the scientific literature of the past decade. We discuss the marker scenarios RCP8.5, RCP6.0, and RCP2.6, corresponding to median global temperature increases of 4.2 °C, 2.7 °C and 1.6 °C by the end of the century.

c. The "Shared Socioeconomic Pathways" (SSP) scenarios (Riahi, et al., 2017) have been designed to analyse future climate impacts, vulnerabilities, adaptation, and mitigation and informing the IPCC 6th assessment report (AR6). The framework is built around a matrix that combines climate forcing on one axis (as represented by the RCPs) and socio-economic conditions on the other. Together, these two axes describe situations in which mitigation, adaptation and residual climate damage can be evaluated.

d. To inform European policy makers, the Global Energy and Climate GECO scenario's (Keramidas et al., 2022) provide regular assessments on climate issues and are based on socio-economic projections of the European Commission. This edition (GECO 2022) presents an updated view on the implications of energy and climate policies in the context of the Paris Agreement targets.

Considerable efforts have been made to better document and understand the underlying assumptions on driving factors. Typically, emission scenarios assume either a full or partial implementation of Current air quality Legislation (CLE). Some scenarios assume a full implementation of best available technologies (MTFR - Maximum Technologically Feasible Reduction). Climate policies (*e.g.* Paris agreement pledges, or 1.5 or 2°C objectives) will impact GHG emissions, and have co-benefits for air pollutants. The actual differences between CLE and MTFR will be determined by economic factors (mitigation costs), and political and societal preparedness to implement these technologies. Generally technological developments such as new, currently not existing, technologies that may further reduce emissions are not included in MTFR, but they may be partly driving other scenarios. A detailed description of the scenarios is provided in Annex 3.

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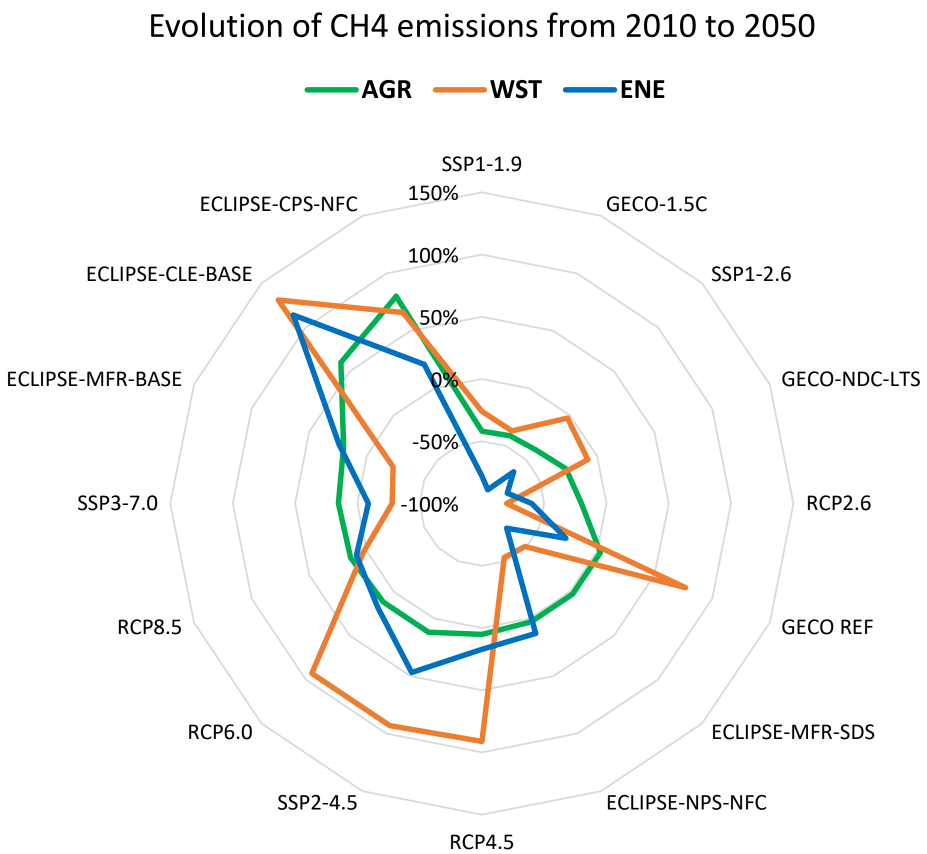
[35] https://previous.iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv6b.html
[36] http://www.iiasa.ac.at/web/home/research/researchPrograms/air/ECLIPSEv6b.html

Figure 13: Radar plots of global methane emissions changes in % expected from 2010 to 2050 of the 3 major sectors and 16 scenarios.

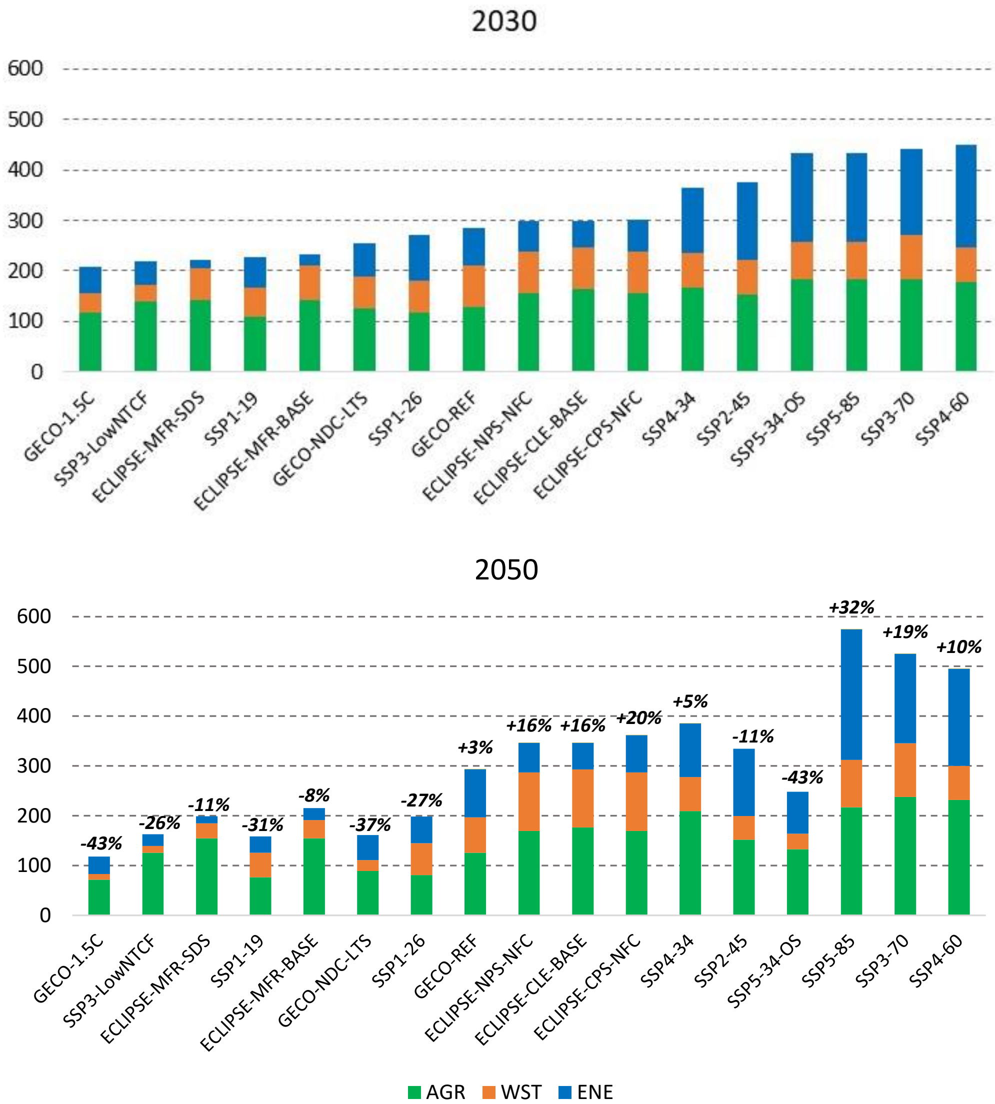


Source: JRC elaboration of emission data (see Annex 3).

Comparing 2050 to 2010, relative sectoral emission changes show that the most ambitious scenarios are (i) GECO-NDC-LTS, GECO-1.5C and SSP1-1.9 with an emission reduction of at least 88% for the energy sector, (ii) SSP1-2.6, GECO-1.5C and SSP1.9 with a reduction of at least 39% for the agriculture sector, (iii) ECLIPSE V6b-MFR-BASE, ECLIPSE-V6b-MFR-SDS and RCP-2.6 with a reduction of at least 51% for the waste sector. The radar plot Figure 13 highlights a certain coherence between the evolution of the agriculture and energy sectors whereas the waste sector is disconnected.

For all scenarios (excepted RCPs), world methane emissions are ranked from lowest to highest in Figure 14 for the year 2030 with a breakdown in the main emitting sectoral activities: agriculture (AGR), waste (WST) and energy (ENE). Differences among scenarios are particularly driven by the energy sector. We note the importance of the agriculture sector in the ECLIPSE scenarios that represents more than half of total (sum of the three main sectors). In relative terms, the ECLIPSE energy contribution is the lowest. Keeping the 2030 ranking for 2050 allows to see the evolution of the total and sectoral contributions. Clearly GECO-1.5C is the most ambitious scenario in 2050 with low emissions already expected by 2030 and the highest emission reductions by 2050 (compared to 2030). SSP2-4.5 and SSP5-34-OS show the largest emission decreases between 2030 and 2050 while the less ambitious SSP scenarios display large emission increases.

Figure 14: 2030 and 2050 World methane emissions for agriculture (AGR) waste (WST) and energy (ENE) sectors in Mt year^{-1} (sorted from the most to least ambitious scenario on total AGR+WST+ENE methane emissions in 2030). For 2050, the % of change compared to 2030 is provided above the bar plots.

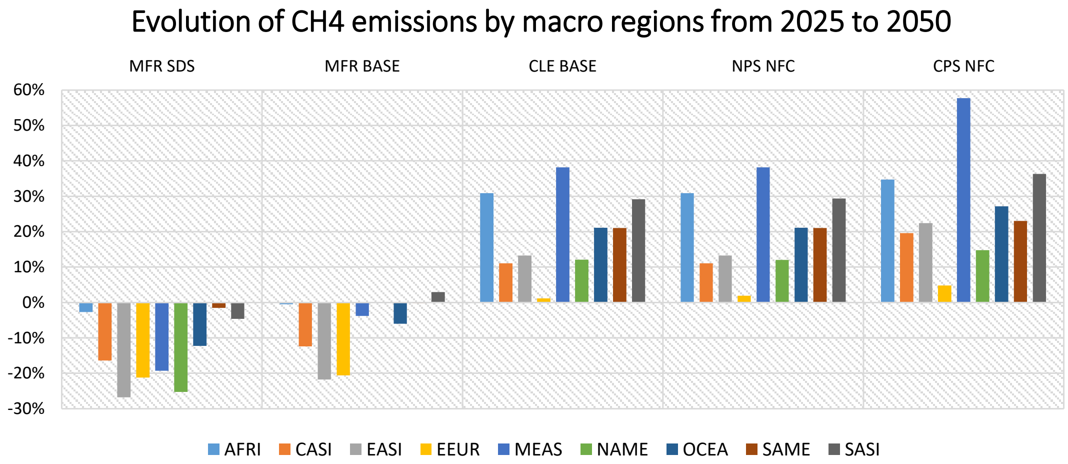


Source: JRC elaboration of emission data (see Annex 3).

Looking at regional differences for the ECLIPSE scenarios (Figure 15), MFR SDS and MFR BASE display the largest emission reductions everywhere but with large variabilities among macro-regions. Africa, the Middle East and the South of Asia show the lowest emission reductions from 2025 to 2050. For the MFR-BASE scenario, in Americas, Africa and the South of Asia no emission reduction is expected between 2025 and 2050. East Asia (including China) and the Extended Europe display the highest emission reductions.

For the most pessimistic scenarios, an emission increase is observed everywhere with the lowest increase in Europe. The Middle East shows a mixed picture with large emission reduction for the MFR SDS scenario and the most important emission increase for the worst scenarios. In general, the large increase between 2025 and 2050 in Africa, Middle-East and South-Asia, which represent a large fraction of world emissions (Figure 16), will have consequence on ozone formation in these tropical and subtropical areas.

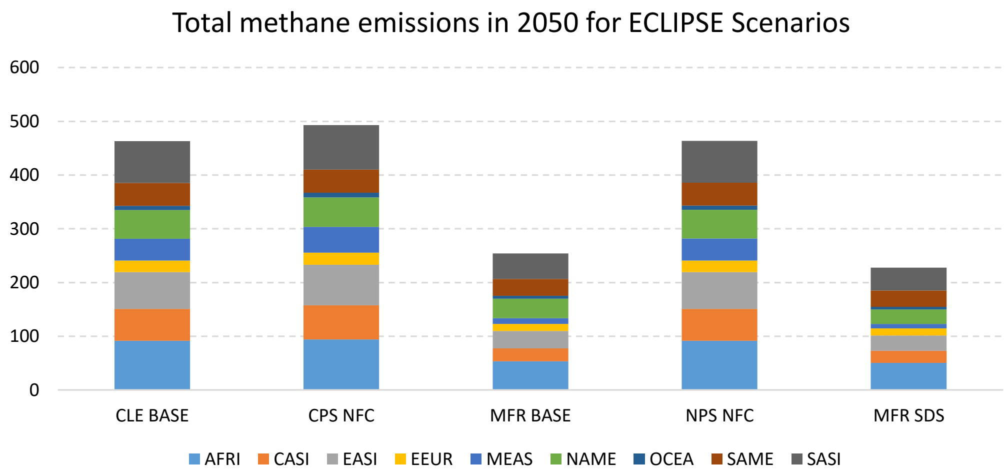
Figure 15: Evolution expected in % by ECLIPSE scenarios for macro regions from 2025 to 2050.



AFRI = Africa; SAME = South America; NAME = North and Central America; CASI = Central Asia; EASI = Eastern Asia; SASI = Southern Asia; MEAS = Middle East; EEUR = Europe; OCEA = Oceania

Source: JRC elaboration of data from IIASA (see Annex 3).

Figure 16: Expected total emissions in Mt year^{-1} for ECLIPSE scenarios in 2050 by macro regions defined in Figure 15.



Source: JRC elaboration of data from IIASA (see Annex 3)..

4 Air quality impacts of CH_4 emissions

In this section, we explore the impact of projected CH_4 emission trends until 2050 on background ozone, and its impacts on human health and crop yields. Other types of vegetation (e.g. forests) can likewise be affected by ozone (Sitch et al., 2007; Paoletti, 2006; De Vries et al., 2017), but are not analysed in this study. We use the five scenarios of the ECLIPSE dataset version 6b (Klimont et al., 2017), to provide insight on the range and magnitude of possible benefits associated with CH_4 mitigation policies (see Annex 2).

The TM5-FASST Screening Tool (TM5-FASST, Van Dingenen et al., 2018b) is used to derive pollutant concentration responses to changing emissions, including CH_4. The methodology used in this report also builds upon results obtained by dedicated model ensemble experiments in the framework of the first and second phases of the Task Force on Hemispheric Transport of Air Pollutants (HTAP1, HTAP2) and is described in Annexes 4 and 5.

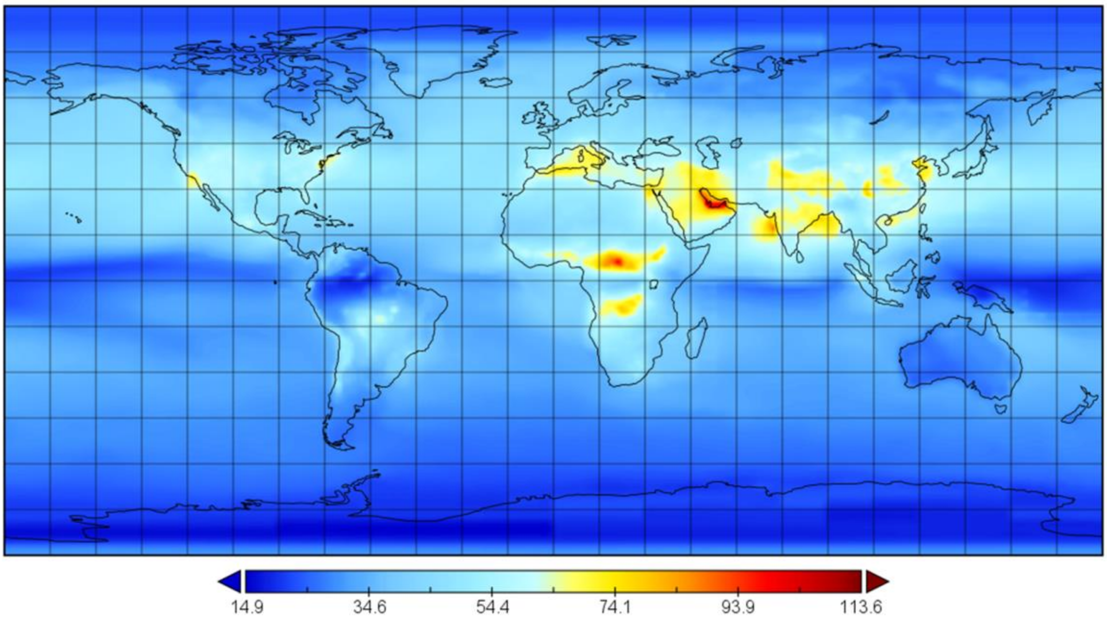
4.1 Current O_3 exposure patterns

In this work we evaluate the health-relevant O_3 exposure metric SDMA8h (as defined in Annex 6), *i.e.* the highest 6-monthly mean of daily maximum 8 hourly ozone running average, applying the widely-accepted O_3 health exposure-impact relationship by (Stanaway et al., 2018).

Figure 17 displays the spatial pattern of the SDMA8h ozone metric calculated with TM5-FASST for 2015. A broad band of SDMA8h above 60 ppb stretches over the Northern Hemisphere mid-latitudes, Middle East, South and East Asia, with peak values of 90 ppb. Maxima of 70-100 ppb over Africa, and 70-80 ppb over South America are related to large-scale open biomass burning.

The contribution of anthropogenic CH_4 emissions to SDMA8h in 2015 was on average 12% (6 ppb) with values ranging from 8% in East Asia to 19% in the Pacific region. In Europe the CH_4 share of SDMA8h was 13% (7 ppb). These estimates are consistent with those made by West et al. (2006) and Fiore et al. (2008). We note that along with CH_4, changes in VOC, and CO and especially NO_x emissions may also affect the lifetime and ozone production efficiency of CH_4. Assessing these non-linear interactions is beyond the scope of this study.

Figure 17: Year 2015 Ozone exposure metric SDMA8h calculated with TM5-FASST (ECLIPSE v6b).



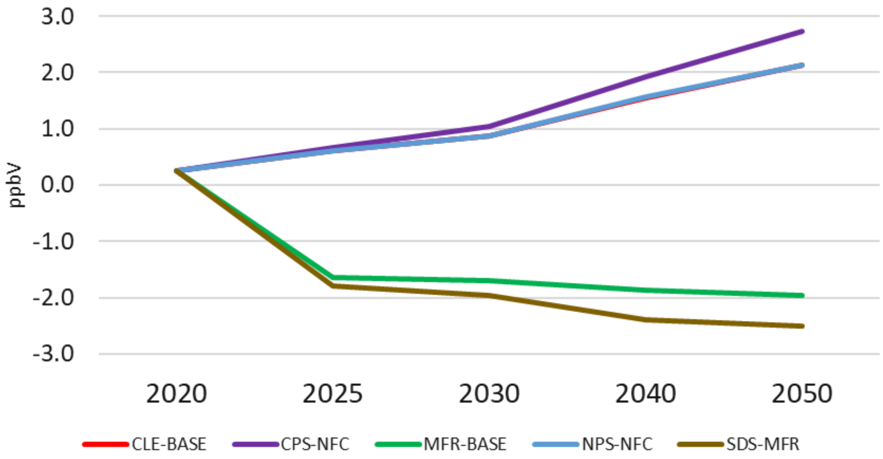
Source: JRC TM5-FASST.

4.2 Future trends in background O_3 related to CH_4 emissions

We have applied the regional HTAP CH_4-ozone response sensitivities, taking into account the 12-year response time of CH_4 (see Annex 4) to estimate the change in ground-level ozone concentrations associated with the changes in projected global CH_4 emissions. To isolate the effect of CH_4 on O_3, we assume that changing CH_4 emissions does not affect O_3 formation from its other precursors[37]. HTAP analysis by Wild et al. (2012), Turnock et al. (2018) and Maas and Grennfelt (2016) of a variety of air pollution scenarios shows that air pollution emission controls can also exert sizeable impacts in and downwind of the air pollutant emission regions. For instance, for Europe, stringent North American emission controls (MFR) will be beneficial. We refer for more information to these publications.

Figure 18 shows the development between 2015 and 2050 of the SDMA8h ozone exposure metric in Europe relative to year 2015, as a response to changing global CH_4 emissions for the scenarios discussed in section 3. In this figure CLE-BASE and NPS-NFC overlap. For Europe region (HTAP2 region definition: see Annex 3), the largest difference between the highest and lowest emission scenario produces SDMA8h O_3 exposure changes of 3 ppb in 2030 and 5.5 ppb in 2050, the latter corresponding to about 5% of the total SDMA8h in 2015 and 36% if the SDMA8h attributable to CH_4 in the same year. The two MFR scenarios lead to a similar outcome by 2050, with CH4 related O_3 exposure reductions between 30% and 36% with respect to 2015.

Figure 18: Projected change in ozone exposure metric SDMA8h over Europe, relative to year 2015, as a consequence of the global CH_4 emission trends (see section 3).

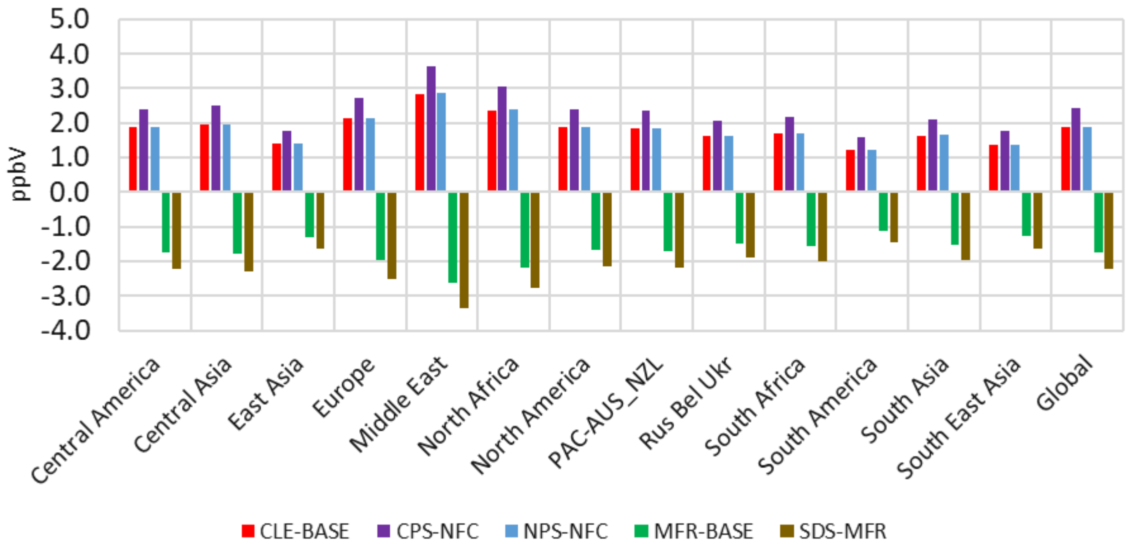


Source: JRC TM5-FASST.

Differences in global and regional SDMA8h O_3 exposure between the most and least stringent emission scenarios for the year 2050 (relative to year 2015) are shown in Figure 19. The difference between the highest (SDS-MFR) and lowest (CPS-NFC) ambition scenarios leads to a difference of 4.6 ppb in ozone exposure, globally, with regional values up to 7.0 ppb in the Middle East. These regional differences depend on NO_x and VOC regimes, further influenced by physical conditions (sunlight, temperature, humidity, and land cover). The behaviour over the Middle East is coherent with the large emissions increase between 2025 to 2050 (see Figure 15).

[37] The HTAP CH_4-O_3 response sensitivities used in the present analysis are representative for year 2000 emissions (see Annex 4). The impact of changing NO_x, VOC, and CO emissions on CH_4 concentrations and CH_4 – O_3 response sensitivities goes via a complex set of reactions influencing O_3 and the OH radical. As a rule of thumb increasing NO_x emissions increase the levels of OH and decrease the chemical residence time of CH_4. In contrast, increasing CO and VOC emissions decrease levels of OH, and increase the residence time of CH_4. As NO_x, VOC, and CO are to some extent co-controlled, some previous studies have suggested a relative stability of the global OH amounts, while other studies suggest larger variability. A more quantitative assessment of this is beyond the scope of this study, but we do not expect large impacts of this assumption.

Figure 19: Projected change in regional mean ozone exposure metric SDMA8h in 2050, relative to year 2015, for the highest and lowest global CH_4 emission in the Eclipse v6b scenarios



Source: JRC TM5-FASST.

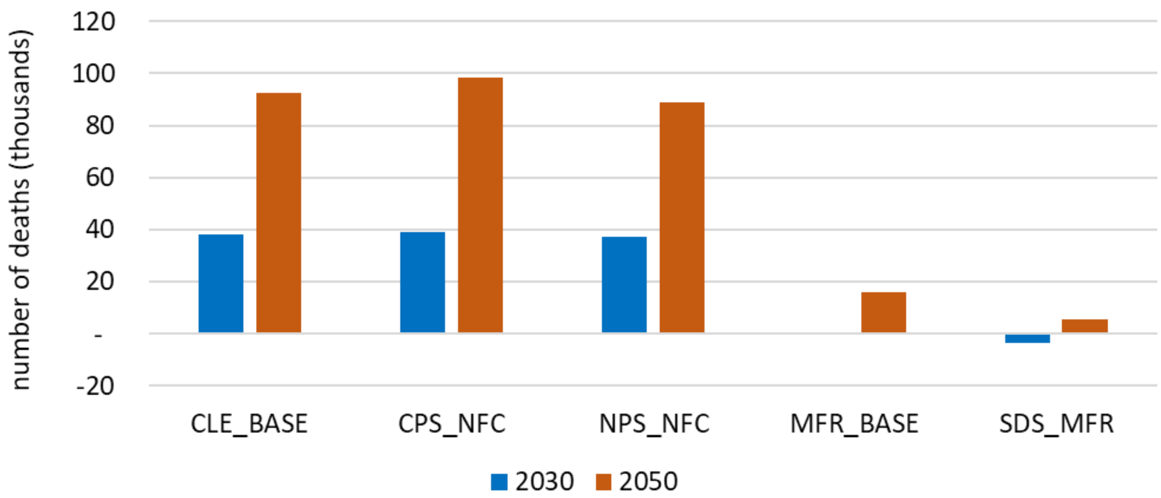
4.3 Future health impacts from CH_4-induced O_3

O_3 exposure is associated with a range of health impacts, including mortality from respiratory disease. WHO's most recent review of evidence on health aspects of air pollution (HEI, 2020) reports a number of cohort studies suggesting an effect of ozone on long-term mortality.

Here we include an estimate of the CH_4-related O_3 health impacts from long-term exposure, following Stanaway et al. (2018), using as exposure metric SDMA8h with a threshold of 29.1 ppb for zero effect (Belis and Van Dingenen, 2023). In 2019, 365,000 premature deaths were associated with ground-level ozone globally, 18000 of which in Europe (HEI, 2020). An important aspect is the effect of growing population and changing base-mortalities (*e.g.* ageing) in future scenarios, which may make it difficult to single out the signal of O_3 on health impacts. In general, demographic developments in emerging economies will increase impacts of air pollution – even with unchanged or even declining pollution. Similarly to earlier studies on impacts of CH_4 emission reductions on O_3 *e.g.* (West et al., 2006), we compare in this work O_3-related mortalities in 2050 and 2015, considering the population exposed for these two years (projected from SSP2 for 2050 scenarios). This means that we consider both emission and demographic changes.

Worldwide, relative to year 2015 exposure levels, the high CH_4 emission scenarios (Figure 20) would lead in 2050 to an estimated additional 89,000 to 98,000 O_3 premature deaths, whereas the low emission-high mitigation scenarios would still lead to a modest increase in mortalities by 5,000 to 16,000 units partly due to the abovementioned demographic changes.

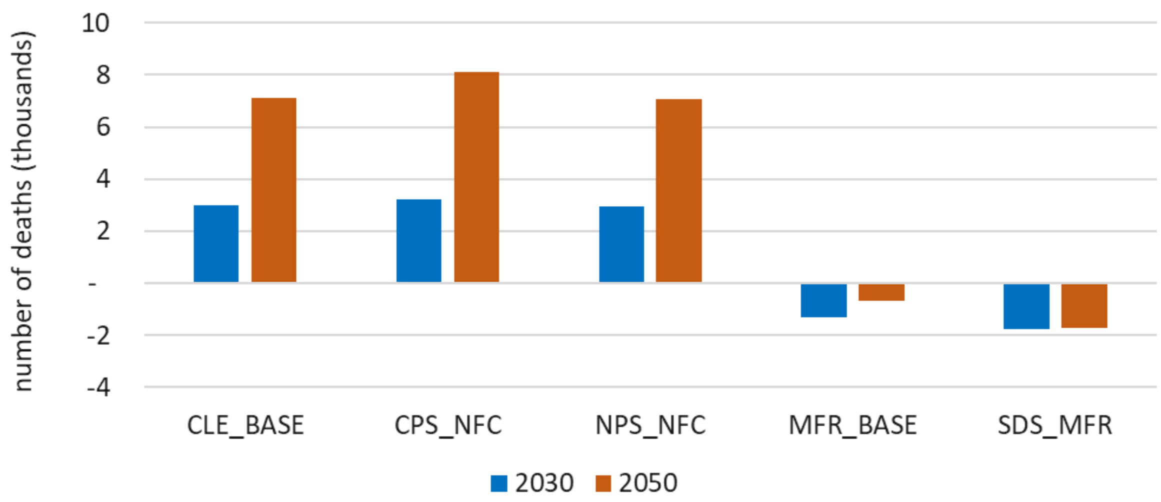
Figure 20: Change in global mortalities from exposure to O3 from global CH_4 emissions in 2030 (blue bars) and 2050 (orange bars), relative to exposure of year 2015 O3 levels.



Source: JRC TM5-FASST.

The number of premature deaths from CH_4-related background ozone in Europe in 2050 is projected to increase by 7000 to 8000 annual deaths in the high emission scenarios and decrease by 700 to 1700 annual deaths for the high mitigation effort scenarios, compared to a population exposed to 2015 O_3 levels (Figure 21).

Figure 21: Change in mortalities in HTAP2 Europe region (see Annex 3) from exposure to O_3 from global CH_4 emissions in 2030 (blue bars) and 2050 (orange bar), relative to exposure of year 2015 O_3 levels.

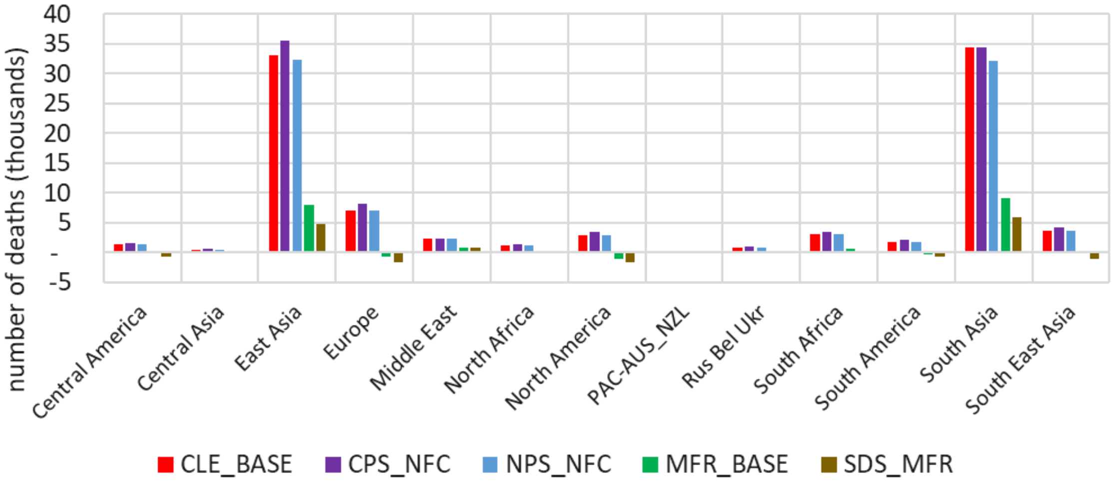


Source: JRC TM5-FASST.

CH_4-related ozone impacts are independent of CH_4 emission locations. In the CLE BASE scenario, Europe is responsible for 5% and 4% of the global CH_4 emissions in 2030 and 2050, respectively but has a mortality burden of 11% and 10% of the global health impact, respectively. This imbalance between emission and impact share is mainly due to the relatively higher population density in Europe, combined with a somewhat higher O_3 response to CH_4 emissions compared to other world regions.

The 2050 global and regional differences in mortality between the highest and lowest emission scenario are given in Figure 22.

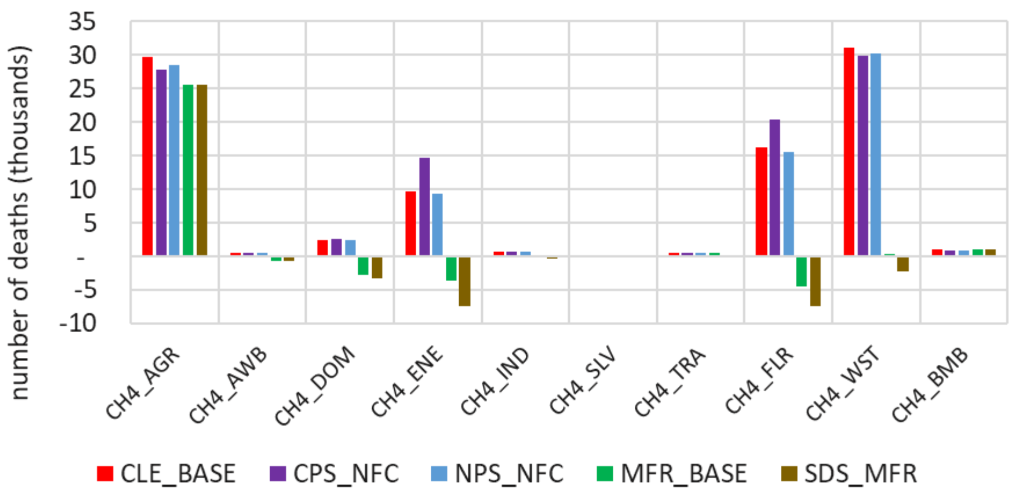
Figure 22: Differences in mortality attributable to methane-induced O_3 in 2050 relative to 2015 in each scenario for HTAP2 world regions (see Annex 3).



Source: JRC TM5-FASST.

East Asia and South Asia are the regions with the highest global mortality shares. From 2015 to 2050, the aggregated mortalities of these two regions are always above 60% of the global total mortality attributable to methane-induced ozone. In 2050, these are the regions with the highest CH_4-related mortality difference between the high and low emission scenarios. This situation is caused by the combination of higher O_3 exposure levels and higher population densities, compared to the global average. Although the trend is upwards compared to 2015 in all scenarios, East Asia and South Asia are the regions showing the highest abatement potential (high-low) in terms of premature deaths due to exposure to CH_4-related O_3. Europe and North America are the regions where the highest decrease in mortality takes place in the most ambitious reduction scenarios. By comparison, the lowest mortality due to CH_4-related O_3 is observed in the Pacific region due to low exposure levels.

Figure 23: Year 2050 O_3 differences in global mortality attributable to CH_4 relative to year 2015 split by anthropogenic sources.



Source: JRC TM5-FASST.

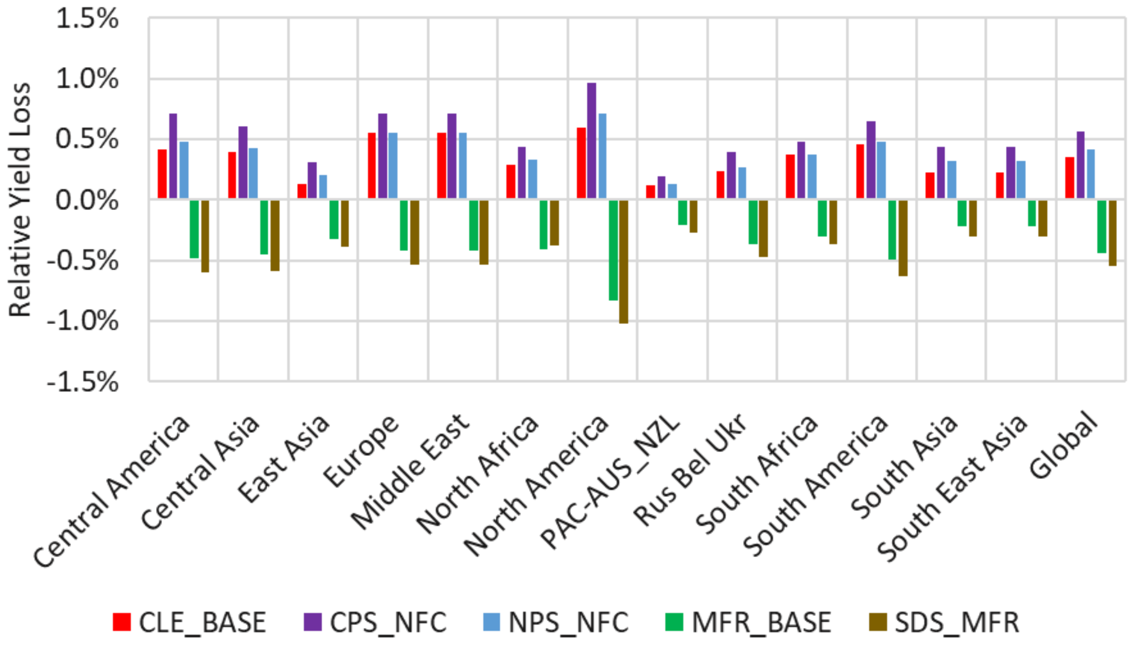
With an appropriate combination of perturbations simulations, it is possible to attribute the O_3 mortality associated with CH_4 to the respective anthropogenic sources. The methodology and limitations of the approach are described in Belis and Van Dingenen (2023). Figure 23 shows the differences between the shares of sources in 2050 compared to 2015. In all scenarios, the role of agriculture increases while energy production, gas flaring and waste management are higher only in scenarios with high emission levels. Domestic, energy production and flaring are the sources showing the most important reductions in the scenarios with high emission abatement. The remaining sources show little influence on the O_3 mortality variation in the considered time window.

4.4 Future crop impacts from CH_4-induced O_3

The yield losses due to methane-induced ozone reported in this section were estimated using the M_i exposure index. More details on the metrics and methods used to calculate yield losses are provided in Annex 5. Global yield losses (based on year 2000 - 2010 crop shares and geographical distributions) for 2015 emissions are 4.2, 7.5, 1.9, and 6.9 million metric tons for four major crops: wheat, maize, rice and soy bean, respectively.

We estimate the change in year 2050 relative crop yield loss (for the aggregated four major crops wheat, maize, rice and soy bean), based on year 2000 - 2010 crop shares and geographical distributions (Figure 24). The high emission scenarios present relative yield loss increasing by 0.4% - 0.6% in 2050 compared with 2015 globally with North America showing higher values (0.7% - 1.0%) mainly associated with increased soybean and maize losses. The high mitigation scenarios global relative yield loss (RYL) improvement in 2050 compared to 2015 is on average 0.4% - 0.5%. When it comes to the single crops, the RYL increase in 2050 compared to 2015 in the highest emitting scenario is 0.5%, 0.6%, 0.3% and 1.4% for wheat, maize, rice and soybean, respectively while the RYL abatement in the lowest emitting scenario for the same period is 0.5%, 0.7%, 0.3% and 1.4%, respectively.

Figure 24: Year 2050 Relative yield loss of 4 major crops relative to year 2015 exposure due to CH_4-induced O_3 for 12 world regions (HTAP2- Annex 3). (Negative loss corresponds to a gain in crop yield).



Source: JRC TM5-FASST.

The economic losses or gains associated with the changes in crop production described above were estimated based on the average international price of commodities in the period 2000 – 2023 (source: FAO[38]).

[38] https://fpma.fao.org/giews/fpmat4/#/dashboard/home

Compared to 2015, the crop yield losses for the high emitting scenarios translate into a global economic damage between 400–570 million USD in 2050 for the four considered crops while the benefits for the low emission scenarios range between 500 and 590 million USD.

4.5 Summary of impacts

Table 5 summarises the health and crop impacts for the globe and for Europe as a consequence of global CH_4 emission reductions (due to their influence on ozone levels) under the highest and lowest emission scenarios.

Table 5: Summary of global and European health and crop impacts for the high and low CH_4 emission global scenarios. Impacts are relative to 2015.

Year	High emission scenarios		High mitigation scenarios	
	Change in global CH_4 emissions relative to 2015 (Tg CH_4 yr^{-1})			
2030	43 to 50		-83 to -96	
2050	104 to 133		-96 to -122	
	Change in ozone exposure metric SDMA8h relative to 2015 (ppb) from CH_4			
	Global	Europe	Global	Europe
2030	0.8 to 0.9	0.9 to 1.0	-1.5 to -1.7	-1.7 to -2.0
2050	1.9 to 2.4	2.1 to 2.7	-1.7 to -2.2	-2.0 to -2.5
	Change in CH_4-related O_3 mortalities relative to 2015 exposure levels (thousands)			
	Global	Europe	Global	Europe
2030	37,000 to 39,000	2,900 to 3,200	-0 to -3,000	-1,300 to -1,800
2050	89,000 to 98,000	7,000 to 8,000	6,000 to 16,000	-0,600 to -1,700
	Percentage change in CH_4-related O_3 mortalities relative to 2015 exposure levels			
	Global	Europe	Global	Europe
2030	46% to 49%	28% to 31%	-4% to 1%	-13% to -17%
2050	112% to 123%	68% to 78%	7% to 20%	-7% to -16%
	Percentage change in crop yield loss (RYL) relative to 2015			
	Global	Europe	Global	Europe
2030	13% to 16%	17% to 20%	-32% to -37%	-27% to -32%
2050	35% to 47%	43% to 55%	-36% to -45%	-32% to -41%
	Change in crop economic loss relative to 2015 (million USD)			
	Global	Europe	Global	Europe
2030	142 to 184	17 to 20	-442 to -497	-34 to -39
2050	404 to 566	43 to 57	-497 to -590	-39 to -48

Source: JRC TM5-FASST.

In relative terms, the high emission scenarios would lead to an increase in global O_3-related mortality between 46% to 49% in 2030, and 112% to 123% in 2050 compared to the year 2015. The mitigation scenarios project a global change in mortalities of 1% to -4% in 2030 and an increase between 7% and 20% in 2050, the latter mainly due to demographic changes overlapping with emission trends. In Europe, the change in methane-induced O_3 mortalities relative to 2015 is lower. An increase by 28% to 31% (2030) and 68 to 78% (2050) is foreseen for the high emission scenarios, while the mitigation scenarios project a decrease between 13% to 17% (2030) and 7% to 16% (2050).

In the high emission scenarios, the global crop yield loss (RYL) rises between 13% and 16% in 2030 compared to 2015 with improvement (decrease) in the high mitigation scenarios between 32% and 37%. In 2050 the RYL relative to 2015 further increases in the high emission scenarios while the values in the low emission scenarios are comparable to those in 2030. In Europe the RYL relative changes are slightly stronger than the global ones in the high emission scenarios and slightly weaker in the low emission scenarios. The increased economic costs due to crops losses associated with methane-induced O_3 in the highest emission scenario in 2050 compared to 2015 is 566 million USD and 57 million USD at the Global and European levels, respectively while the corresponding benefits in the lowest emission scenario are 590 million USD and 48 million USD, respectively.

5 Conclusions

This report updates the 2018 report (Van Dingenen, et al., 2018) and syntheses the most recent studies on CH_4 and its impact on O_3, based on JRC and external organisations' data. It also reviews international developments concerning CH_4. Recent bibliography discussing the links between methane and ozone is reviewed and synthetized. EDGARv8 emissions are used to provide an overview of global scale emissions with a focus on the main macro-regions. The FASST-TM5 model evaluated the ECLIPSE V6b scenarios to obtain up-to-date impacts of methane-induced ozone on mortalities and crop yields.

5.1 Current understanding of observed changes of CH_4 and O_3 concentrations

After a short period (2000-2008) of stagnation, global CH_4 concentrations are again increasing and exceed now 2000 ppb, compared to 1705 ppb in 1990. These trends are based on a relatively accurate GHG observing system and not disputed. Scenarios show that except for the most optimistic scenarios, concentrations would continue to increase until 2100.

There are several scientific hypotheses on what is causing the renewed trend- with recent literature providing evidence for increasing fossil-fuel production and agricultural emissions. Other studies point to large uncertainties in natural emissions, specifically from tropical wetlands, which may contribute to inter-annual variability and thus contribute to shorter-term (few years) trend fluctuations. More research on the drivers of the recent CH_4 trends is needed for informing both climate and air pollution policies.

In contrast to global CH_4 concentration trends, our knowledge of long-term historic global surface O_3 changes is relatively limited, and relies on inaccurate observations at the beginning of the 20th century and a very limited set of more accurate surface stations that stretch back to the 1970s. Global atmospheric chemistry transport models, that include state-of-the art knowledge on changes in O_3 precursor gas emissions (including methane), meteorology and natural processes (such as ozone transported from the stratosphere), can only partly reproduce the observed annual O_3 trends at surface stations and the free troposphere since the 1970s, but models and observations do agree on relatively constant *annual* O_3 concentrations since the 2000s in large parts of Europe and the USA. Observations clearly show that peak O_3 values in summer have gone down in large parts of Europe and the US, resulting from reductions of O_3 precursor emissions. Observations also show that O_3 is strongly increasing in East Asia. In winter, O_3 concentrations are increasing almost everywhere. The contribution of CH_4 to O_3 trends can only be estimated by models. Based on observed CH_4 concentrations and relatively well known degradation chemistry of CH_4 derived from field and laboratory studies, the literature finding that methane changes have contributed 1.8 [range 1-3] ppb to *annual* O_3 concentration changes from 1960-2000 is relatively well understood. This represents less than 15% of the annual O_3 changes observed at a limited number of rural surface stations and 20-40% trends observed in the free troposphere. Our TM5-FASST analysis indicates an averaged global contribution of 12% (6 ppb) of anthropogenic CH_4 emissions to the health-relevant O_3 exposure metric SDMA8h. Values are around 13% in Europe and range from 8% in East Asia to 19% in the Pacific region.

Recent literature indicates the need for policy actions targeting methane emissions within Europe, North America and Asia to reduce exceedances of the O_3 air quality standards and guidelines, given the important contribution of intercontinental transport.

5.2 Current knowledge on the geographical distribution of CH_4 emissions and on contributing sources

The global amount of CH_4 emissions, from both natural and anthropogenic sources, can be relatively accurately determined from combined information on observed atmospheric CH_4 concentrations and chemical destruction in the troposphere. It amounts in average to 580 ±34 Tg CH_4 yr^{-1} during the period 1980-2017. Natural sources contribute by ca. 40% and human activities to 60%. Natural and anthropogenic contributions in different world regions can be derived from emission inventories and natural emission process models, while inverse models, that combine information derived from observations, emissions, and atmospheric transport, can determine regional emissions.

Methane contributes with 35 % to the global tropospheric ozone burden and with 41 % to the Northern Hemisphere (about 37% in Europe), which is more than any other source of reactive carbon.

According to the JRC Global Emission Database EDGARv8 and in coherence with other databases, China and surrounding regions are in 2022 the dominant and growing emitters of anthropogenic CH_4. South Asia, Central and South America, Africa, South East Asia, the former Soviet Union, and North America have contributions, fluctuating between 10% and 20%. The EU27 contributes by about 6% to the global anthropogenic CH_4 emissions.

In coal, oil and gas producing countries (Russia, Central Asia and the Middle East), fossil fuel production and distribution tends to be the dominating sector. In Europe, emissions from this sector have decreased (especially from coal mining) whereas in other countries, gas and oil production related emissions have increased since 1970. Substantial opportunities exist to further reduce emissions in this sector, although the EU reduction potential may be more limited. However, the EU27 increasingly relies on oil and gas imports and it expanded its transmission and gas distribution network, resulting in increased CH_4 leakages along the entire production and distribution chain. Satellite observations can be used to reduce the uncertainties associated with this sector.

In Europe and South America, agriculture is the largest contributor to CH_4 emissions. Livestock, especially enteric fermentation in ruminants, but also manure management, are important emission contributors. Tackling this sector is beneficial for both climate and air quality. While emissions from rice cultures are not very important in the EU, it is an important source in Asian countries with scope for further reductions.

Solid waste and waste-water related CH4 emissions globally amount to 93 Tg CH_4 yr^{-1} (or 23% of the global total) in 2022. Landfills emissions decreased in EU27 by 40% from 1970 to 2022, in particular in Germany, Great Britain and the Netherlands. Over the same period, we find a 39% reduction in the USA, while these sector emissions strongly increased in China, India, Middle East, Russia and Turkey.

5.3 Policy-relevant CH_4 emission scenarios until 2050 and contributions to O_3 concentrations in Europe and other parts of the world

The air pollutant and climate research communities have used integrated assessment models, along with socio-economic, technological and policy assumptions, to develop scenarios of air pollutants and greenhouse gases emissions, including methane. In total, we analysed twelve methane scenarios, ranging between unambitious, middle-of-the-road and ambitious developments regarding sustainability, climate and air pollutant mitigation. Depending on scenarios, methane emissions would range between 150 to 650 Tg yr^{-1} in 2050, and by 100 to 900 Tg yr^{-1} by the end of the century.

Comparing 2050 to 2010, relative sectoral emission changes show that the most ambitious scenarios are:

(i) GECO-NDC-LTS, GECO-1.5C and SSP1-1.9 with a reduction of at least 88% for the energy sector,

(ii) SSP1-2.6, GECO-1.5C and SSP1.9 with a reduction of at least 39% for the agriculture sector

(iii) ECLIPSE V6b-MFR-BASE, ECLIPSE-V6b-MFR-SDS and RCP-2.6 with a reduction of at least 51% for the waste sector.

5.4 Benefits for human health, crops and climate of CH_4 emission reductions in the EU alone, and through collaboration with other parties

CH_4 and O_3 are both important climate gases. The significance for climate of CH_4 emission mitigation is demonstrated by the latest decision of COP28 to progressively abandon fossil fuels including methane gas.

In this work, we evaluate the health-relevant O_3 exposure metric SDMA8h*, i.e.* the highest 6-monthly mean of daily maximum 8 hourly ozone running average, applying widely-accepted O_3 health exposure-impact functions. The spatial pattern of the SDMA8h ozone metric calculated with TM5-FASST for 2015 shows a large variability of the indicators ranging from less than 20 ppb over the highest latitude to more than 100 ppb over tropical and sub-tropical areas. A broad band of SDMA8h above 60 ppb stretches over the Northern Hemisphere mid-latitudes, Middle East, South and East Asia, with peak values of 90 ppb. Over Africa maxima of 70-100 ppb and 70-80 ppb in South America are related to large-scale open biomass burning.

Worldwide, at least 80% mortalities would be avoided in 2050 when implementing the most stringent CH_4 emission reduction scenarios. CH_4-related O_3 mortalities would decrease in Europe for the most optimistic scenarios (high mitigation) whereas at global scale an increase would still be observed due to the evolution of demography. A recent study shows that applying high mitigation scenarios only in Europe (and other signatories of the Air Convention) while keeping baseline emissions in the rest of the world only leads to limited additional abatement of the human exposure to ozone in Europe compared to the baseline (Belis and Van Dingenen, 2023). In addition, such scenario fails to revert the upward trend of ozone-related mortality in Europe, which has been attributed to the increasing impact of CH_4 emissions from the rest of the world.

Reduction of methane emissions also leads to less exposure of crops to ozone. The crop yield loss (RYL) in 2050 will decrease by at least 27% (relative to 2015) at global scale for the most optimistic scenarios while an increase of at least 40% will be observed for the most pessimistic scenarios, both in Europe and elsewhere. In terms of benefits, optimistic scenarios lead to global benefits of 590 million USD whereas the cost of inaction may be up to 566 million USD (increased economic costs due to crops losses).

Impacts of short-lived air pollutants ($PM_{2.5}$, NO_2) are strongly linked to emission location and emission controls are largely driven by countries' self-interest. In contrast, the transboundary nature of the air quality impacts of CH_4 emissions justifies international cooperation. In this context, the availability of scientific assessment tools, encompassing the full impact chain from CH_4 emissions to impacts as well as the evaluation of economic costs and benefits is essential in building trust and confidence among collaborating partners.

5.5 Promising economic sectors to effectively achieve CH_4 emission reductions

This report shows that there is a substantial mitigation potential in the three major emitting sectors: energy, waste and wastewater, and agriculture, especially for the global contribution from developing countries.

These mitigation potentials are reflected in the emission scenarios analysed in this report. Lower energy consumption, fuel substitution, but also upgrading old gas and oil production and gas distribution infrastructure are important factors. According to IEA, almost 50% of methane emissions from the energy sector can be mitigated at negative marginal costs.

Likewise, for waste related emissions, alignment with several sustainable development goals in developing countries may help to realize these emission reductions.

The scenario analysis indicates a somewhat smaller emission reduction potential for agriculture than for energy and waste. Improvement in animal health and efficiency of milk and meat production is a straightforward strategy to mitigate emissions. Especially in Eastern Europe, but also outside Europe, substantial emission reductions per unit production may still be achieved. Worldwide, and especially in Asia, further improvements in rice production would be key to achieve important emission reductions. A wide range of technological options exist to reduce CH_4 emissions from agriculture, but there is not yet much experience with a wide-spread implementation and with possible implementation barriers. Economic studies suggest that targeted subsidies (e.g. to support CH_4 anaerobic digesters, feed supplements, and vaccination), may avoid displacement of production to abroad and emission leakage. There is a mounting evidence that substantial reductions of the current animal products protein consumption would have a large potential to reduce CH_4 emissions. Dietary change would also reduce nitrogen emissions to water and air (including the GHG N_2O), and would have additional health benefits. Scenarios that assume reductions of meat and dairy consumption by 50%, suggest a reduction of CH_4 emissions by up to 45%, but the societal change in food attitudes will require time.

Literature reviews indicate that many CH_4-emission reduction technologies may have low cost or even be profitable, in particular in waste and fossil fuel production [39]. However, uncertainties associated to the cost of such ambitious mitigation strategies remains large.

While switching to a renewable hydrogen (H_2) economy would be a way to abandon methane in the future, H_2 leakages during the production, supply and usage chain will increase the lifetime of methane in the atmosphere, via atmospheric chemical processes, and hence its impacts.

5.6 The way forward

Methane emission abatements have benefits in terms of O_3-exposure, crop production, air quality and climate. The following considerations are put forward to support the prioritisation of future actions.

1) To improve our knowledge about atmospheric processes and emissions

- Our understanding of large-scale O_3 trends in the last decades is limited by the lack of reliable remote and rural stations, even if tropospheric ozone satellite observations become increasingly available with higher accuracy and resolution. Funding for continuation of long-term background ozone and methane observations is under pressure, while they are essential to characterise long-

[39] https://iopscience.iop.org/article/10.1088/2515-7620/ab7457/meta

term background changes and imperative to test models - a prerequisite for most of the points below.

- Bottom-up emission inventories are highly uncertain, in particular for fugitive emissions from fossil fuels and solid waste treatment. Top-down inverse modelling emission estimates as well as satellite data can be used to improve CH_4 inventories, but they are highly dependent on observations, from facility scale to regional. Detection at high resolution of methane leakages and hotspots by satellite is useful to improve emission inventories.
- Although we have relatively good knowledge on the specific contributions of methane to ozone, improving the understanding of the overall ozone budget (ozone production from anthropogenic emissions, natural emissions, stratospheric inflow and deposition processes), will also provide a scientifically more convincing case for the role of methane in determining ozone trends. Continuation of model development and systematic testing of parameterisations and processes in global and regional atmospheric models *will help in further understanding ozone trends.*

2) To achieve a better understanding of the CH_4 impacts

- It is recommended that WHO reviews this new evidence and if appropriate gives guidance on its possible inclusion in health impacts assessment methodologies. The WHO has revised in 2021 the 8-hourly averaged O_3 concentration guideline threshold to 100 µg m^{-3} (ca. 50 ppb). If those concentrations would again increase due to increasing methane emissions, there is limited possibility for local emission controls. Accurate quantification of the factors that may drive ozone away from or towards these limit values remains essential.
- Estimates of ozone impacts on crop yields, quantity and quality of production are based on fairly simplified methods, which are gradually replaced by more advanced approaches that measure and model ozone fluxes into crops, and consider other confounding factors. The understanding of the interplay of ozone, climate change, CO_2 and climate change adaptation is very limited and needs to be addressed to properly understand the relative benefits of methane emission reductions. Similar analysis is needed for the impact on (semi-)natural vegetation.

3) To assess the potential of CH_4 emission abatements and developing efficient abatement strategies

- Substantial work on understanding realistic mitigation potentials, cost-barriers etc. is needed. A recent study showed that mitigation actions in NDCs could achieve the GMP goal, but only if implemented to their fullest possible extent (Malley et al., 2023). There are also multiple opportunities to increase methane mitigation ambition further. Additional commitments to implement technical methane mitigation measures could lead to mitigation in excess of the GMP goal. Behavioural measures, such as dietary shifts and reduction in waste generation could further reduce methane, and are included in few NDCs currently.
- In a perspective of global increasing emissions, the relative contribution of Europe to the global emissions declined from ca. 12% in 1970, to 11% in 1990, and 5.2% in 2022. Since the benefits of CH_4 of emission reductions are globally distributed, global mitigation strategies are most effective in reaching substantial health benefits within and outside world regions.
- Feedback mechanisms involving methane in atmospheric chemistry, through OH radicals impacts the formation of $PM_{2.5}$ though species like sulfur dioxide, nitric acid (and indirectly ammonia), and organic components. Policies targeting methane emission should therefore consider implications on $PM_{2.5}$ concentrations as well.
- Acting as soon as possible on the reduction of methane emissions will be beneficial for both climate and air quality. International scientific collaboration on understanding the benefit of CH_4 emission abatement on O_3 and air quality in general, and implementing the findings in a shared policy perspective, remains key to making progress in such complex issues.

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List of abbreviations and definitions

AMAP	Arctic Monitoring and Assessment Programme
ASEAN	Association of Southeast Asian Nations
AR	Assessment Report
CAMS	Copernicus Atmospheric Monitoring Service
CAPRI	Common Agricultural Policy Regional Impact Analysis Model
CCAC	Climate and Clean Air Coalition
CH_4	Methane Simplest alkane, and component of natural gas Contributes to greenhouse Gas Warming and ozone production
CLE	Current Legislation (scenario)
CLRTAP	Convention Long Range Transport Air Pollution under the UN Economic Commission for Europe https://wwwuneceorg/env/lrtap/welcomehtml
CMIP	Climate Model Intercomparison Project
EDGAR	Emissions Database for Global Atmospheric Research JRC in-house worldwide database of air pollutant and GHG emissions
EcAMPA	Economic assessment of GHG mitigation policy options for EU agriculture
ECLIPSE	Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants projects which created an emission dataset (the so called GAINS emission scenario)
EDGAR	Emissions Database for Global Atmospheric Research maintained at JRC
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
EU27	the 27 Member States of the European Union from 1st February 2020 EU15 pertains to the original EU Member States: Belgium, Denmark, Germany, Ireland, Greece, Spain, France, Italy, Luxembourg, Netherlands, Austria, Portugal, Finland, Sweden, United Kingdom and EU13 to new EU Member States: Bulgaria, Czechia, Estonia, Croatia, Cyprus, Latvia, Lithuania, Hungary, Malta, Poland, Romania, Slovenia, Slovakia Leave of United Kingdom 31st January 2020
EU28	EU27 + United Kingdom
ETS	Emission trading System currently covering 45% of EU GHG in 31 European countries Non-ETS comprises all sectors not covered by ETS
FAO	Food and Agricultural organisation of the United Nations
GAINS	Greenhouse gas Air pollutant Interactions and Synergies
GECO	Global Energy and Climate Outlook initiated by JRC and CLIMA to inform EU policy making on future scenarios
GHG	Greenhouse gas absorbs and emits radiant energy within the thermal infrared range, and the principal cause of global warming
GMI	Global Methane Initiative
GMP	Global Methane Pledge
GWP	Global Warming Potential, a measure of the relative importance of a kg of Greenhouse gas emission compared to carbon dioxide typically a timescale of 20 or 100 years is chosen
HEI	Heath Effects Institute
HTAP	Hemispheric Transport of Air Pollution Task Force of the UNECE CLRTAP HTAP1- phase 1 (2005-2010), HTAP2- phase 2 (2011-2018)
IAM	Integrated Assessment Modelling

IEA	International Energy Agency
IIASA	International Institute of Applied Sciences Analysis
IPCC	Intergovernmental Panel on Climate Change; AR4, AR5, and AR6 refer to the 2007, 2013 and forthcoming 2021 assessment reports
JRC	Directorate General Joint Research Centre of the European Commission
MFR	Maximum Feasible Reduction
NECD	National Emission Ceilings Directive
NDC	Nationally Determined Contribution, efforts by each country to reduce national emissions and adapt to climate change
NOAA	National Ocean and Atmosphere Administration (U.S.A.)
O_3	Ozone A powerful oxidising gas which can cause damage in respiratory tissues of human and animals, and stomatal tissues of plants
PM25	Particulate matter with an aerodynamic diameter smaller than 25 micrometer
OECD	Organisation for Economic Co-operation and Development
ppb	parts per billion volume mixing ratios 1 ppb is about equivalent to a concentration of 2 μg m^{-3} for Ozone
RCP	Representative Concentration Pathways- concentrations and associated global emission scenarios to inform the IPCC AR report
RF	Radiative Forcing
RYL	Relative Yield Loss
SLCF	Short-lived climate forcer
SSP	Shared Socioeconomic Pathways analysis framework adopted by the climate change research community to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation Informing the IPCC AR6 report
Tg	Teragram (= 1 Mt, MegaTon)
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
WHO	World Health Organisation
WMO	World Meteorological Organisation

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Annexes

Annex 1. The EDGAR v8.0 CH_4 emissions

In this Annex, pertinent details about the methodology and assumptions used in EDGAR v8.0 to estimate CH_4 emissions for major emitting sectors are reported. The EDGARv8.0 CH_4 emissions are publicly available at: https://edgar.jrc.ec.europa.eu/dataset_ghg80.

Full description of the EDGAR methodology for calculations CH_4 emissions can be found (Janssens-Maenhout et al., 2019; Crippa et al., 2023).

Table 6 provides the EDGAR to IPCC sectors aggregation, while Figure 25 presents CH_4 for major world regions from EDGARv8.0.

Table 6: EDGAR sectors (https://edgar.jrc.ec.europa.eu/dataset_ghg80) relevant for CH_4 emissions, using following the Common Reporting Format (CRF)/Nomenclature For Reporting (NFR) described in IPCC (2006).

Aggregated emissions	EDGAR8.0	IPCC NFR classification
Agriculture	Agricultural soils (mainly rice production)	3C2+3C3+3C4+3C7
	Agricultural waste burning	3C1b
	Manure management	3A2
	Enteric fermentation	3A1
Fuel Production and transformation	Fuel exploitation (including fuel production, oil refineries, transformation industry and fossil fuel fires)	1A1b+1A1ci+1A1cii+1A5biii+1B1b+1B2aiii6+1B2biii3+1B1c+1B1a+1B2aiii2+1B2aiii3+1B2bi+1B2bii+5B
Processes[40]	Iron and steel production	2C1+2C2
	Chemical processes	2B
Waste	Solid waste landfills	4A+4D
	Waste water handling	4B
	Solid waste incineration	4C
Fuel combustion	Power generation industry	1A1
	Road transportation	1A3b
	Aviation (international/domestic)	1A3a
	Non-road transport: Railways, off-road transport, pipelines	1A3c+1A3e
	Shipping (international/domestic)	1A3d
	Combustion for manufacturing	1A2
	Energy for buildings	1A4

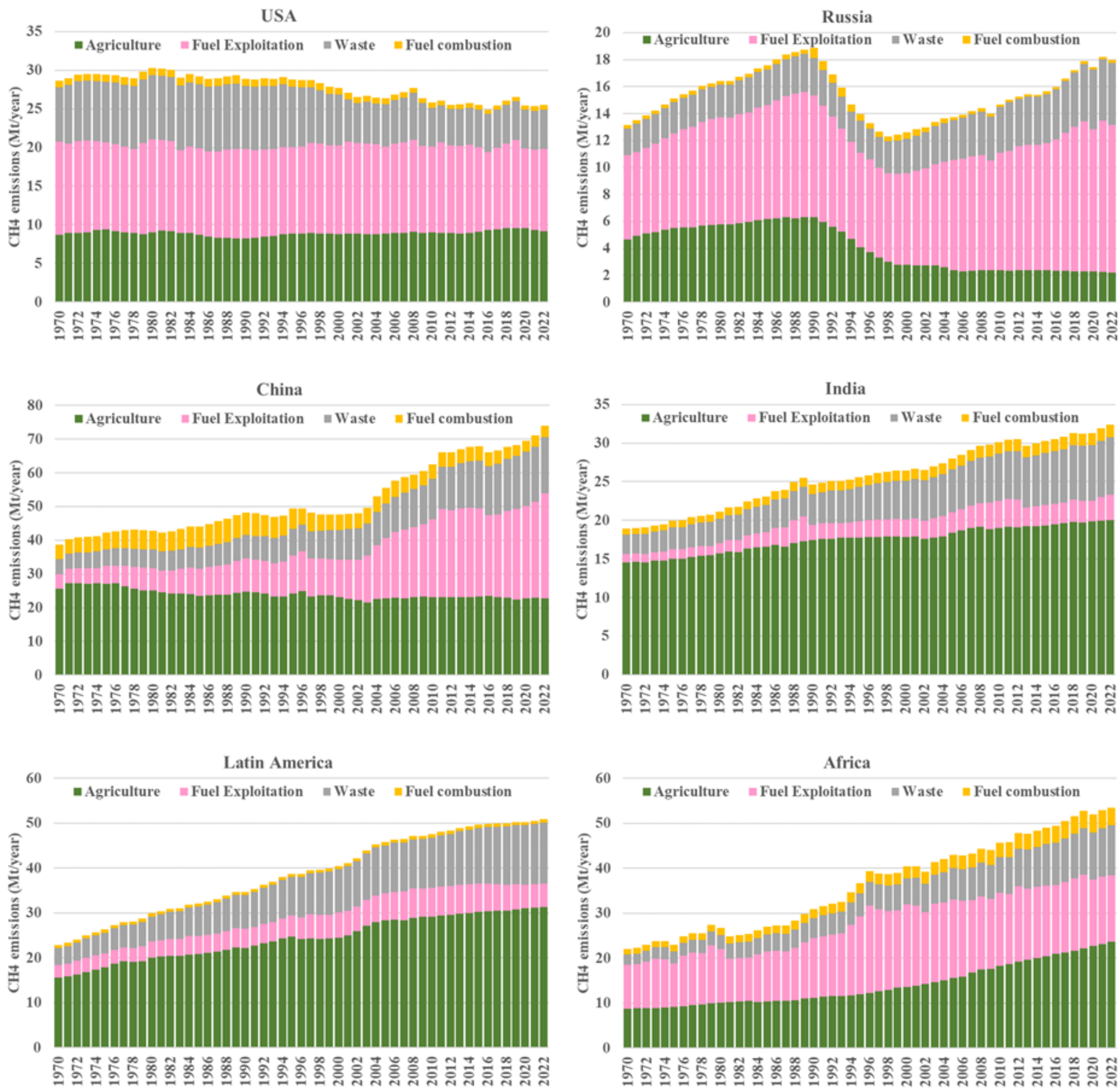
Source: EDGARv8.0.

Figure 25Figure 25 shows the regional trends of CH_4 emissions for major world regions outside Europe. In China and India the large growth of fuel production/transformation are notable. Increases in waste/wastewater are

[40] Due to their small contribution to total CH4 emissions, emissions from processing are represented together with fuel combustion emissions in this report.

important in India, Africa and Latin America, while they are decreasing in the USA. Growth of agricultural emissions is strongly contributing to trends in India, Africa and Latin America.

Figure 25: CH_4 emissions (in Mt CH_4 year^{-1}) for major world regions: fuel exploitation (including production and transformation), waste, fuel combustion and agriculture.



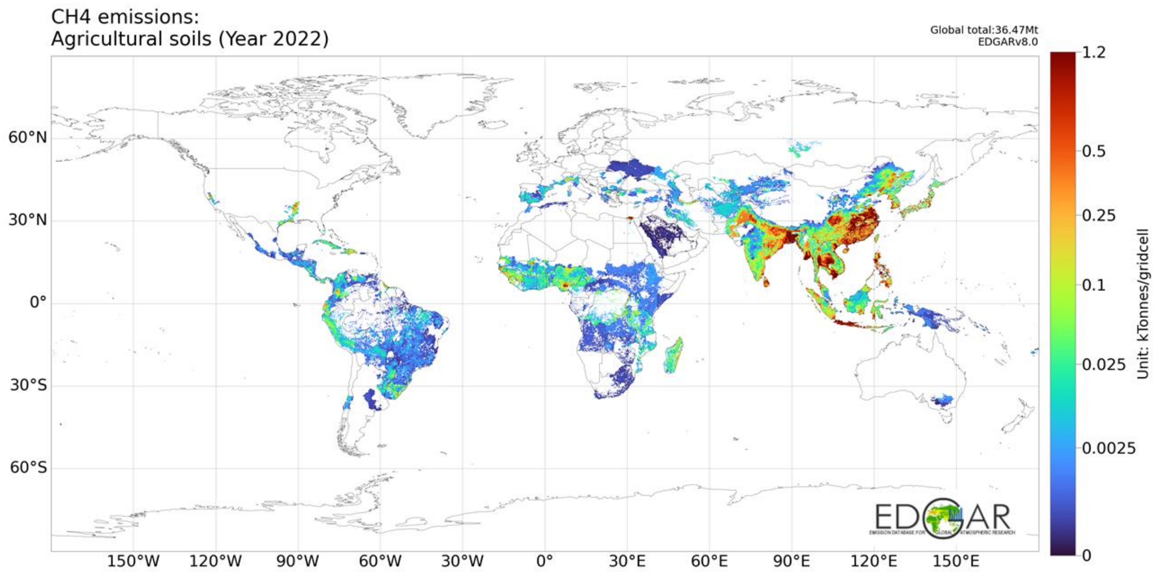
Source: EDGARv8.0.

Annex 2. Sectoral break-down of the anthropogenic CH_4 emissions

A2.1 Emissions from agricultural soils, livestock and other agricultural sources

Global CH_4 emissions from the agricultural sector as a whole were 164 Tg CH_4 yr^{-1} (or 42% of the global anthropogenic total) in 2022, with contributions from agricultural soils (primarily rice production) amounting to 37 Tg CH_4 yr^{-1} or 9% of the global total, and livestock (including both enteric fermentation and manure management) to 125 Tg CH_4 yr^{-1} or 32%. Figure 26 and Figure 27 represent the global distribution of CH_4 emissions from the agricultural soils (mainly rice) and enteric fermentation sectors, respectively, with major

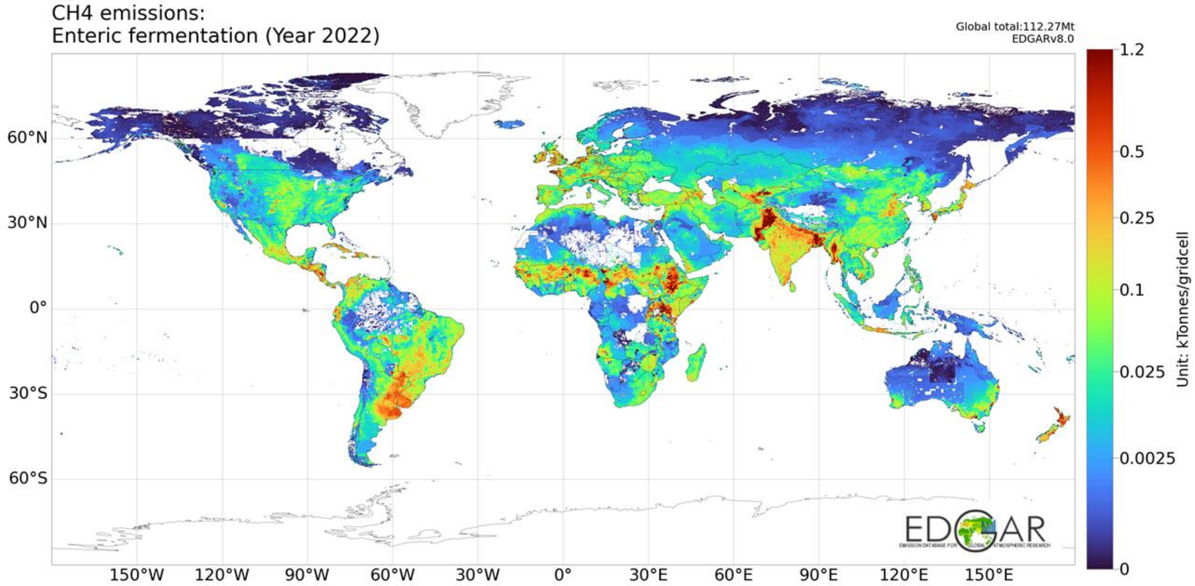
Figure 26: CH_4 emissions from agricultural soils (mainly rice production) in 2022.



Source: EDGAR v8.0.

contributions from agricultural soils in India, China and Asia, and important contributions from enteric fermentation in Europe, USA and Latin America. Global rice emissions declined by 22% during the period 1970-2022, despite a factor 2.3 production increase (FAO data: https://www.fao.org/faostat/en/#home).

Figure 27: CH_4 emissions from enteric fermentation in 2022.



Source: EDGAR v8.0.

Livestock is a dominant source of GHG emissions. In the EU27, enteric fermentation is responsible for about 74% of the agricultural CH_4 emissions, manure for 25%, while contributions from rice cultivation are about 1%. These ratios are rather constant between 1990 and 2022. Including all GHG (i.e. CH_4, N_2O, CO_2) agriculture-related emissions from the energy, industry or land-use sectors would more than double agricultural emissions, with livestock responsible for 81% of the overall agricultural GHG emissions (Life cycle analysis based on the CAPRI model (Leip et al., 2015).

A2.2 Fugitive emissions from fuel production, transport by pipelines and other energy industries

Global fugitive methane emissions from fossil fuel production and transmission amounted to 132 Tg CH_4 yr^{-1} in 2022, representing 33% of the estimated global total anthropogenic CH_4 emissions. An increase from charcoal production in the transformation industry (1.3% of global CH_4 emissions) is seen in particular in African countries and China, where emissions more than doubled (factor 2.3) over the period 1970-2022. The need for reducing emissions from charcoal production to mitigate climate change and improve local livelihoods is addressed in a FAO report (FAO, 2017). Figure 28 provides a spatial overview for the fossil fuel production sector.

Venting (5.5% of the global total) is an important source of CH_4 emissions in specific regions, contributing to up to 28% in the Middle East, 11% in Africa, 10% in USA and 5% in Russia. Such high fuel exploitation regions are important candidates to develop effective emission reduction policies. Fugitive emissions from oil and gas production, transmission and distribution are another rapidly changing and challenging source to quantify. In North America over the period 2005-2012 a shift from coal mining in the North-East (-21%) to gas & oil production in North-Dakota, Montana and Texas in particular (+65%) took place. The USA has become the world's largest producer of both shale gas and tight oil, which together make up almost half of total US gas and oil production (IEA, 2017).

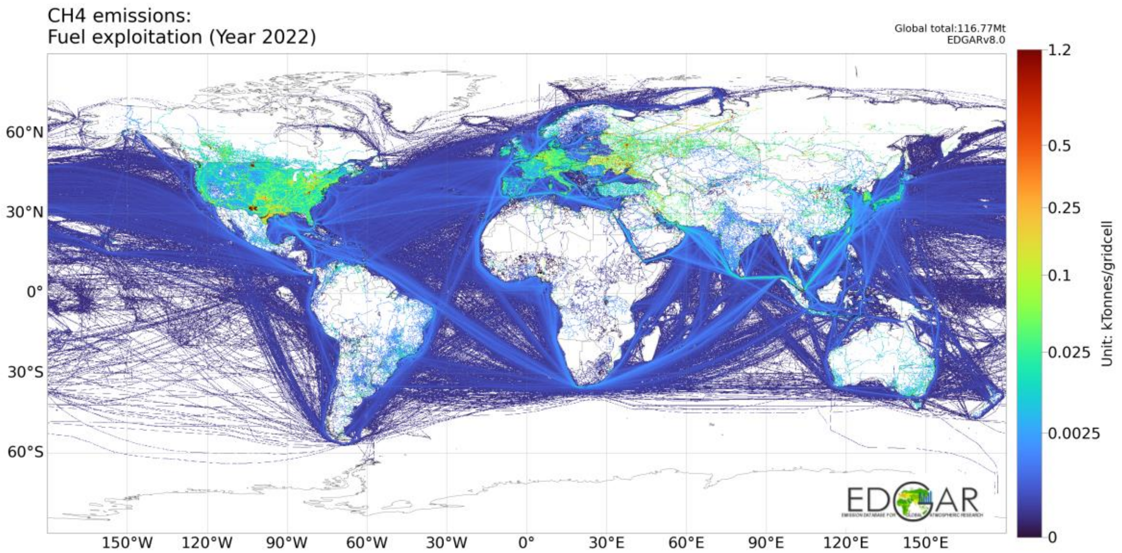
In Europe a much larger 90% reduction in coal production emissions occurred from 1970-2022 (mainly in the late 1980s), while emissions from gas production and transmission increased by 25%. Consequently, the EU27 increasingly relied on oil and gas imports and expanded its transmission and gas distribution network with corresponding increases in CH_4 leakages along the entire distribution chain.

Aside from the USA, the Middle East is also a global world player on the oil and gas market, shifting from oil production (40% decrease over 1976-1985) to gas production (12-fold increase from 1985 to 2022), mainly driven by Iran, Saudi Arabia and Qatar. African countries with the highest CH_4 emissions fuel exploitation are in decreasing order of importance: Nigeria and Algeria (oil and gas production) and South Africa (coal mining).

In Latin America, Brazil, Mexico and Argentina have the highest emissions from oil and gas production with increasing trends over the 5 decades. Russia's gas and oil production shows the world's largest CH_4 venting and leakage emissions, overtaking the USA in importance in 1985. Several studies, *e.g.* Lyon et al. (2015); Peischl et al. (2015), suggest that emissions from this sector could be higher than currently estimated (see also section 3.2 for global studies). Recently, Alvarez et al. (2018) reassessed the magnitude of the leakage of U.S. oil and natural gas supply chain and found that in 2015, supply chain emissions were ~60% higher than the U.S. Environmental Protection Agency inventory estimate. They suggest that this discrepancy exists because current inventory methods miss emissions that occur during abnormal operating conditions.

Methane can be trapped underground when organic strata are converted over time into coal. Fugitive emissions may therefore occur during mining operations and venting as part of normal safety operations. Coal mining has become important in China, which since 1982 has become the largest bituminous coal producer in the world, overtaking the USA. China is also the largest coal importer since 2011 (overtaking Japan), as domestic coal production (mainly in the western and northern inland provinces) faced a transportation bottleneck, lacking southbound rail lines[41] towards the southern coast that has the highest coal demand. CH_4 emissions from coal mining activities increased by 6.7 times from 1970 to 2022, representing 36% of Chinese CH_4 emissions in 2022. Note, however, that emission factors for the oil and gas production and distribution sectors are particularly uncertain.

Figure 28: CH_4 emissions from fossil fuel production in 2022, including areas with intense coal mining and gas & oil production activities with venting. Ship tracks show minor CH_4 leakage during crude oil and natural gas liquids tanker transport.



Source: EDGAR v8.0.

Flaring is widely used by the fossil fuel industry to dispose of natural gas. Industry and governments generally assume that flares remain lit and destroy methane. Neither assumption, however, is based on real-world observations. In a recent study (Plant et al., 2022) flare efficiency were calculated using airborne sampling across three basins responsible for >80% of US flaring and combine these observations with unlit flare prevalence surveys. They find that both unlit flares and inefficient combustion contribute comparably to ineffective methane destruction, with flares effectively destroying only 91.1% of methane. This represents a fivefold increase in methane emissions above present assumptions and constitutes 4 to 10% of total US oil and gas methane emissions, highlighting a previously underappreciated methane source and mitigation opportunity

[41] https://carnegieendowment.org/2012/02/16/understanding-china-s-rising-coal-imports-pub-47215

A2.3 Solid waste and waste water emissions

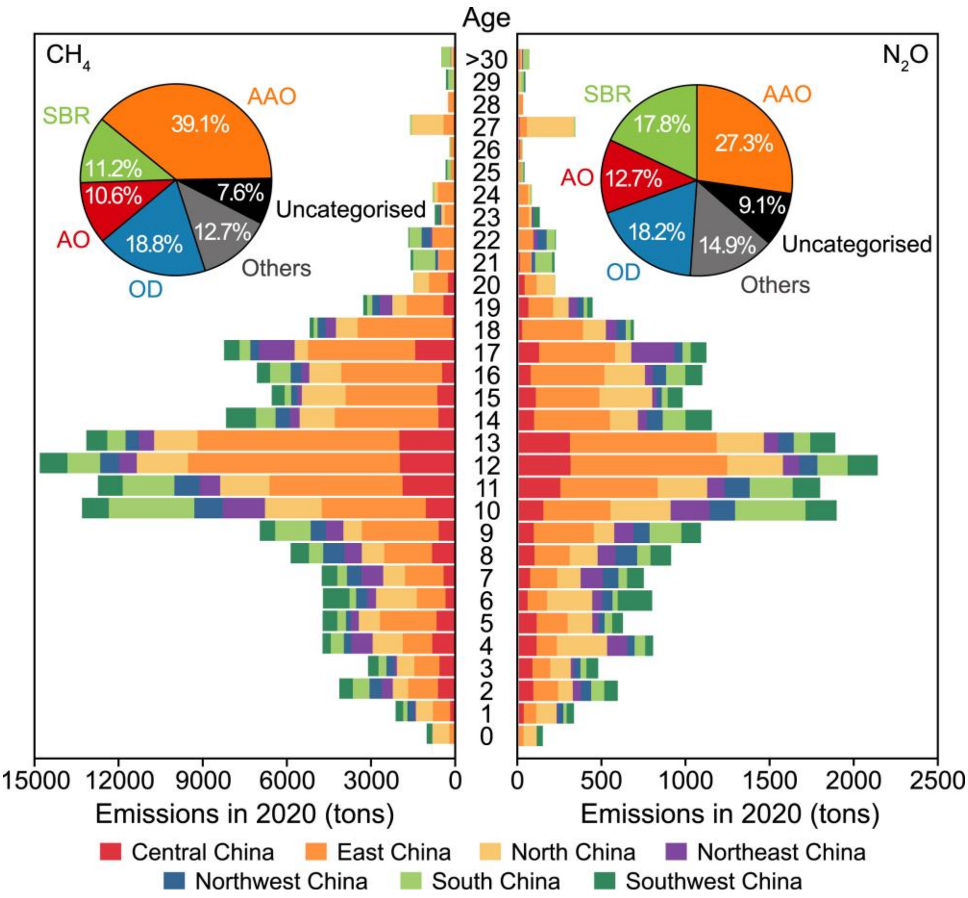
Solid waste and waste-water CH_4 emissions globally amount to 93 Tg CH_4 yr^{-1} (or 23% of the global total) in 2022. Landfills emissions decreased by 40% in EU27 from 1970 to 2022, in particular in Germany, Great Britain and the Netherlands. Over the same time period, they reduced similarly in the USA, while they strongly increased in China, India, Middle East, Russia and Turkey. Emissions from waste water handling in the EU27 increased from 1.7 to 1.8 Tg CH_4 yr^{-1} from 1970 to 2022, while they increased by factors of 2.4 and 2.8 in China and India, respectively.

Song et al. (2023) stressed the likely underestimation of methane emissions from this sector. With updated data sets, they estimated annual CH_4 emission from the U.S. centralized municipal wastewater treatment to be approximately 10.9 ± 7.0 MMT CO_2-eq $year^{-1}$, i.e. about twice the IPCC (of 2019) Tier 2 estimate (4.3–6.1 MMT CO_2- eq $year^{-1}$). This study is coherent with other findings (Moore et al., 2023) in which emissions from US centrally treated domestic wastewater were 1.9 times greater than the US EPA estimates.

De Foy et al. (2023) identified increases of methane over 61 urban areas around the world, mainly driven by waste management that may be underestimated by a factor 3–4 in current emission databases. Scaling these results to the 385 urban areas with more than 2 million inhabitants would mean that these emissions account for up to 22% of the global methane emissions.

A high-resolution mapping of CH_4 (and N_2O) emissions from MWWTPs (municipal wastewater treatment plants) performed in a recent study (Li, You, et al., 2023) highlights that an emission inequality exists with the richest cities emitting two times more CH_4 and N_2O per capita than the poorest. They also show the importance of the age of the MWWTPs on emissions (Figure 29).

Figure 29: Age of MWWTPs (municipal wastewater treatment plants) and related CH_4 and N_2O emissions in China. Bars detail the regional share. Note: 0 years old means that the WWTP began operating after 2020. Pie charts show the contribution of different biological treatment technologies to the total CH_4 and N_2O emissions.



Source: Li, You, et al., 2023.

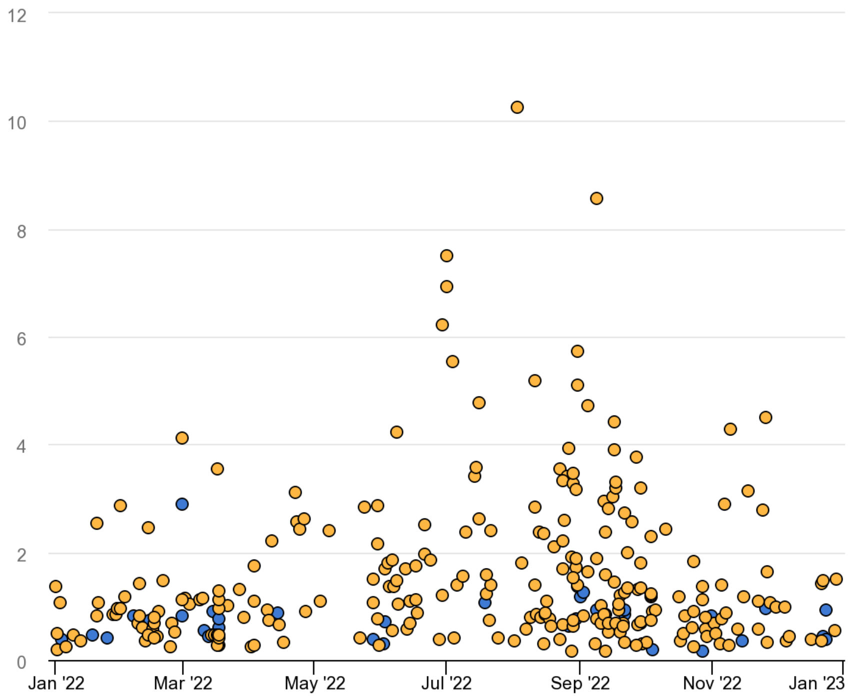
A2.4 Other remaining sources and uncertainties

Other remaining sources of CH_4 emissions are related to production processes of chemicals, iron and steel, the manufacturing industry, fossil fuel fires (*e.g.* Kuwait fires), transformation industry and ground transport (road, inland shipping, and rail) residential and other sectors. In 2022, these sectors amount to 21 Tg CH_4 yr^{-1} (or 5% of the global total of which 3% from the residential sector).

Satellites are now used to evaluate the quality of emission inventories. Shen et al. (2023) find global current emissions of 62.7 ± 11.5 (2σ) Tg $year^{-1}$ for oil-gas and 32.7 ± 5.2 Tg $year^{-1}$ for coal. They estimate that oil-gas emissions are 30% higher than the global total from UNFCCC reports, mainly due to under-reporting by the four largest emitters including the US, Russia, Venezuela, and Turkmenistan.

The use of satellite instruments to detect and quantify methane emissions from fossil fuel production activities is highly beneficial to support climate change mitigation (Gorroño et al., 2023). Large leaks of methane can now be detected by satellites (Figure 30). Satellites detected more than 500 very large leaks from fossil fuel operations in 20 countries. A small portion of these were from coal, likely because coal mine methane emissions are often diffuse and therefore harder to detect (IEA, 2023).

Figure 30: Estimated (kt) Satellite-detected large leaks of methane from fossil fuel operations in 2022 yellow bullets for oil & gas sources, blue for only gas emitters.



Source: IEA, 2023.

In general, the disagreement among emission inventories is larger for the oil/gas sector as compared to coal. This arises mostly from disparate data sources for emission factors. Moreover, emissions reported to the UNFCC are lower than bottom-up and inversion estimates, with many countries lacking reporting in the past decades. Comparison with previous global inverse-modelling studies by Tibrewal et al. (2024), revealed a strong influence of the input emission inventory on the magnitude of the sectoral contributions. . This highlights the need to improve bottom-up inventories to obtain more consistent inverse modelling results at the sub-sectoral level.

Annex 3. Description of the emission Scenarios

Table 7: ECLIPSE scenarios description (Amann et al., 2018; Belis et al., 2022), *In NPS, fossil fuel subsidies phased out in all net-importing countries, and in net-exporting countries where specific policies have been announced.**In CPS fossil fuel subsidies phased out only in countries that already have relevant policies in place.

Scenario V6b	Description	Air quality policy	Climate policy
CLE BASE	Current legislation (baseline)	Current baseline projections according to the IEA World Energy Outlook 2018 New Policy Scenario (NPS*) which includes EU 2030 renewable energy and energy efficiency targets and announced energy policies by China, USA, Japan and Korea.	Incorporates only commitments made in the national determined contributions (NDC) under the Paris Agreement.
MFR BASE	Maximum technical reduction baseline	Stringent policy assuming introduction of best currently available technology and no cost limitations. However, no further technological improvements are foreseen. Same activity drivers as CLE following NPS.	Incorporates only commitments made in the NDCs under the Paris Agreement.
MFR SDS	Maximum technical reduction sustainable development (most ambitious scenario)	Similar to MFR base. However, relies on the most ambitious IEA sustainable development scenario (SDS). Includes outcomes of energy-related SDGs: reducing dramatically premature deaths due to energy-related air pollution and universal access to modern energy by 2030.	Aligned with Sustainable Development Goal #13 and Paris Agreement goal of keeping global average temperature increase below 2 C.
NPS NFC	No further control baseline	No new measures beyond 2015–2018. Turnover of stock is included. However, the impact of recent stringent legislation like diesel-gate related measures, low-sulfur fuel for marine vessels and eco-design (e. g. residential heating devices) is not considered. Same activity drivers (NPS) as CLE.	Incorporates only commitments made in the NDCs under the Paris Agreement.
CPS NFC	No further control current energy policies (most pessimistic scenario)	Similar to NFC base. However, relies on IEA current policy scenario (CPS**) based on laws and regulations existing as of mid-2018. Excludes the announced policies.	Paris Agreement NDCs are missing implying higher share of fossil fuels and less fuel efficiency than NFC base.

Source: https://iiasa.ac.at/models-tools-data/global-emission-fields-of-air-pollutants-and-ghgs.

Table 8: Description of RCP scenarios in AR5. In all three scenarios, Kuznets -curve assumptions were made for air pollutants, leading to relatively similar air pollutant emissions across scenarios.

RCPs	Description	Warming by 2100 compared to pre-industrial world
RCP8.5	RCP8.5 (8.5 W m^{-2}) is characterised by increasing greenhouse gas emissions over time representative for literature scenarios leading to high greenhouse gas concentration levels. CO_2 emission projections are 75.6 and 105.5 Tg CO_2 yr^{-1} in 2050 and 2100, respectively.	Median global increase of 4.2°C
RCP6.0	Stabilisation scenario (6.0 W m^{-2}) where total radiative forcing is stabilised after 2100 without overshoot by employment of a range of technologies and strategies for reducing greenhouse gas emissions. By the end of the century, CO_2 emission projections are 45.9 and 50.7 Tg CO_2 yr^{-1} in 2050 and 2100, respectively.	Median global temperature increase of 2.7 °C
RCP4.5	Scenario described by the IPCC as an intermediate scenario. Emissions in RCP4.5 peak around 2040, then decline. RCP4.5 is the most probable baseline scenario (no climate policies) taking into account the exhaustible character of non-renewable fuels.	Mean global temperature increase of 2.2°C
RCP2.6	The emission pathway is representative of scenarios in the literature leading to greenhouse gas concentration levels near or below the present day values. It is a so-called "peak" scenario: radiative forcing level first reaches a value around 3.1 W m^{-2} mid-century, returning to 2.6 W m^{-2} by 2100. In order to reach such radiative forcing levels, greenhouse gas emissions (and indirectly emissions of air pollutants) are reduced substantially over time. CO_2 emissions evolve from 35.6 Tg CO_2 yr^{-1} in 2010, 12.9 in 2050 to -1.5 Tg CO_2 yr^{-1} in 2100.	Median global temperature increase of 1.6°C

Source: IIASA https://tntcat.iiasa.ac.at/RcpDb.

Table 9: List of SSP scenarios and short description. Grey rows highlight the priority scenarios for IPCC, others are variants. More information on the integrated models used for the development of the SSP scenariosl in Riahi, van Vuuren, et al., 2017; Meinshausen et al., 2020 and https://tntcat.iiasa.ac.at/SspDb.

SSPs	Climate policy GHGs	Air pollution control	Warming (2081-2100)
SSP1_1.9 (Vuuren et al., 2017)	Very low GHGs emissions CO_2 emissions cut to net zero around 2050	strong	1.4°C
SSP1_2.6 (Vuuren et al., 2017)	Low GHGs emissions, \newline CO_2 emissions cut to net zero around 2075	strong	1.8°C
SSP2_4.5 (Fricko et al., 2017)	Intermediate GHGs emissions, CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100	medium	2.7°C
SSP3_7.0 (Fujimori et al., 2017)	High GHGs emissions, CO_2 emissions double by 2100	low	3.6°C
SSP3_7.0-LowNTCF (Fujimori et al., 2017)	Reduce CH_4 as if SSP1's stringent climate mitigation policy is implemented in the SSP3 world	strong	-
SSP4_3.4 (Calvin et al., 2017; O'Neill et al., 2017)	"Inequality" or "A Road Divided," scenario, characterized by low challenges to mitigation and high challenges to adaptation : limitation to RF=3.4 W m^{-2} at the end of century	low	-
SSP4_6.0 (Calvin et al., 2017)	"Inequality" or "A Road Divided," scenario, characterized by low challenges to mitigation and high challenges to adaptation : limitation to RF=6.0 W m^{-2} at the end of century	low	-
SSP5_8.5 (Kriegler et al., 2017)	Very high GHGs emissions, CO_2 emissions triple by 2075	strong	4.4°C
SSP5_3.4-OS (Kriegler et al., 2017)	Represent a world in which action towards climate change mitigation is delayed but vigorously pursued after 2050, resulting in a forcing and mean global temperature overshoot	strong	2.25°

Source: Lee and et al., 2023.

Table 10: Description of GECO 2022 scenarios.

GECO 2022	Description
GECO-REF	This scenario corresponds to a world where existing policies related to energy supply and demand policies and targets, as well as legislated GHG policies and targets that are backed by supporting energy sector policies, are enacted. No additional policies are considered compared to what had been legislated as of June 2022. Exogenous macroeconomic projections (GDP and population), with endogenously calculated energy prices and technological development specific to the POLES-JRC model, combine with the effect of enacted policies resulting in projections of the energy system and GHG emissions. As a consequence, this scenario may differ from energy and emissions projections from official national sources and international organisations. This scenario does not aim to reach stated policies or targets that have not been translated into law and accompanied by concrete action plans.
GECO-NDC-LTS	Ahis scenario considers the policies of NDCs in the medium term and the LTSs in the longer term. This scenario assumes that the objectives in the NDCs (including conditional objectives) are reached in their relevant target year (2030 in most cases). To this end, carbon values and other regulatory instruments are put in place on top of the existing, legislated measures of the Reference Scenario. Beyond 2030, the objectives of the countries' LTS, where they exist, are pursued; if the country has not announced an LTS, it is assumed that no additional decarbonisation effort is made, and carbon values, if any, are kept constant to their 2030 level. This scenario includes the net zero targets announced by many countries. The NDC-LTS scenario also considers decarbonisation proposals related to international aviation and maritime transportation sectors (international bunker fuels). An NDC-Only case was also modelled, where the effect of the LTSs was removed from the NDC-LTS scenario in order to quantify the impact of each mechanism; carbon prices of the NDC-LTS scenario, if any, were kept constant after 2030 in the NDC-Only case
GECO-1.5C	A decarbonisation scenario designed to limit global temperature increase to 1.5°C Scenario. The scenario was designed with a global carbon budget over 2020-2100 (cumulated net CO_2 emissions) of approximately 400 $GtCO_2$, resulting in a 50% probability of not exceeding the 1.5°C temperature limit in 2100

Source: Keramidas et al., 2022.

Table 11 displays the emission ratio (2050/2010) for the main sectoral activities for 16 scenarios. The high emission scenarios are typically characterised by increases between 50 and 150% (increase by 100-300 Tg CH_4 yr^{-1} by 2050). In the middle group, emissions remain close to their 2010 values (ca. 300 Tg CH_4 yr^{-1}h) whereas they reduce by 50% (or more) in the low range to reach values around 200-250 Tg CH_4 yr^{-1}. RCP and SSP scenarios are calibrated to the reference year 2000, and projected to 2010, thereby missing effects of policies implemented between 2000 and 2010. In contrast, ECLIPSE and GECO are calibrated to 2010.

Concerning the ECLIPSE scenarios, V6b shows a lower ambition than V5a for the mid-century MTFR projections with slight increases for the energy and waste activity sectors. For the CLE scenario the picture is different with larger reductions expected for the energy sector and a slightly lager increase for the waste management. The wide range of assumptions regarding the implementation of mitigation measures and to some extent also demand for fuel and food, are the primary reason for the wide diversity of future emissions. This diversity is more prominent for the energy and waste sectors than for agriculture.

Comparing 2050 to 2010, relative sectoral emission changes show that the most ambitious scenarios are (i) GECO-NDC-LTS, GECO-1.5C and SSP1-1.9 with an emission reduction of at least 88% for the energy sector, (ii) SSP1-2.6, GECO-1.5C and SSP1.9 with a reduction of at least 39% for the agriculture sector, (iii) ECLIPSE V6b-MFR-BASE, ECLIPSE-V6b-MFR-SDS and RCP-2.6 with a reduction of at least 51% for the waste sector. The radar plot Figure 13 highlights a certain coherence between the evolution of the agriculture and energy sectors whereas the waste sector is disconnected.

Table 11: Ratio of global methane emissions in 2050 relative to 2010 of the 3 major sectors in 16 scenarios sorted from the less to most ambitious on agriculture emissions - *Into brackets we remind the ratio for the ECLIPSE V5a scenario.

Scenarios	Energy	Agriculture	Waste
SSP3-7.0	1.21	1.80	1.66
RCP8.5	2.14	1.60	2.31
RCP6.0	1.24	1.20	0.77
SSP2-4.5	0.91	1.15	0.72
RCP4.5	1.09	1.14	1.03
ECLIPSE-V6b-CPS-NFC	1.47	1.12	1.93
ECLIPSE-V6b-NPS-NFC	1.18	1.12	1.93
*ECLIPSE-V6b-CLE-BASE (V5a)**	1.17 (1.79)	1.05 (1.24)	1.91 (1.86)
*ECLIPSE V6b-MFR-BASE (V5a)**	1.13 (0.55)	1.03 (1.13)	0.47 (0.41)
GECO REF	0.73	1.03	1.77
ECLIPSE-V6b-MFR-SDS	0.28	1.03	0.49
RCP2.6	0.40	0.80	0.20
GECO-NDC-LTS	0.22	0.73	0.92
SSP1-2.6	0.36	0.61	0.97
GECO-1.5C	0.12	0.59	0.63
SSP1-1.9	0.22	0.58	0.74

Source: JRC elaboration of emission data (see Tables 7 to 10)

Annex 4. Overview of methane-focused mitigation measures whose inclusion in Nationally Determined Contributions

Table 12: Methane mitigation measures.

N°	Sector	Mitigation measures	IPCC source sector where emissions are reduced	Maximum emission reduction factor (maximum % reduction in sectoral methane emissions from implementation of mitigation measure)	Source	No. of countries including measure in NDCs
1	Energy—Coal, Oil and Gas	Reduce gas flaring in oil and gas sector	1.B.2 Oil and Natural Gas	99%	(Höglund-Isaksson et al., 2020)	19
2		Minimise venting, flaring and fugitive emissions from oil and gas sector	1.B.2 Oil and Natural Gas	85%–96% 99%—extended recovery and utilization of vented associated gas	IPCC, (Höglund-Isaksson et al., 2020)	30
3		Minimise methane emissions from coal mining	1.B.1 Solid Fuels	90% pre-mine degasification on both surface and underground coal mines	(Höglund-Isaksson et al., 2020)	4
4		Avoid future expansion of coal, oil and gas infrastructure	1.B.2 Oil and Natural Gas	100%		1
5	Agriculture	Reduce emissions from livestock enteric fermentation (e.g. through feed optimization, breeding and genetic improvements)	3.A.1 Enteric Fermentation	30%	(Höglund-Isaksson et al., 2020)	49
6		Reduce emissions from livestock manure management	3.A.2 Manure Management	50–75%—anaerobic digestion 94–99%—Conversion from solid storage or liquid slurry to daily spread manure management system	(Höglund-Isaksson et al., 2020), IPCC	57
7		Implement intermittent aeration of continuously flooded rice paddy fields	3.C.7 Rice Production	45%—Reduction from conversion from continuously flooded to multiple drainage period water management system	IPCC)	33
8		Increase proportion of people with diets that have lower climate impact (e.g. reducing red meat consumption)	3.A.1 Enteric Fermentation 3.A.2 Manure Management	25%—shifting to healthy diets that reduces red meat consumption	(UNEP and CCAC, 2021)	3

9		Reduce proportion of food wasted	3.A.1 Enteric Fermentation 3.A.2 Manure Management 3.C.7 Rice Production	Average proportion of meat (and dairy) wasted by region (agricultural production to consumption) Europe—24.8% North America and Oceania—25.5% Industrialised Asia—22.5% Sub-Saharan Africa—29.7% North Africa, West and Central Asia—24.8% South and Southeast Asia—21.4% Latin America—22.4%	FAO	7
10		Reduce methane emissions from solid waste at landfill sites (including methane capture and use for waste to energy)	4.A Solid Waste Disposal	80%—high-end of recovery efficiencies from available studies	IPCC	99
11	Waste	Increase percentage of solid waste separated and recycled or composted	4.A Solid Waste Disposal	90% 100%	IPCC, (Höglund-Isaksson et al., 2020)	94
12		Reduce solid waste generation	4.A Solid Waste Disposal	100%	IPCC	33
13		Upgrade wastewater treatment plants with methane gas recovery (or use biodigesters)	4.D Wastewater Treatment and Discharge	93%—biogas recovery and utilisation 96% (difference in CH_4 emission factor between anaerobic reactor and aerobic wastewater treatment plant) 75% high end efficiency for methane recovery from anaerobic treatment plant	IPCC, (Höglund-Isaksson et al., 2020)	59

Source: Malley et al., 2023

Annex 5. World regions aggregation

Table 13: HTAP2 receptor region aggregation.

Region name	Aggregation
North America	US + Canada (up to 66 N; polar circle)
Europe	Western + Eastern EU + Turkey (up to 66 N polar circle)
South Asia	India, Pakistan, Nepal, Bangladesh, Sri Lanka
East Asia	China, Korea, Japan
South East Asia	South East Asia
PAC-AUS_NZL	Pacific, Australia+ New Zealand
North Africa	Northern Africa
South Africa	Sub Saharan Africa
Middle East	Middle East; Gulf countries, Iran, Iraq
Central America	Mexico, Central America, Caribbean, Guyanas, Venezuela, Columbia
South America	South America
Rus Bel Ukr	Russia, Belarus, Ukraine
CAS	Central Asian Republics

Source: TF HTAP. www.htap.org.

Annex 6. O_3 impact on health and crop yields

A.5.1 Health

In this work, cause-specific excess mortalities are calculated using a population-attributable fraction approach as described in Murray et al. (2003) from ΔMort = m0 × AF × Pop, where m0 is the baseline mortality rate for the exposed population, AF = 1–1/RR is the fraction of total mortalities attributed to the risk factor (exposure to air pollution), RR = relative risk of death attributable to a change in population-weighted mean pollutant concentration, and Pop is the exposed population (adults ≥ 30 years old

For O_3 exposure, $RR = e^{\beta(\Delta \mathrm{SDMA8h})}$, β is the concentration–response factor, and RR = 1.040 [95% confidence interval (CI): 1.013, 1.067] for a 10 ppb increase in SDMA8h according to Jerrett et al. (2009). We apply a default counterfactual concentration of 33.3 ppb, the minimum SDMA8h (or simply also abbreviated as M6M in some studies) exposure level in the Jerrett et al. (2009) epidemiological study.

A.5.2 Crop impacts

The methodology applied in TM5-FASST to calculate the impacts on four crop types (wheat, maize, rice, and soy bean) is based on (Van Dingenen et al., 2009). In brief, TM5 base and -20% perturbation simulations of gridded crop O_3 exposure metrics (averaged or accumulated over the crop growing season) are overlaid with crop suitability grid maps to evaluate receptor region-averaged exposure metrics SR coefficients.

We use as metrics the seasonal mean 7 hr or 12 hr day-time ozone concentration (M7, M12) for which exposure-response functions are available from the literature (Wang and Mauzerall, 2004) and which is a more robust metric in a linearized model set-up.

Both M_i metrics are calculated as the 3-monthly mean daytime (09:00 – 15:59 for M7, 08:00 – 19:59 for M12) ozone concentration, evaluated over the 3 months centred on the midpoint of the location-dependent crop-growing season. The Weibull-type exposure-response functions express the crop relative yield (RYL) loss as a function of Mi:

$$RYL = 1 - \frac{exp\left[-\left(\frac{Mi}{a}\right)^{b}\right]}{exp\left[-\left(\frac{c}{a}\right)^{b}\right]}$$

The parameter values in the exposure response functions and the applied methodology are described in detail by Van Dingenen et al. (2009), however gridded crop data (growing season and suitability, based on average climate 1961 – 1990) have been updated using Global Agro-Ecological Zones data set (IIASA and FAO, 2012, available at http://www.gaez.iiasa.ac.at/). Again we note that the non-linear shape of the RYL(Mi) function requires the ΔRYL for 2 scenarios (S1, S2) being evaluated as RYL($M_{i,S2}$) – RYL ($M_{i,1}$), and not as RYL ($M_{i,S2}$- $M_{i,S1}$).

Using average 2000 to 2010 global market prices we estimate for the four crops a global associated loss in 2010 of US$ 19 to 39 billion, and for wheat alone in Europe US$ 1.5 to 4.4 billion. This number can be compared to the estimate in (Maas and Grennfelt, 2016): 4.6 billion for wheat alone in the entire EMEP region.

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