# The contribution of historical methane emissions to present-day warming

**Andy Reisinger, June 2024**

**Prepared for the Parliamentary Commissioner for the Environment**

## Summary

Global average surface temperature has increased by about 1.06°C between 1850-1900 and 2010-2019 and is continuing to rise. The Intergovernmental Panel on Climate Change (IPCC) found that virtually all of this global warming is due to human activities, mainly in the form of greenhouse gas emissions. While carbon dioxide emissions are the main driver of global warming, a sizable fraction of about 0.5°C of present-day warming is due to emissions of methane, mainly arising from agriculture, fossil fuel extraction and use, and waste.

The purpose of this brief study was to better understand how much individual sources of methane emissions have contributed to present-day warming. This includes clarification of the relative contributions from fossil methane (associated with fossil fuel extraction and use), and biogenic methane (associated with the decay of organic matter and arising from agriculture, waste and to a lesser extent the burning of biomass), and specifically of the contribution from agricultural emissions compared to other biogenic sources.

I used the relatively simple climate model FAIR to simulate the warming caused by different methane sources, based on estimates of historical global emissions used in global climate studies. The FAIR model reproduces the observed overall warming and the contribution of 0.5°C from methane emissions quite closely, giving confidence that the model is indeed suitable to determine the relative contributions to warming from different methane sources.

I found that out of the estimated 0.5°C due to methane emissions, about 60% (0.3°C) were due to biogenic methane and about 40% (0.2°C) were due to fossil methane. The simulated warming from fossil methane includes warming due to carbon dioxide generated when methane decays. This carbon dioxide is additional in the case of fossil methane, but is merely part of the short-term carbon cycle in the case of biogenic methane. The contribution from this carbon dioxide is very small, however: only about 2% of the total warming caused by all historical methane emissions is due to carbon dioxide generated by the decay of fossil methane. This demonstrates that most of the warming from $CH_4$ emissions comes from the radiative and chemical properties of $CH_4$ itself, regardless of its biogenic or fossil origin.

Within biogenic methane, agriculture is the dominant contributor to warming. About two thirds (65%) of the warming from biogenic methane is due to agriculture, just under one third (28%) is due to waste, and the remainder (about 7%) is due to biomass burning.

The 0.5°C of warming from historical global methane emissions arises despite the relatively short atmospheric lifetime of methane, given the sustained and growing emissions from both fossil and biogenic sources. However, in contrast to carbon dioxide, this warming does not constitute a lasting legacy: if methane emissions from any of these sources were reduced

substantially, this warming would also reduce over time. The only exception is the warming from carbon dioxide generated by the decay of fossil methane; but at only 2% of the total warming from global methane emissions to date, this is only a small fraction of the warming from methane itself that could be avoided by reducing future methane emissions.

## Context and findings by the IPCC

The Intergovernmental Panel on Climate Change (IPCC) in its most recent assessment report found that global average surface temperature has increased by 1.06°C (0.88-1.21°C, 5-95 percent confidence interval) in the period 2010-2019, relative to average temperature in 1850-1900 (Gulev et al. 2021). For the remainder of this report I will refer to the temperature increase in the period 2010-2019 relative to 1850-1900 as "present-day warming", but note that global average temperatures have continued to increase since then, with 2023 marking the warmest year on record to date (Forster et al. 2024).

Virtually all of this warming has been attributed to human activities, mainly in the form of the emission of greenhouse gases. In fact, the warming attributable to greenhouse gases is greater than the observed warming, because the concurrent emission of cooling aerosols has offset some of the warming from greenhouse gases (see Figure 1, panel b). Natural factors affecting the climate have not played a material role in the overall warming over the past 150 years, as can be seen from the same figure: the best estimates of warming attributed to changes in solar radiation and volcanic eruptions, and to internal variability of the climate system, are zero.

The IPCC also provided a more detailed breakdown of the different contributions of the emission of individual gases and other climate forcers associated with human activities to the modelled and observed warming (see Figure 1, panel c).

The dominant contribution to the observed global warming comes from emissions of carbon dioxide ($CO_2$) associated with human activities, mainly the burning of fossil fuels (about 69%) and to a lesser extent from deforestation (about 31%). These estimated relative contributions are based on cumulative emissions from those sources from 1850 to 2019 (Friedlingstein et al. 2022). Those emissions are estimated have caused about 0.8°C of warming in 2010-2019, relative to 1850-1900.

The next biggest contribution to global warming comes from human-caused emissions of methane ($CH_4$), associated with agriculture; fossil fuel extraction, transport and use; waste; and biomass burning. These emissions are estimated to have caused about 0.5°C of warming in 2010-2019, relative to 1850-1900. This estimate includes warming caused by tropospheric ozone and stratospheric water vapour that are generated when $CH_4$ decays naturally in the atmosphere. These indirect effects add to the direct warming caused by every $CH_4$ emission.

The combined contribution to present-day warming from historical $CO_2$ and $CH_4$ emissions can therefore be estimated at about 1.3°C. This is greater than the observed warming because other human activities have had a slight net cooling effect that partly offset the warming from those two gases. The largest cooling effect came from the emission of sulphur dioxide in smokestacks, which causes a slight dimming of incoming solar radiation.

The gross warming effect from $CO_2$ and $CH_4$ emissions and the overall cooling effect from other activities results in an attributed **net** warming *attributed to human activities* of 1.07°C in 2010-2019, relative to 1850-1900. This closely matches the observed warming of 1.06°C over the same period. The close agreement of those two numbers indicates that human activities are responsible for basically all of the observed warming, and that natural effects (changes in solar radiation, volcanic eruptions, and internal variability of Earth's climate system) have not played a material role in the observed temperature changes over the past 150 years (IPCC 2021).

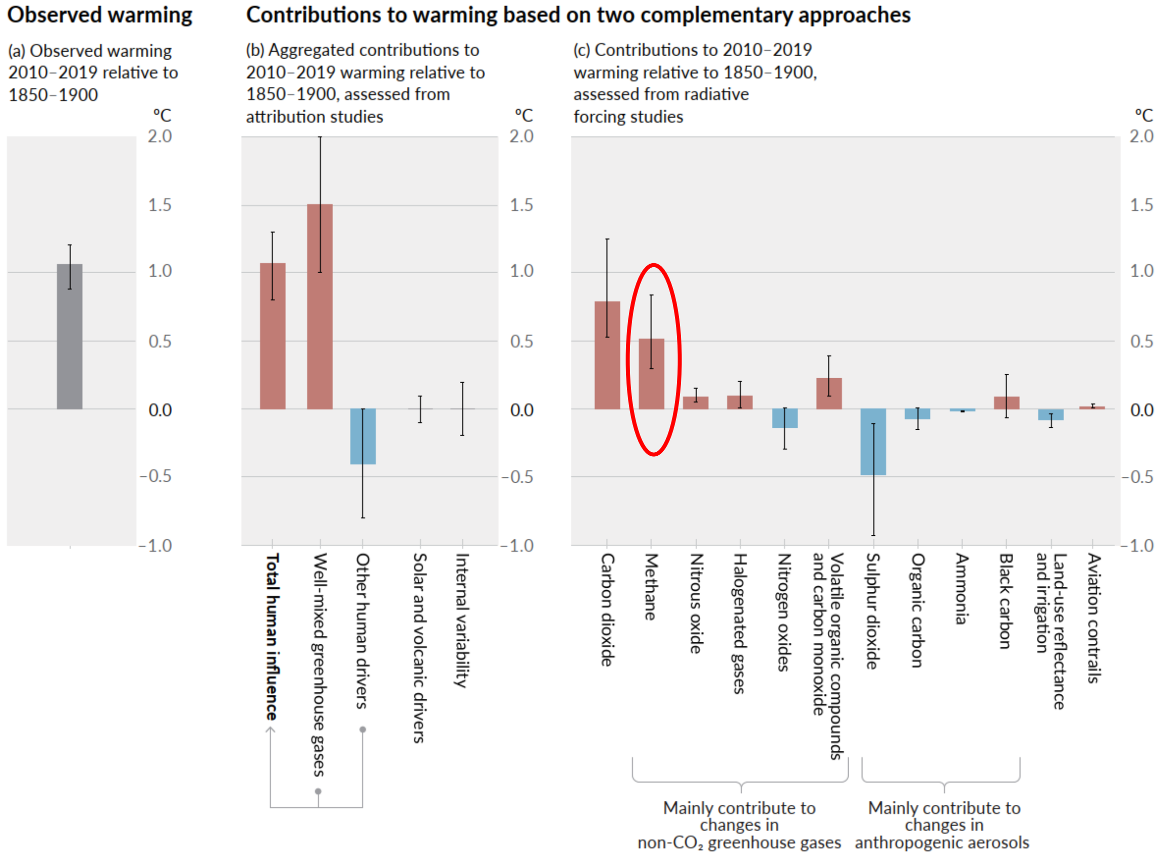


*Figure 1. Contribution of human activities to observed warming between 1850-1900 and 2010-2019 as assessed by the IPCC. Panel (a) indicates the observed warming. Panel (b) shows the aggregated contributions from human activities releasing greenhouse gases, other human drivers, solar and volcanic activity, and internal variability. Panel (c) breaks down the contributions from human activities for emissions of different greenhouse gases and other climate forcers. The assessed contribution from methane emissions to warming, estimated at 0.5°C, along with the uncertainty range of this contribution, is highlighted. Figure SPM.2 from IPCC (2021).*

The IPCC assessment used a range of atmospheric chemistry models and radiative forcing studies to arrive at the central estimate of 0.5°C for the warming caused by $CH_4$ emissions, with a 5-95 percent confidence interval of 0.29-0.84°C. However, the IPCC assessment did not explore in detail how much different $CH_4$ sources (e.g. fossil fuels, agriculture, waste) contributed to the overall warming of 0.5°C.

The main purpose of this report is therefore to provide a more detailed understanding and evaluation of the contribution of different global $CH_4$ emission sources to present-day warming. This includes understanding the relative respective contributions from fossil and biogenic $CH_4$ emissions (including the $CO_2$ component in fossil $CH_4$ emissions), and from the individual biogenic $CH_4$ sources (agriculture, waste, and biomass burning).

Fossil $CH_4$ is associated with the extraction, transport and use of fossil fuels (such as coal, oil and gas) and arises from fugitive emissions and incomplete combustion of those fuels. By contrast, biogenic $CH_4$ is generated when recently produced biomass breaks down through microbial processes in agriculture and landfills or incomplete combustion of vegetation in forest fires or the burning of crop residues. The distinction between fossil and biogenic $CH_4$ matters from a climate perspective because $CH_4$ emitted into the atmosphere eventually breaks down into $CO_2$. The $CO_2$ that is generated when fossil $CH_4$ breaks down constitutes an additional emission of $CO_2$ that will in itself have a long-lasting warming effect on the climate. By contrast, the $CO_2$ produced in the decay of biogenic $CH_4$ is not considered to be additional since roughly the same amount of $CO_2$ would have been absorbed when the relevant biomass was produced with the aid of photosynthesis. By undertaking a detailed model study, this report also seeks to clarify to what extent the distinction between fossil and biogenic $CH_4$ emissions has made a material difference for the present-day warming caused by different $CH_4$ sources.

# Historical methane emissions from different sources

$CH_4$ has a relatively short lifetime in the atmosphere of just over a decade. However, this does not mean that a tonne of $CH_4$ emitted at a given point in time will have disappeared entirely a decade later, since the term 'lifetime' is a technical term used to indicate the exponential rate of decay of the gas. Further, the warming caused by an emission lingers for significantly longer than the emission itself, similar to the way that even a poorly insulated room remains warm for some time after the heater has been turned off. This is illustrated in Figure 2. As a rule of thumb, it will take almost 50 years for a given $CH_4$ emission to disappeared almost entirely, and while most of the warming caused by an individual emission will occur in the two decades following the emission, some warming lingers for more than century into the future (Reisinger 2018).

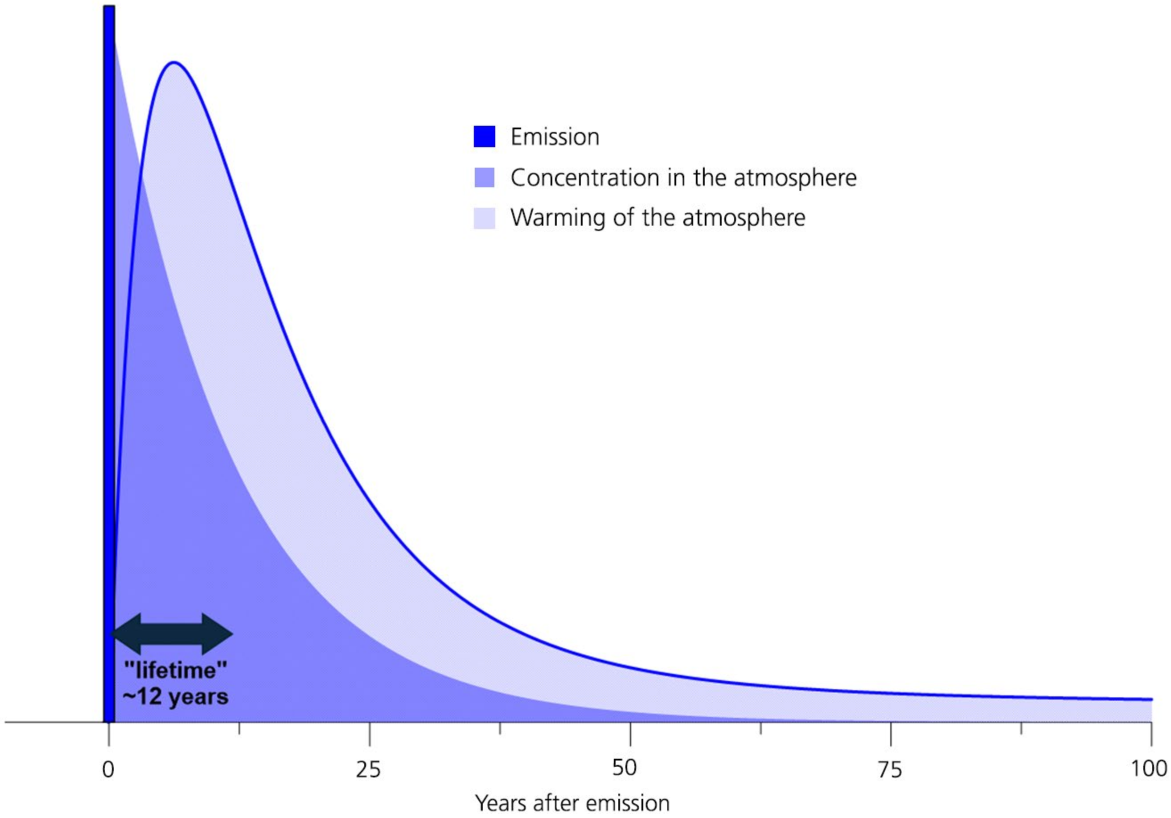


*Figure 2. The change in atmospheric concentration and resulting warming caused by an individual emission of biogenic $CH_4$. The changes over time in concentration and warming apply to the present-day atmosphere and are taken from the most recent IPCC assessment (Forster et al. 2021).*

The relatively short lifetime of $CH_4$ means that the contribution of $CH_4$ emissions from any source to global warming depends mostly on the recent rate of those emissions, not its cumulative emissions since the preindustrial period as is the case for $CO_2$. It is therefore not critically important to know exactly the amount of $CH_4$ emissions in the late 19$^{th}$ century if we wish to know how much different $CH_4$ sources have contributed to present-day warming. However, this is only approximately true, since (as Figure 2 shows) some of the warming from more distant historical $CH_4$ emissions will accumulate over time. In addition, the generation of $CO_2$ from the decay of fossil $CH_4$ will also result in a cumulative warming effect that is not captured if one simply compares recent rates of $CH_4$ emissions from different sources.

For this reason, this report uses a simple climate model that can simulate the warming caused by past emissions over different times, together with an estimate of historical $CH_4$ emissions from different sources. This allows a detailed exploration of the contribution of different $CH_4$ emission sources to present-day warming.

For historical emissions, I used the emissions dataset generated in support of the Coupled Model Intercomparison Project Phase 6 (CMIP6). CMIP is an on-going global collaborative effort to improve and test our understanding of the global climate system and the ability of complex models to reproduce past changes in climate and compare future changes projected by different models. In support of this project, global datasets of historical and future emissions of greenhouse gases as well as aerosols have been produced (Hoesly et al. 2018).

Figure 3 shows the historical $CH_4$ emissions up to 2020 from fossil and biogenic sources, and individual contributions to biogenic $CH_4$, based on the CMIP6 emissions dataset that has also been used in other model intercomparisons. For this report, I assumed that all $CH_4$ emissions associated with energy extraction, transport and use are fossil, and all $CH_4$ emissions arising from agriculture, forestry and other land uses, as well as from waste, are biogenic.

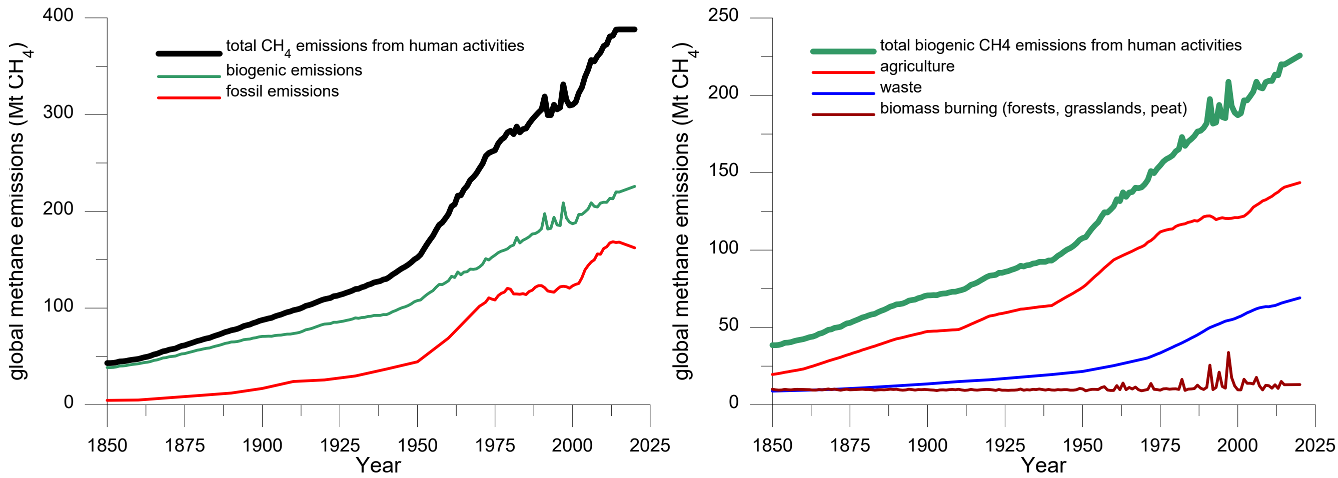


*Figure 3. Estimated historical methane emissions from human activities from a range of sources. The left panel shows total methane emissions from human activities, and the relative contribution of fossil and biogenic sources. The right panel shows the contribution of different biogenic sources (agriculture, waste, and biomass burning) to the total biogenic methane emissions from human activities. Data from 1850 to 2015 are from Hoesly et al. (2018) as produced for the Coupled Model Intercomparison Project Phase 6 (CMIP6) and as used in the Reduced Complexity Model Intercomparison (RCMIP), summarized in the most recent IPCC assessment (Forster et al. 2021). Emissions from 2015 to 2020 were extrapolated using the SSP 2-4.5 global emissions scenarios which approximately resembles current global climate policies (IPCC 2022).*

Based on this classification, about 42% of recent (average over the 20 years from 1996 to 2015) $CH_4$ emissions are fossil, and 58% are biogenic. Within biogenic $CH_4$ emissions, almost two thirds are from agriculture, just under one third from waste, and a small fraction with high interannual variability from biomass burning. Emissions from all sources other than biomass burning have increased substantially since the mid-19th century, but at different rates. Agricultural $CH_4$ emissions occupied a larger share of total $CH_4$ during the 19th century, while fossil $CH_4$ emissions have risen rapidly since the mid-20th century associated with the equally rapid increase in $CO_2$ emissions from fossil fuel use (Minx et al. 2021).

Estimates of historical emissions of all greenhouse gases, especially those that occur outside the energy sector (including fugitive emissions of $CH_4$ during fossil fuel extraction), have significant uncertainties. Other global historical emissions databases exist and could give slightly different answers for emissions especially from agriculture and waste. However, it was beyond the scope of this report to investigate let alone reconcile different datasets. The CMIP6 emissions data for $CH_4$ from all sources are within 10% of other global datasets, but differences can be larger for specific sectors (Hoesly et al. 2018). Global datasets can also suffer from biases in that can result in systematic under- or overestimates. Examples include fugitive $CH_4$ emissions associated with the recent expansion of gas extraction and use that are thought to have contributed to the recent rise in $CH_4$ concentrations but that may not be fully captured in official inventories (Shindell et al. 2024), and estimates of $CH_4$ from enteric fermentation where data gaps limit the quality of emissions estimates and differences between different global datasets can be as high as 30% (Wolf et al. 2017; Hristov et al. 2018; Nabuurs et al. 2022).

Uncertainties in estimates of $CH_4$ emissions from different sources will directly flow into uncertainties of the relative contributions of those sources to global warming. The impacts of uncertainties in $CH_4$ emissions prior to about 1970 are likely to be small since, as noted above, most of the present-day warming from historical $CH_4$ emissions will come from emissions that occurred over the past two to three decades, where global emissions data are more robust.

# Reproduction of attributed warming using FAIR

Apart from datasets of historical emissions, the second important tool to understand the contribution of historical emissions to present-day warming is a simple climate model that simulates the contribution of each emission to global warming at a given point in time. For this report I used the Finite Amplitude Impulse Response (FAIR), version 2.13, that has been used extensively in scientific research and in recent IPCC reports (Forster et al. 2021; Leach et al. 2021). The model has been calibrated to emulate the assessed historical and projected warming based on the IPCC 6th Assessment Report; for this report I used calibration dataset 1.3.1 (Smith 2023).[1]

Figure 4 demonstrates the ability of FAIR to reproduce the observed warming trend, based on the complete CMIP6 dataset of historical emissions (greenhouse gases, greenhouse gas precursors and aerosols) as well as natural drivers of climatic variability (changes in solar irradiation and volcanic activity). The modelled best estimate of warming in 2010-2019, relative

[1] For an evaluation of the performance of FAIR compared to complex global climate models and other reduced complexity models see Cross-Chapter Box 7.1: Physical Emulation of Earth System Models for Scenario Classification and Knowledge Integration in AR6, in Forster et al. (2021).

to 1850-1900, is 1.05°C, in close agreement with the IPCC assessed contribution to global warming of 1.07°C derived from a range of complex climate models (Eyring et al. 2021).

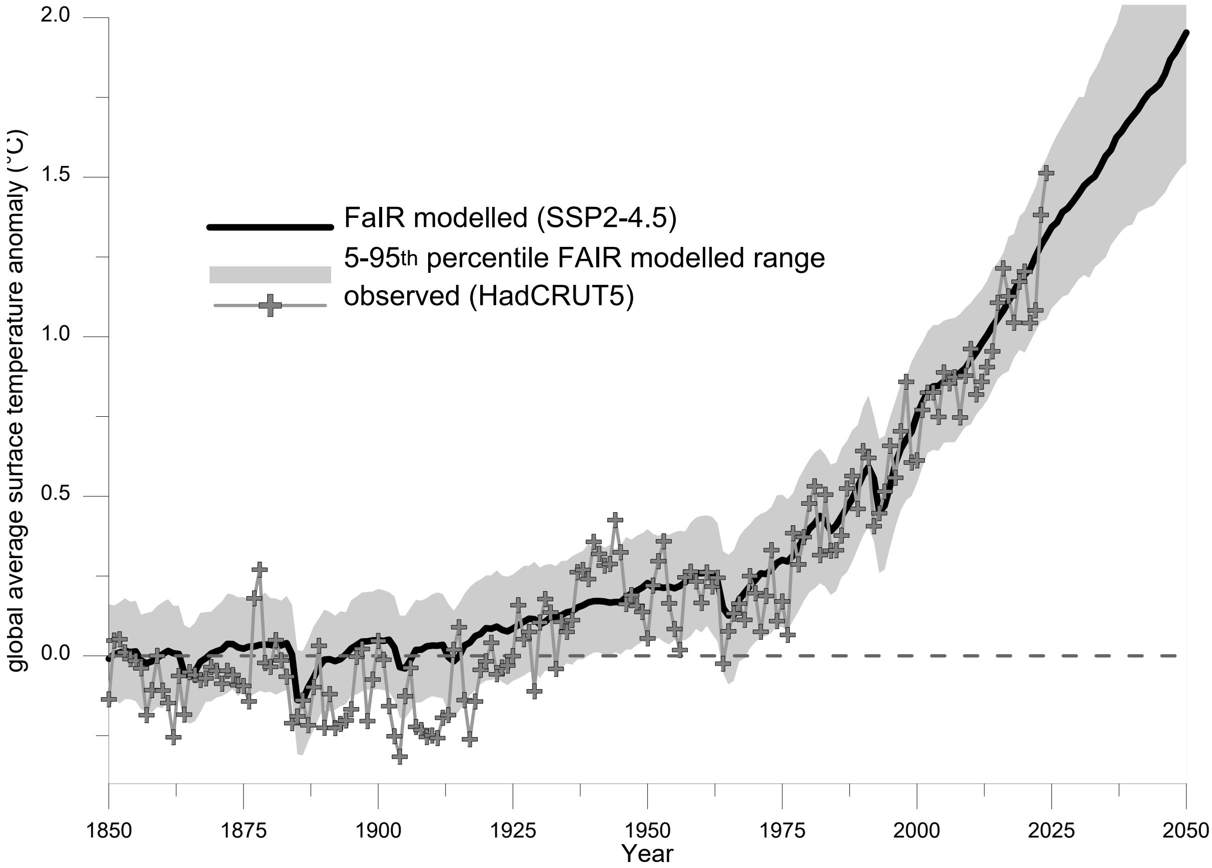


*Figure 4. Observed and modelled change in global average surface temperature. The black line shows the modelled change in temperature using FaIR (Leach et al. 2021), relative to the average modelled temperature during 1850-1900, calibrated to reproduce the warming as assessed by the IPCC (Forster et al. 2021; Smith 2023). The grey area indicates the 5-95th percentile range of modelled warming for the 1001-member calibration parameter set (Smith 2023). Historical emissions use the CMIP6 dataset up to 2015, with emissions after that following the SSP2-4.5 emissions scenario. Crosses and thin gray lines represent the change in observed annual average temperature, using the UK MetOffice's global temperature dataset HadCRUT5 (Morice et al. 2021), offset to result in the same average temperature change during the period 1961-1990 as the modelled temperature change.*

The advantage of the FAIR model is that it allows users to not only reproduce the results from more complex climate models, but also to ask what-if questions. A key what-if question relevant to this report is how much global average surface temperature would have increased if there had been no historical $CH_4$ emissions, but all other emissions and natural drivers had been the same. The difference between the warming from all emissions shown above, and the warming that results from all emissions except historical global $CH_4$ emissions, can then be interpreted as the contribution of historical $CH_4$ emissions to present-day warming.

Implementing this approach using FAIR indicates that global historical $CH_4$ emissions have contributed 0.49°C to present-day warming (i.e. average temperatures in 2010-2019, relative to 1850-1900), in very close agreement with the IPCC-assessed central estimate of 0.5°C. The close agreement is to be expected given that FAIR was calibrated based on results from the same model intercomparison that was used in the IPCC assessment (Thornhill et al. 2021).

The 5-95 percent confidence interval based on FAIR is 0.34-0.77°C; the uncertainty range represents the 5-95$^{th}$ percentile range of outcomes for the 1001 different parameter sets with which FAIR is run to reflect uncertainties in key aspects of the climate system (Leach et al. 2021; Smith 2023). The 5-95 percent confidence interval assessed by the IPCC of 0.29-0.84°C is about 25% greater than the range from FAIR simulations. This makes sense since the FAIR parameter set does not include uncertainties in the atmospheric lifetime of $CH_4$ or in some of its chemical interactions that are included in the full IPCC uncertainty assessment.

The close reproduction of the IPCC assessment results for total $CH_4$ emissions gives high confidence that this approach using FAIR is a valid way to explore the contribution of individual $CH_4$ emission sources to present-day warming.

# Warming attributed to different methane sources

The approach outlined above was implemented for the different $CH_4$ emission sources shown in Figure 3. For each individual emission source, the FAIR model was first run with the complete set of emissions, and secondly with all emissions except for the specific $CH_4$ emissions source; the difference in global temperature between those two runs is then interpreted as the contribution of that emissions source to global warming.

The warming from different sources based on this approach is not strictly additive, because the radiative efficacy of a given emission depends on the $CH_4$ concentration in the atmosphere due to other emission sources. For example, the warming from $CH_4$ emitted from landfills is greater if this is assumed to be the only source of $CH_4$ emissions, than if concurrent emissions from agriculture are included in the model calculations. In the methodology used here, warming is calculated first with all $CH_4$ emissions and secondly with all emissions *except* for the source of interest. This attributes slightly less warming due to each source than if that source is run as the only source of $CH_4$ emissions and all other sources being zero.

FAIR assumes natively that all $CH_4$ emissions are biogenic (C. Smith, personal communication). To simulate warming specifically for fossil $CH_4$ emissions, I therefore added a separate source of fossil $CO_2$ emissions that represents the atmospheric decay of fossil $CH_4$; that is, for each molecule of fossil $CH_4$ emitted, I prescribe to the model in addition the emission of a molecule of $CO_2$. Taking into account the different molecular weights of $CH_4$ and $CO_2$, this means that each tonne of fossil $CH_4$ emitted also results in the emission of 2.75 tonnes of $CO_2$. The overall amount of $CO_2$ emitted from this process is small compared to $CO_2$ emitted from fossil fuel combustion directly (the estimated 150 Mt of fossil $CH_4$ emitted in 2020 result in an additional emission of 413 Mt fossil $CO_2$ globally, which is about 1% of the roughly 40,000 Mt $CO_2$ emitted directly globally from the burning of fossil fuels).

Note that the fate of carbon contained in $CH_4$ is more complex than this simple assumption. The recent IPCC assessment indicated that not all carbon contained in $CH_4$ ends up as $CO_2$ in the atmosphere, but only about 75%. This applies to both biogenic and fossil $CH_4$, and in principle means that a full modelling of $CH_4$ emissions should include both $CO_2$ emissions and removals associated with the production and atmospheric decay of $CH_4$.[2] However, the *difference* between fossil and biogenic $CH_4$ is always that the emission and subsequent decay of fossil $CH_4$ causes the emission of one complete additional $CO_2$ molecule compared to the

[2] for a more detailed discussion of the fate of $CO_2$ in the decay of $CH_4$ see Section 7.6.1.3, page 1014, in Forster et al. (2021)

production, release and subsequent decay of biogenic $CH_4$. Since the purpose of this report is to understand the relative contributions of biogenic and fossil $CH_4$ emissions to the IPCC-assessed overall present-day warming from all $CH_4$ emissions, I assumed that each fossil $CH_4$ molecule generates one complete additional $CO_2$ molecule at the same time.

Table 1 summarises the results, and Figure 1 illustrates graphically the contributions to global warming from the different global sources of $CH_4$ emissions.

Fossil $CH_4$ (including warming due to $CO_2$ generated in the decay of this fossil $CH_4$) contributed about 40% (0.20°C) to the total warming from $CH_4$, while biogenic $CH_4$ contributed about 60% (0.29°). Agriculture contributed roughly the same amount of warming (39% or 0.19°C) as fossil $CH_4$ from all sources, and waste contributed about 16% (0.08°C). Out of the warming due to biogenic $CH_4$ alone, about two thirds (65%) come from agriculture and just under one third (28%) come from waste, with the remainder (about 7%) from biomass burning.

*Table 1. Contribution to present-day warming (i.e. the increase in global average surface temperature in 2010-2019 relative to 1850-1900) from different $CH_4$ emission sources, modelled using FAIR. Temperature estimates have been rounded to two significant digits. Uncertainties represent the 5-95 percentile range of temperature simulations using FAIR. Taking into account other sources of uncertainty as assessed by the IPCC would increase the uncertainty range by about 25% in each case. Note that uncertainties for the warming from different sources are highly correlated since they would apply equally to all emission sources and describe only uncertainties in the climate response to emissions. Uncertainties in the emissions estimates themselves are not included. For details see text.*

| | total $CH_4$ | biogenic $CH_4$ | agriculture $CH_4$ | waste $CH_4$ | fossil $CH_4$ | … of which fossil $CO_2$ from the decay of fossil $CH_4$ |
|---|---|---|---|---|---|---|
| **warming (°C)**<br>**5-95 percent confidence** | 0.49<br>(0.34-0.77) | 0.29<br>(0.20-0.46) | 0.19<br>(0.13-0.30) | 0.08<br>(0.06-0.12) | 0.20<br>(0.14-0.30) | 0.01 |
| **best estimate percent of warming from all $CH_4$** | | 59% | 39% | 16% | 41% | 2% |
| **best estimate percent of warming from biogenic $CH_4$** | | | 65% | 28% | | |

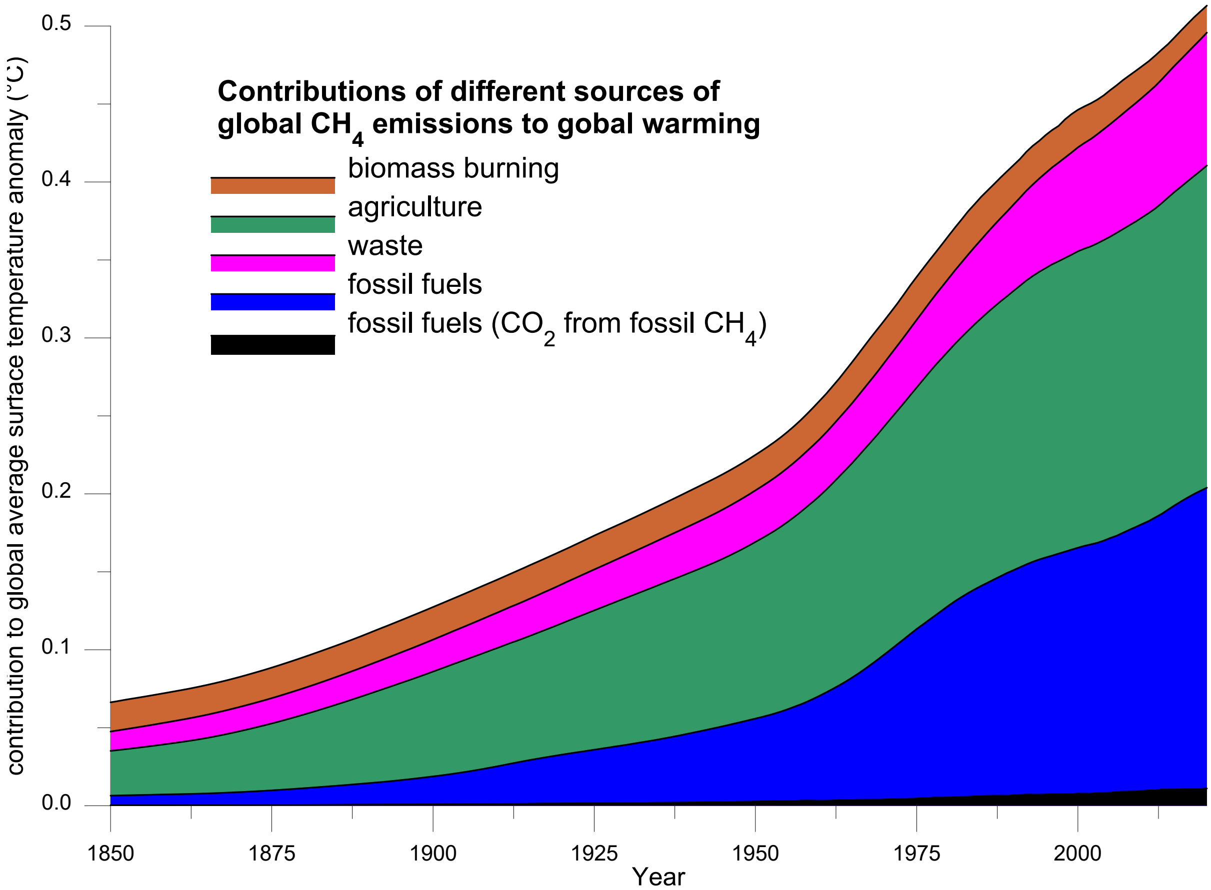


*Figure 5. Contributions of different sources of global $CH_4$ emissions to global warming over the period 1850 to 2020. Contributions have been modelled using FAIR and CMIP6 historical emissions data (for details, see text).*

As Table 1 and Figure 5 show, the additional $CO_2$ released by the atmospheric decay of fossil $CH_4$ contributes only a small fraction of about 2% (0.01°C) of the total present-day warming from global $CH_4$ emissions, and about 4% of the present-day warming from historical fossil $CH_4$ emissions. While the warming from this additional source of $CO_2$ is not necessarily negligible and is effectively permanent (unless compensated by future $CO_2$ removals), this demonstrates that most of the warming from $CH_4$ emissions comes from the radiative and chemical properties of $CH_4$ directly, regardless of its biogenic or fossil origin.

The warming from the $CO_2$ component of fossil $CH_4$ is slightly higher than the warming included in the IPCC assessment. The IPCC assessment assumed a constant split between biogenic and fossil $CH_4$ emissions and resulted in a contribution of about 1.5% to the total warming from $CH_4$ (S. Blichner and T. Berntsen, personal communication). However, this is considered to be in reasonable agreement given the simplified treatment of fossil vs biogenic $CH_4$ emissions in the IPCC assessment, and in either case demonstrates the relatively small role of this source of $CO_2$ in the overall warming from $CH_4$ emissions.

## Comparison with recent emission rates

As noted earlier, given the relatively short atmospheric lifetime of $CH_4$, simply comparing recent rates of emission of different sources should serve as a reasonable approximation of the relative contributions of those sources to global warming.

Using average emissions in the 20-year period from 1996 to 2015 as a basis for comparison, fossil and biogenic $CH_4$ emissions were about 42% and 58% of total $CH_4$ emissions, respectively of that period. These percentages are indeed very similar to the modelled contribution to global warming from those emissions of 41% and 59%, respectively (see Table 1). Similarly, agricultural $CH_4$ emissions constituted about 63% of total biogenic $CH_4$ emissions during 1996-2015 and were modelled to have contributed about 65% of the total present-day warming from biogenic $CH_4$ emissions.

These comparisons demonstrate that using recent (here, the average over the preceding two decades) rates of $CH_4$ emissions can indeed serve as a useful proxy for the total contribution to global warming from those emission sources. This is in contrast to CO2, whose contribution to global warming depends on the cumulative total emissions over the entire historical period (i.e. where emissions that occurred a century ago contribute almost the same to present day warming as an emission that occurred only a decade ago).

However, the close relationship between the recent rate of $CH_4$ emissions and the overall contribution of $CH_4$ to global warming does not necessarily always hold to such a high degree. In scenarios where emissions change rapidly or in different directions between two different emission sources, the actual warming realized at a given point in time could be less well approximated by a simple comparison of recent emission rates. For example, in a situation where $CH_4$ emissions from a given source have been rising rapidly, the warming due to emissions from that source would not have been fully realized yet. Vice versa, if emissions from a given source are falling rapidly, the actual warming will still be influenced by the higher emissions over the preceding two decades.

## Summary and conclusions

This report explored the contribution of individual global sources of $CH_4$ emissions to present-day global warming (where present-day warming is used as short-hand for the increase in global average surface temperature in the period 2010-2019, relative to 1850-1900).

I used the relatively simple climate model FAIR and a global emissions database to simulate the warming attributable to individual $CH_4$ sources, specifically fossil $CH_4$ associated with the extraction, transport and use of fossil fuels, and biogenic $CH_4$ from agriculture, waste and biomass burning. The FAIR model reproduces very closely the present-day warming as assessed by the IPCC from all human-caused emissions (1.06°C) as well as the warming specifically from human-caused $CH_4$ emissions (0.5°C).

I find that out of the 0.5°C of present-day warming attributable to total $CH_4$ emissions from human activities, about 60% is due to biogenic $CH_4$ and 40% is due to fossil $CH_4$. Out of the warming from biogenic $CH_4$ emissions, about two thirds are due to agriculture and just under one third to waste. Note that these fractions depend strongly on the assumed emissions over the past few decades from those different sources. It was beyond the scope of this report to quantify the uncertainty of these results due to uncertainties in global emission estimates, but it should be noted that different global datasets for $CH_4$ emissions have an uncertainty of up to 30%. This directly translates into uncertainty about the relative contribution from agriculture and biogenic methane to the total warming from all $CH_4$ emissions from human activities.

The additional $CO_2$ that is generated by the decay of fossil $CH_4$ makes a small contribution of only about 2% to the overall warming from all $CH_4$ emissions. This indicates that most of the warming from $CH_4$ comes from $CH_4$ itself, regardless of its fossil or biogenic origin.

The 0.5°C of present-day warming from historical global $CH_4$ emissions arises despite the relatively short atmospheric lifetime of $CH_4$, given the sustained and growing emissions from both fossil and biogenic sources. However, in contrast to $CO_2$, this warming does not constitute an on-going commitment or responsibility: if $CH_4$ emissions from any of these sources were reduced substantially in the future, the warming would also reduce over time. The only exception is the warming from $CO_2$ generated by the decay of fossil $CH_4$, but at only 2% this warming commitment from historical emissions is only a small fraction of the warming from $CH_4$ itself that could be avoided if its future emissions could be reduced substantially.

# Bibliography

Eyring V, Gillett N, Achuta Rao KM, et al (2021) Chapter 3: Human influence on the global climate system. In: Masson-Delmotte V, Zhai P, Pirani A, et al. (eds) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Oxford, UK, pp 423–551

Forster PM, Smith C, Walsh T, et al (2024) Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence. Earth System Science Data 16:2625–2658. https://doi.org/10.5194/essd-16-2625-2024

Forster PM, Storelvmo T, Armour K, et al (2021) Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In: Masson-Delmotte V, Zhai P, Pirani A, et al. (eds) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Oxford, UK, pp 923–1054

Friedlingstein P, Jones MW, O'Sullivan M, et al (2022) Global Carbon Budget 2021. Earth Syst Sci Data 14:1917–2005. https://doi.org/10.5194/essd-14-1917-2022

Gulev S, Thorne PW, Ahn J, et al (2021) Chapter 2: Changing State of the Climate System. In: Masson-Delmotte V, Zhai P, Pirani A, et al. (eds) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Oxford, UK, pp 287–422

Hoesly RM, Smith SJ, Feng L, et al (2018) Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). Geoscientific Model Development 11:369–408. https://doi.org/10.5194/gmd-11-369-2018

Hristov AN, Kebreab E, Niu M, et al (2018) Symposium review: Uncertainties in enteric methane inventories, measurement techniques, and prediction models. Journal of Dairy Science. https://doi.org/10.3168/jds.2017-13536

IPCC (2021) Summary for Policymakers. In: Masson-Delmotte V, Zhai P, Pirani A, et al. (eds) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, pp 3–32

IPCC (2022) Summary for Policymakers. In: Shukla PR, Skea J, Reisinger A, et al. (eds) Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, pp 3–48

Leach NJ, Jenkins S, Nicholls Z, et al (2021) FaIRv2.0.0: a generalized impulse response model for climate uncertainty and future scenario exploration. Geoscientific Model Development 14:3007–3036. https://doi.org/10.5194/gmd-14-3007-2021

Minx JC, Lamb WF, Andrew RM, et al (2021) A comprehensive and synthetic dataset for global, regional, and national greenhouse gas emissions by sector 1970–2018 with an extension to 2019. Earth System Science Data 13:5213–5252. https://doi.org/10.5194/essd-13-5213-2021

Morice CP, Kennedy JJ, Rayner NA, et al (2021) An Updated Assessment of Near-Surface Temperature Change From 1850: The HadCRUT5 Data Set. Journal of Geophysical Research: Atmospheres 126:. https://doi.org/10.1029/2019jd032361

Nabuurs G-J, Mrabet R, Abu Hatab A, et al (2022) Agriculture, Forestry and Other Land-uses (AFOLU). In: Shukla PR, Skea J, Slade R, et al. (eds) Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, pp 747–860

Reisinger A (2018) The contribution of methane emissions from New Zealand livestock to global warming. Parliamentary Commissioner for the Environment, Wellington, New Zealand

Shindell D, Sadavarte P, Aben I, et al (2024) The methane imperative. Front Sci 2:. https://doi.org/10.3389/fsci.2024.1349770

Smith C (2023) FaIR calibration data (version 1.3.1). https://zenodo.org/records/10208609

Thornhill GD, Collins WJ, Kramer RJ, et al (2021) Effective radiative forcing from emissions of reactive gases and aerosols – a multi-model comparison. Atmospheric Chemistry and Physics 21:853–874. https://doi.org/10.5194/acp-21-853-2021

Wolf J, Asrar GR, West TO (2017) Revised methane emissions factors and spatially distributed annual carbon fluxes for global livestock. Carbon Balance Manage 12:16. https://doi.org/10.1186/s13021-017-0084-y