Methane science and target review

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Executive Summary

In 2016, New Zealand (NZ) signed the Paris Climate Agreement, which aims to hold the increase in global average temperatures to well below 2 °C above pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5 °C. This agreement also seeks to 'adapt and foster resilience and low greenhouse gas development in a manner that does not threaten food production' and reach 'global peaking of greenhouse gas emissions as soon as possible.'

The Climate Change Response (Zero Carbon) Amendment Act was passed in 2019 to establish a framework for emission reductions in support of the Paris Agreement. This legislation focuses specifically on pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels and for NZ to prepare for and adapt to the effects of climate change. The 2050 domestic climate change targets are based on a split gas approach recognising that to stabilise temperatures, long-lived gases need to be reduced to net zero while short-lived gases do not. The Act further distinguished biogenic methane from other short-lived gases, setting targets for biogenic methane of 'a 24 to 47 per cent reduction below 2017 biogenic methane emissions by 2050, including 10 per cent reduction below 2017 biogenic methane emissions by 2030'.

The purpose of this Methane Review is to deliver an independent review of methane science and the 2050 targets and provide estimates of biogenic methane emissions reductions needed in 2050 and 2100 to achieve and maintain a state of no additional warming from New Zealand's biogenic methane emissions relative to 2017 levels of warming.

The idea of "net zero" emissions has its origins in the relationship between cumulative emissions of long-lived greenhouse gases and temperature. Additional warming calculations have been applied to carbon dioxide (CO_2) budgets. A similar concept of additional warming can be applied to methane (CH_4), but different calculations are needed because of its shorter lifetime in the atmosphere. New Zealand's split gas target is consistent with this need for different calculations and is in line with calls to indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets.

In simple terms, to stabilise temperatures from short-lived gases there should be no further increase in short-lived gases emitted. Anthropogenic methane emissions can be described as 'current' or 'new'. Biogenic methane sources are 'current' carbon, the result of bacteria in anaerobic environments breaking down plant matter recently formed through photosynthesis. In contrast, methane sourced from fossil fuel production, when it is broken down by atmospheric chemistry, adds 'new' carbon to the atmosphere, carbon that had been locked up for many years underground. While the source makes no difference to the warming impact of methane once it gets into the atmosphere, the additive nature of 'new' carbon in fossil fuel methane distinguishes it from the recycled carbon in biogenic methane. The profile of NZ's methane emissions is dominated by biogenic emissions from 'current' carbon.

Reported inventories show NZ's methane emissions have been largely stable for some years and gradually decreasing since 2019. The contribution of NZ's biogenic methane emissions to the increase in atmospheric methane concentrations has slowed over the past decade, reflecting the reduction in emissions. Modelling suggests that the global temperature contribution of NZ biogenic methane emissions has been approximately stable since 2017.

In contrast, global average methane concentrations in the atmosphere have grown rapidly since 2007. In 2020 and 2021 they were at the highest since records began in the 1980s. The growth rate slowed again in 2023 and 2024, yet the 2023 and 2024 growth rates remain the 3rd and 5th highest recorded since methane began to rise again in 2007. One of the global scenarios developed by the IPCC had a target of limiting the temperature increase to less than 1.5 °C above pre-industrial levels. This involved rapid reductions in emissions of CO_2 and CH_4, beginning in 2015, which has not happened. Under this scenario, 2023 global anthropogenic emissions of CO_2 were modelled to be 32.3 Gt CO_2, and 324.1 Mt CH_4, respectively (Meinshausen et al., 2020); actual emissions were 39 Gt CO_2, and 350 Mt CH_4 (UNEP, 2024). Global emissions need to drop more rapidly now to achieve that scenario's aspirational target.

To better understand the relationship between NZ biogenic methane and additional warming, a range of potential methane emission futures for NZ were mapped against possible, plausible pathways (the IPCC scenarios) the world might take. The results show that the warming effect of New Zealand's methane is not solely dependent on NZ's actions. The extent to which New Zealand's methane causes warming is also affected by emissions of methane and other greenhouse gases from the rest of the world. Historic NZ methane emissions also have an impact, as heat caused by them was trapped in, and is now being released from, the oceans.

The results show that under a low emission global scenario, akin to limiting the temperature increase to 1.5 °C above pre-industrial levels, cuts amounting to 24% reductions by 2050 are sufficient to keep or return warming to at or below 2017 levels. For mid-range global scenarios and those most like the International Energy Association's emissions scenarios and current NDCs, which are still focused on holding average temperatures to less than 2.0°C, cuts of 14-15% by 2050 are consistent with meeting the no additional warming condition. For high emission scenarios, in which countries contribute less in the way of emissions reductions, maintaining 2022 domestic emissions levels is sufficient for no additional warming.

Unless global emissions of methane reduce extremely rapidly in the next couple of decades, cuts of around 14-15% by 2050 from 2017 are sufficient to keep warming from NZ's biogenic methane to levels at or below 2017 levels. These results are consistent with previous modelling efforts looking at emission reductions from biogenic methane in NZ that would stabilise temperatures.

Contents

Introduction

The purpose of the Methane Review Panel, as described in the Terms of Reference (Appendix 1) is to deliver an independent review of methane science, and the 2050 target, for consistency with no additional warming from agricultural methane emissions. In this report, we review the science of methane and its warming impact and provide advice on what a biogenic methane target consistent with the principle of no additional warming would look like for New Zealand (NZ).

NZ's 2050 target was set as part of the Climate Change Response (Zero Carbon) Amendment Act 2019[1], which amended the Climate Change Response Act 2002 (CCRA). Further details on the legislation are provided in the next section. Under the CCRA, NZ adopted a split-gas approach to the 2050 target based on scientific evidence that biogenic methane, as a short-lived gas, has a different warming impact in comparison to other greenhouse gases so does not have to reduce to zero to limit global warming. The legislated 2050 target for biogenic methane requires that NZ's gross emissions of biogenic methane in a calendar year are 24-47% less than 2017 emissions by 2050 and for each subsequent calendar year.

NZ is unusual for a developed country in having a relatively high proportion of methane emissions in its inventory, and these arise largely from agriculture. Our portfolio of emissions is more typically found in developing countries. In most other developed countries, a larger proportion of methane emissions are associated with fossil fuel production. In such instances, decreasing methane emissions from both fossil fuel production and waste have been identified as low cost solutions to mitigate climate change and have been included in policy directions such as the Global Methane Pledge Energy Pathway[2]. Reducing the emissions from agriculture, by contrast, is more problematic due to the challenges in meeting the Paris Agreement stipulation that it must be 'in a manner that does not threaten food production' and the availability of cost-effective technology to do so for both rice paddies and farm animals within this constraint. Accordingly, NZ is striving to develop the technology to monitor and mitigate its own methane emissions consistent with meeting the legislative requirements.

In the five years since NZ's emissions targets were devised, there have been advancements in the scientific understanding of climate change. This is reflected in how methane is modelled scientifically. Furthermore, the way short- and long-lived gases are compared in a policy context has changed. This report reviews methane science, defines what no additional warming means and assesses what targets are consistent with no additional warming from biogenic methane.

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[1] Climate Change Response (Zero Carbon) Amendment Act 2019 No 61, Public Act – New Zealand Legislation

[2] https://www.globalmethanepledge.org/annual-report/energy-pathway

Terms of Reference

The scope defined in the Terms of Reference (Appendix 1) is for the report to include:

a. a background on New Zealand’s climate change targets and legislation;
b. an overview of the concept of no additional warming, including a clear definition of what no additional warming is in the context of a biogenic methane target;
c. a review of previous studies that estimate a no additional warming target for biogenic methane (including any differences between them);
d. an up-to-date explanation and summary of the warming impact of biogenic methane, specifically including biogenic methane from New Zealand’s agricultural sector;
e. a brief explanation of the global emissions scenarios relevant for determining target ranges for biogenic methane emissions;
f. consideration of a range of no additional warming biogenic methane emission reductions targets that reflect different background global emissions scenarios, including a scenario that is consistent with limiting global warming to 1.5 degrees Celsius (e.g., Shared Socioeconomic Pathway 1-1.9 from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6)); and
g. estimates of biogenic methane emissions reductions needed in 2050 and 2100 to achieve and maintain a state of no additional warming from New Zealand’s biogenic methane emissions relative to 2017 levels of warming.

Out of scope was making any conclusions or recommendations that go beyond performing the scientific review and providing the evidence-based advice required by these terms of reference, and reviewing any other aspects of the 2050 Target as set out in s5Q of the Climate Change Response Act 2002.

The Panel Approach

The Panel has endeavoured to capture the most up to date scientific evidence on methane and its impact to address the challenges raised in the terms of reference. The approach taken has been to first summarise the legislation, critical in the fact that it distinguishes between short- and long-term gases and gives them separate targets.

The science of methane is then presented to provide clarity and to inform the modelling assumptions used later in the report. This is followed by an explanation of NZ's methane profile and how it has evolved in recent years within the context of the global methane budget. As the topic of this report is methane, no attempt is made to present it as carbon dioxide equivalents or any other metric. Throughout the report we present methane emissions in megatonnes[3] of methane (Mt CH_4).

The complex role of methane as a greenhouse gas and the basis for the modelling of future emissions possibilities is then explained. A definition of additional warming follows with examples given of previous studies that have determined targets that are consistent with no additional warming from agricultural methane emissions.

To simulate the temperature effects of a range of potential changes in future NZ methane emissions, it is necessary to apply these to possible, plausible global scenarios for future emissions from the rest of the world. As global methane levels increase, the warming effect of additional methane reduces and therefore the warming impact of NZ's methane emissions depends on what the rest of the world does. Because NZ's methane emissions are around just 0.35% of global anthropogenic methane emissions, a range of global scenarios provide essential context for the evaluation of NZ biogenic methane's contribution to warming. The scenarios chosen for this review to provide that context, the socio-economic pathways (SSPs) adopted by the IPCC as possible, plausible futures, are then outlined along with an explanation of the dynamic relationship between them and methane lifetime, a critical variable in the analysis.

The impact of a range of methane emissions futures within each scenario were explored to assess conditions under which there is no additional warming from NZ's biogenic methane. The range includes both per annum and straight line reductions as well as the two targets for 2050 currently in the legislation. The results of this modelling are presented and discussed with reference to how they deliver to the challenges raised in the terms of reference.

The Appendices include the full terms of reference, the methodology of the modelling, further legislative details, the per annum results and the time series plots. They are followed by a 'Frequently Asked Questions' section that provides answers on challenges not central to the report but received in the submissions.

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[3] One megatonne (Mt) equals one million metric tonnes.

Legislation

The Paris Agreement and NZ’s response

NZ signed the Paris Agreement in 2016. The aim of the agreement, as described in Article 2, is to have a stronger response to the danger of climate change; it seeks to enhance the implementation of the United Nations Framework Convention on Climate Change through:[3]

a. Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;

b. Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production;

c. Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.

Countries furthermore aim to reach “global peaking of greenhouse gas emissions as soon as possible.”

NZ’s Climate Change Response (Zero Carbon) Amendment Act 2019, which amended the Climate Change Response Act 2002, established the domestic climate change 2050 target, designed to contribute to the global effort to pursue efforts to limit warming to 1.5°C. It enables NZ to:

- meet international obligations under the United Nations Framework Convention on Climate Change (UNFCCC) Kyoto Protocol and the Paris Agreement;
- contribute to the global effort under the Paris Agreement to pursue efforts to limit the global average temperature increase to 1.5° C above pre-industrial levels;
- allow NZ to prepare for and adapt to the effects of climate change.

The 2019 amended act resulted in four key actions:

1. Set the domestic climate change target (the 2050 target).
2. Establish the emissions budgets (EBs) system.
3. Develop a framework for policies for climate change adaptation and mitigation.
4. Establish the Climate Change Commission (CCC) to provide independent expert advice and monitoring.

International reporting

The Paris Agreement transparency framework requires that emissions data be reported according to the United Nations Framework Convention on Climate Change (UNFCCC) guidelines.

NZ’s Greenhouse Gas Inventory (MfE, 2024) is published annually as part of international reporting obligations under the Paris Agreement and UNFCCC. The inventory is the official annual report of estimated human-induced emissions and removals of greenhouse gases in NZ.

The inventory reports greenhouse gas emissions and removals from five sectors: agriculture; energy; industrial processes and product use (IPPU); land use, land use change and forestry (LULUCF), waste. Gross emissions are reported as the total emissions from agriculture; energy, IPPU and waste. Net emissions are reported for the LULUCF sector.

The latest Greenhouse Gas Inventory (MfE, 2024) reported on greenhouse gases (controlled by the Kyoto Protocol) that have direct warming effects: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, nitrogen trifluoride. Indirect gases are also reported but not included in NZ's greenhouse gas total.

NZ's Greenhouse Gas Inventory presents all gases as CO_2 equivalents (CO_2-e). To obtain CO_2-e values, methane emissions (in kilotonnes, kt) are multiplied by their 100-year global warming potential of 28 (see Frequently Asked Questions). This is to enable international reporting and, as stated in the report, is consistent with decisions 1/CP.24, 18/CMA.1 and 5/CMA.3 (IPCC, 2013). In this report we consider methane emissions only by their mass and not as CO_2 equivalent to assess emissions consistent with no additional warming.

NZ's greenhouse gas emissions projections to 2050 are reviewed every two years as part of international reporting. In addition, NZ is required to submit national climate change action plans known as Nationally Determined Contributions (NDCs) to UNFCCC every five years to help achieve long-term goals. Further details on the NDC process are provided in Appendix 3.

Domestic targets

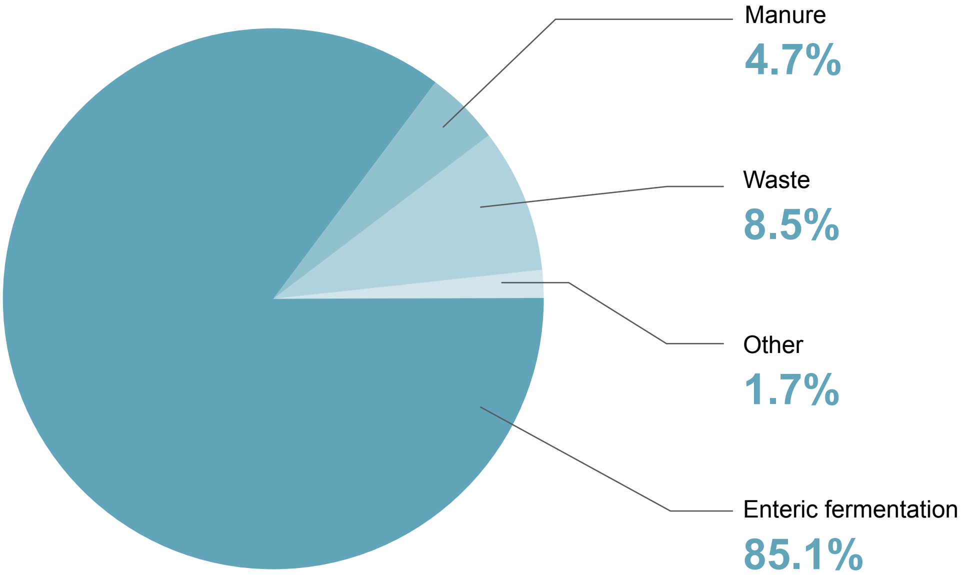
NZ's domestic climate change targets are established under the Climate Change Response (Zero Carbon) Amendment Act. The 2050 targets are:

- Net zero emissions of all greenhouse gas (GHG) emissions other than biogenic methane by 2050.
- 24 to 47 per cent reduction below 2017 biogenic methane emissions by 2050, including 10 per cent reduction below 2017 biogenic methane emissions by 2030.

NZ's domestic target is a split-gas approach, reflecting that methane, as a short-lived gas, has a different warming impact in comparison to other greenhouse gases, such as carbon dioxide. Under the Act, biogenic methane refers to all methane greenhouse gases produced from the agriculture and waste sectors (reported as CO_2 equivalents in the NZ Greenhouse Gas Inventory Report).

The NZ Greenhouse Gas Inventory states that in 2022, NZ's methane emissions were 38,339.3 kt CO_2-e or 1.369 Mt CH_4 (MfE, 2024). Unlike most developed countries, most of NZ's methane emissions are produced by livestock's enteric fermentation, equating to emissions of 32,617.2 kt CO_2-e (1.164 Mt CH_4) in the agriculture sector (Figure 1). Methane is also the largest component of waste sector emissions, contributing 1,803.7 kt CO_2-e (0.064 Mt CH_4). Based on this information the biogenic methane emissions in 2022, including manure CH_4, is calculated as 37,679.6 kt CO_2-e, or 1.345 Mt CH_4. This is a 1.2% reduction on the 2017 level of 1.361 Mt CH_4.

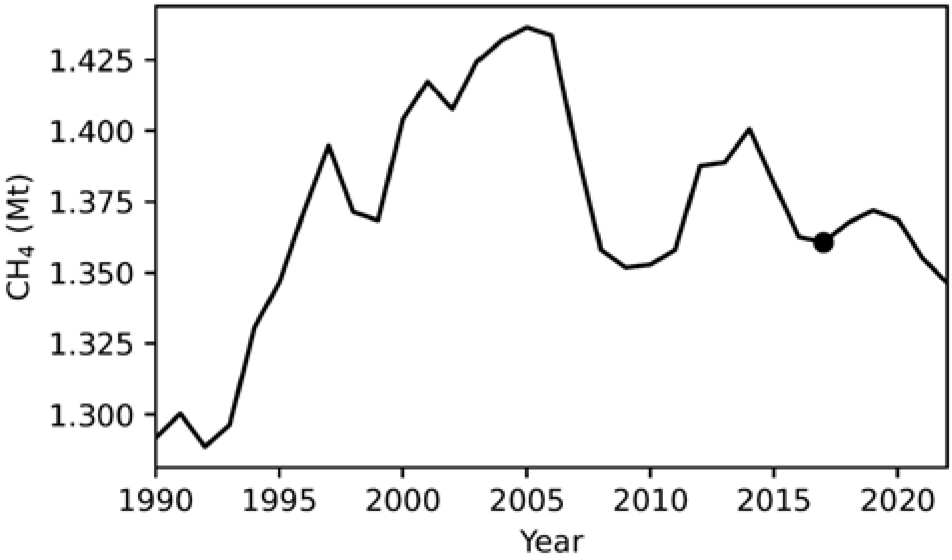
Figure 1: Breakdown of NZ CH_4 emissions in 2022. Data sourced from MfE (2024).



From 1990 to 2006, biogenic methane emissions increased, peaking in 2005 at 1.436 Mt (MfE, 2024). Since then, despite some fluctuations, methane emissions have largely stabilised at a lower level than the 2006 peak (averaging 1.370 Mt over the last decade for which data are available, 2013-22), and consistently decreasing each year since 2019 (Figure 2).

The idea of “net zero” emissions has its origins in the relationship between cumulative emissions of long-lived greenhouse gases and temperature (Allen et al., 2009). Exactly how short-lived greenhouse gases like methane fit within this framework depends on how gases are aggregated (Fuglestvedt et al., 2018). Most scientists working actively on the issue of comparing gases endorse the idea that policy should indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets (Allen et al., 2022b; Lynch et al., 2021). Conventional reporting of aggregated CO_2-equivalent emission rates is described as “highly ambiguous and does not straightforwardly reflect historical or anticipated contributions to global temperature change” (Lynch et al., 2021).

Figure 2: **New Zealand's biogenic (agricultural + waste) methane emissions. Emissions in 2017 were 1.361 megatonnes (Mt), indicated by the black circle. Data source: MfE (2024).**



NZ's split-gas target is consistent with these scientists' recommendations. However, despite NZ legislation specifying split gases, the Greenhouse Gas Inventory report presents methane emissions and compares them with other gases as CO_2 equivalents; the snapshot of the inventory makes no mention of methane being a short-lived gas[4]. International reporting requirements are given as the reason for presenting the gases as CO_2-equivalents but the same reporting requirements also encourage the reporting of other relevant information. The full report similarly provides no mention of methane being a short-lived gas: it provides CO_2 equivalents by sector and by gas, the sector amount combines all gases and the gas amount includes all sectors. Biogenic methane emissions as CH_4 can be calculated from breakdowns provided in the body of the report or spreadsheets provided alongside the report. As previously mentioned, this review focuses on biogenic methane, so reported CO_2-e values from the Greenhouse Gas Inventory Report have been converted to methane emissions throughout.

NZ's 2050 target for biogenic methane was informed by values from a table in the IPCC's special report on Global Warming of 1.5°C (SR1.5) published in 2018 (IPCC, 2018). The SR1.5 Report found that to limit warming to 1.5°C, the world would need to reach net-zero emissions of carbon dioxide by about 2050, along with deep reductions in other GHGs.

The biogenic methane component of the 2050 target was set based on simulations using Integrated Assessment Models (IAMs), and evaluated the range of modelled pathways for biogenic methane from Agriculture, Forestry and Other Land Use (AFOLU) from global scenarios consistent with limiting warming to 1.5°C with no or limited overshoot (Table SPM3b). These pathways were illustrative, and only those models that managed to meet the 1.5°C target were included. The table presenting the results bore the following caveat: "these pathways illustrate relative global differences in mitigation strategies, but do not represent central estimates, national strategies, and do not indicate requirements."

None of the IAMs in the SR1.5 modelling resolve NZ - in all of the IAMs the NZ economy is aggregated alongside Australia's. In several of the IAMs both NZ and Australia are included in a larger OECD Asia-Pacific grouping which includes Japan and Korea. Therefore the table used to set NZ's biogenic methane target did not evaluate the feasibility of the target from a domestic perspective.

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[4] New Zealand's Greenhouse Gas Inventory 1990–2022: Snapshot | Ministry for the Environment

The Treasury Regulatory Impact Assessment (RIA)[5] includes economic analyses that are predicated on innovation and forestry being key to success, with their modelling results being highly sensitive to assumptions on each. The RIA provides an interesting background to the decision making in that various options were analysed ranging from taking CO_2 to net zero to taking all gases to net zero by 2050. An addendum was added to the RIA that introduced another option that distinguished biogenic methane from all other GHGs and set a gross emission reduction level of 35% below 2016 levels, with the proviso that this be reviewed in 2025. As this option was not included in any of the target options modelled the economic impacts of it were approximated from the other options. The impact estimated was a reduction in the Net Present Value in 2018 from -$94.8b (Option 2 that included a 50% reduction in short lived gases) to -$38.9b, with reliance still on significant afforestation. This option became the basis for the legislation. The addendum outlines how, to stabilise temperatures, long-lived gases need to be reduced to net zero while short-lived gases do not.

The RIA addendum proposed that while the biogenic methane levels be set in legislation they should be subject to review in 2025; the review would also consider 'whether it is necessary to achieve 'net zero' emissions of biogenic methane by 2050'. This would have provided the opportunity to incorporate new scientific and technical advances, growing policy understanding and to reflect global actions. However, this proposed review was not included in the Act, instead any review was captured at the periodic setting of emissions budgets or at any other time the Minister requests a review.

Additional sources of information were also considered as part of the decision-making process for setting the biogenic methane target. These included evidence related to the achievability of the target as discussed in the Biological Emissions Reference Group (BERG) Report (2018) and Reisinger (2018) and consideration of technological advancements, scientific advice and NZ's national circumstances[6]. While food production is not mentioned at all in the RIA a report that informed it on competitiveness, leakage and innovation[7] concluded that there was non-trivial leakage risk for NZ agriculture in the next decade or two with consumption of animal proteins, including those exported from NZ, not expected to decline any year soon.

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[5] Zero Carbon Bill - 8 May 2019 - Regulatory Impact Assessment - Ministry for the Environment

[6] Economic analysis for the proposed Climate Change Response (Zero Carbon) Amendment Bill | Ministry for the Environment

[7] Countervailing-forces-Sense-Partners-2018-FINAL-report.pdf

Methane (CH_4)

Methane (CH_4) gas is naturally present in Earth's atmosphere. In 2023, the global average concentration of methane in Earth's atmosphere was 1922 ppb (parts per billion)[8]. Although it is present in small amounts, methane plays an important role in Earth's radiative balance – that is, the energy balance between solar radiation received by the Earth, and terrestrial (thermal infrared) radiation emitted by the Earth.

As with any atmospheric trace gas, there are two quantities that scientists draw on which are related, but distinct. One is the emissions, which correspond to the quantities (megatonnes CH_4) directly released into the atmosphere. The other is the abundance or concentration (parts per billion CH_4) that are found in a volume of air. This reflects the amount, net of emissions and depletion, which, for short-lived gases, is very relevant. In simple terms, if there is no increase in emissions of a short-lived gas then there is no increase in concentration. By contrast, for long-lived gases the concentration will increase and reflect the accumulation of those gases over time.

Methane is produced by bacteria in anaerobic environments, including wetlands, inland freshwaters, rice paddies, landfills, and the digestive tracts of animals; fossil fuel production and use; and fires. It is broken down by chemical reactions in the atmosphere and by bacteria in well oxygenated soils. The global sources and sinks are summarised in Figure 3, which is produced by the Global Carbon Project, an international consortium of experts that review the literature and provide a regularly updated global methane budget. Methane sources and sinks can be estimated in two different ways: 1) "bottom up" approaches that model the physical or chemical processes of methane emissions to estimate emissions by sector, and 2) "top down" approaches that infer emissions from measurements of methane in the atmosphere from sites at the surface, satellites, or other platforms and atmospheric models.

Between 2010 and 2019, atmospheric methane grew by an average of 21 Mt/yr, with a range of 19-33 Mt/yr, called 'change in atmospheric abundance' in Figure 3. Alongside the 'top-down' growth in atmospheric methane, which is based on observations, Figure 3 also reports a 'bottom-up' growth in methane of 36 Mt/yr which is based on model estimates. A previous report by this consortium taken from 2008 to 2017 (Saunois et al., 2020) gave numbers of 13 (0-49) Mt/yr and >100 Mt/yr for the top down and bottom up methods respectively. The difference between reports demonstrates the evolution of scientific understanding and modelling of methane. In particular, the two reports accounted for freshwater sources differently. Both the top-down and bottom-up methods confirm that atmospheric methane abundances have increased in recent years, and anthropogenic activities are responsible for two thirds of this growth (Jackson et al., 2024.)

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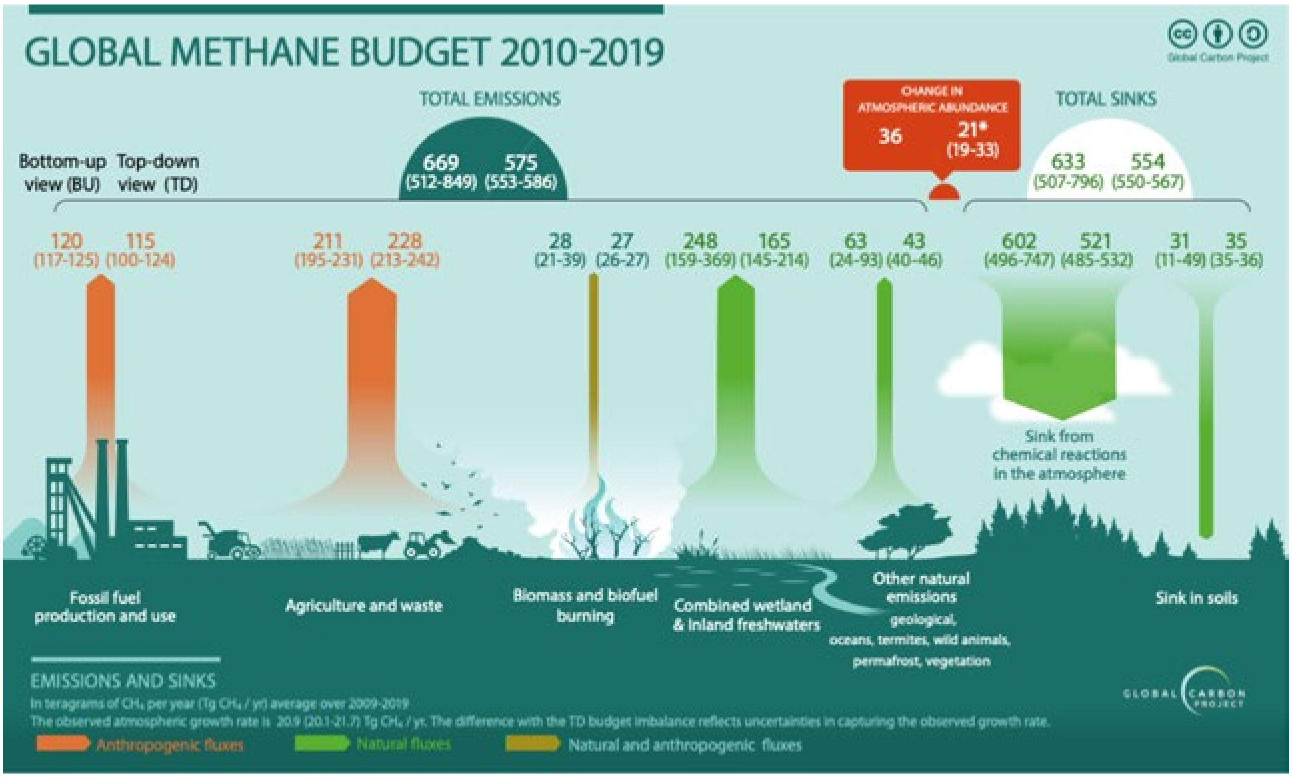
[8] This means that for every billion molecules in the atmosphere, 1922 of them are methane.

Figure 3: **Summary of global methane sources and sinks between 2010-2019. (Saunois et al., 2024). Fluxes are given in teragrams (Tg) of methane per year. One teragram is equivalent to one megatonne (Mt), the unit used elsewhere throughout this report.**



Methane Sources

Agriculture

Agriculture, food production, is the largest global source of methane from human activities (Figure 3). Methane emissions from livestock primarily come from the digestive processes of ruminant animals, such as cows and sheep. These animals have a special stomach, the rumen, that ferments food and produces methane as a byproduct. In addition, manure from livestock can emit methane when it decomposes, especially in wet conditions.

Methane is also emitted from rice paddies primarily due to the flooded conditions in which rice is typically grown. When fields are flooded, water creates a low-oxygen environment in the soil. This environment allows bacteria that break down organic matter and produce methane to thrive. The methane then escapes to the atmosphere, especially when the water is drained or disturbed during harvesting.

Waste

Methane is emitted from the breakdown of organic matter in landfills and wastewater treatment facilities. Like flooded rice paddies, landfills and wastewater treatment plants are low-oxygen environments that favour methane-producing bacteria. Thus, methane is generated from the decomposition of organic materials such as food scraps, yard waste, human waste and paper in these environments. Managing waste effectively, such as through composting or capturing methane for energy, can significantly reduce these emissions.

Fossil fuels

While carbon dioxide emissions are a byproduct of combustion, methane emission from fossil fuels are an inadvertent byproduct of extraction, transport, and incomplete combustion of fuel. Natural gas is primarily composed of methane. When extracted, it can escape into the atmosphere through leaks in pipelines, during transportation, and at drilling sites. Methane can also be released from coal seams, a phenomenon known as coalbed methane production. This occurs when organic matter in the coal breaks down, producing methane that can escape during mining operations. When oil is extracted and refined, methane can be emitted during drilling, transport, and combustion. Incomplete combustion of oil products can also release methane into the atmosphere.

Fossil methane has become a focus in international climate policy, in part because addressing methane leaks from fossil extraction and transport are more economically feasible than many other climate mitigation activities.

Biomass burning and biofuels

Methane is also emitted from the combustion of organic materials such as wood, crop residues, biofuels, and other plant materials. When biomass is burned for energy, incomplete combustion can release methane to the atmosphere along with carbon dioxide and other pollutants. This is particularly common in uncontrolled or open burning practices, such as slash-and-burn agriculture or forest clearing. Similarly, methane is emitted from human caused and natural wildfires.

Wetlands, peatlands, and inland freshwaters

Natural methane emissions are dominated by wetlands, peatlands and inland freshwaters such as lakes, rivers and reservoirs. Methane emissions from these ecosystems arise primarily from the decomposition of organic matter in low-oxygen conditions in waterlogged environments. Wetland and peatland methane emissions are characterised by large year-on-year variability driven by temperature, water level, nutrients, and land use practices.

Termites

Termites are key decomposers in many ecosystems, particularly in tropical regions. They digest cellulose from plant material using symbiotic microorganisms in their guts, which include bacteria and protozoa. The digestive process occurs in a low-oxygen environment within the termite gut, leading to methane production.

While termite emissions are a smaller fraction of total methane emissions compared to sources like wetlands and agriculture, they are still significant. Estimates suggest that termites contribute about 1–3% of global methane emissions.

Wild animals

Wild animals such as deer, moose, elk, and other herbivores grazing produce methane through their digestive systems, similarly to livestock. In addition, the droppings of wild animals can contribute to methane emissions when decomposed in wet or low-oxygen environments.

Other natural sources

Methane generated within the Earth’s crust can be emitted to the atmosphere through tectonic faults and fractured rocks. Geologic methane can be emitted from gas-oil seeps where hydrocarbons rise to the surface naturally on land or beneath the ocean surface and volcanic activity.

Methane can also be emitted from methane hydrates, which are crystalline structures in which methane molecules are trapped within a lattice of water ice. Methane hydrates are stable under high pressures and low temperatures typically found in deep sediment regions and permafrost regions. Emissions from these sources are presently thought to be small, but it has been hypothesised that changes in these conditions driven by climate change can destabilise them leading to additional methane emissions.

Methane Sinks

Chemical destruction by hydroxyl radical

Methane emitted to the atmosphere is broken down over time by chemical processes, unlike carbon dioxide which can remain in the atmosphere for hundreds of years once emitted. The dominant methane sink is its reaction with hydroxyl (OH) radicals[9] in the atmosphere. Hydroxyl reacts with methane, ultimately breaking it down into carbon dioxide and water. Hydroxyl is often referred to as the ‘detergent’ of the atmosphere, because it is the primary sink for not only methane but also a range of trace gases. This rate of methane loss by reaction with hydroxyl is faster at higher temperatures so methane is lost more rapidly in a warmer climate.

The amount of hydroxyl in the atmosphere can vary due to changes in solar radiation, water vapour, and the amount of methane and other atmospheric constituents. Hydroxyl is produced by sunlight-driven reactions, so variability in solar radiation from either solar activity or cloud cover can impact hydroxyl concentrations. Changes in water vapour from climate change and natural climate variability also influence hydroxyl production, because the reactions that produce hydroxyl involve water molecules.

The amount of hydroxyl in the atmosphere is affected by short-lived atmospheric constituents such as nitrogen oxides[10] (NOx = NO + NO2) and volatile organic compounds (VOCs), which have natural and human-created sources. In general, increased NOx emissions will increase hydroxyl production whereas increased VOC emissions will increase its loss. Finally, while hydroxyl breaks down methane, hydroxyl is also destroyed in the process. Thus increasing methane concentrations can decrease the methane sink from hydroxyl, leading to a feedback effect that accelerates warming (Staniaszek et al., 2022). This effect will be explored in our model simulations to assess methane targets consistent with no additional warming.

Minor methane sinks

Certain microbes in soils can consume methane, acting as a biological sink. These microorganisms metabolise methane and convert it into carbon dioxide. Methane that reaches the stratosphere (a layer of the atmosphere about 15 to 50 km above the Earth’s surface, Figure 10) is destroyed by chemical reaction with chlorine produced from the breakdown of chlorofluorocarbons, and other trace gases. In the lowermost atmosphere, methane can also be destroyed by naturally occurring chlorine emitted from oceans.

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[9] A radical is a highly reactive chemical species containing an unpaired electron.

[10] Not to be confused with nitrous oxide (N2O), an important greenhouse gas.

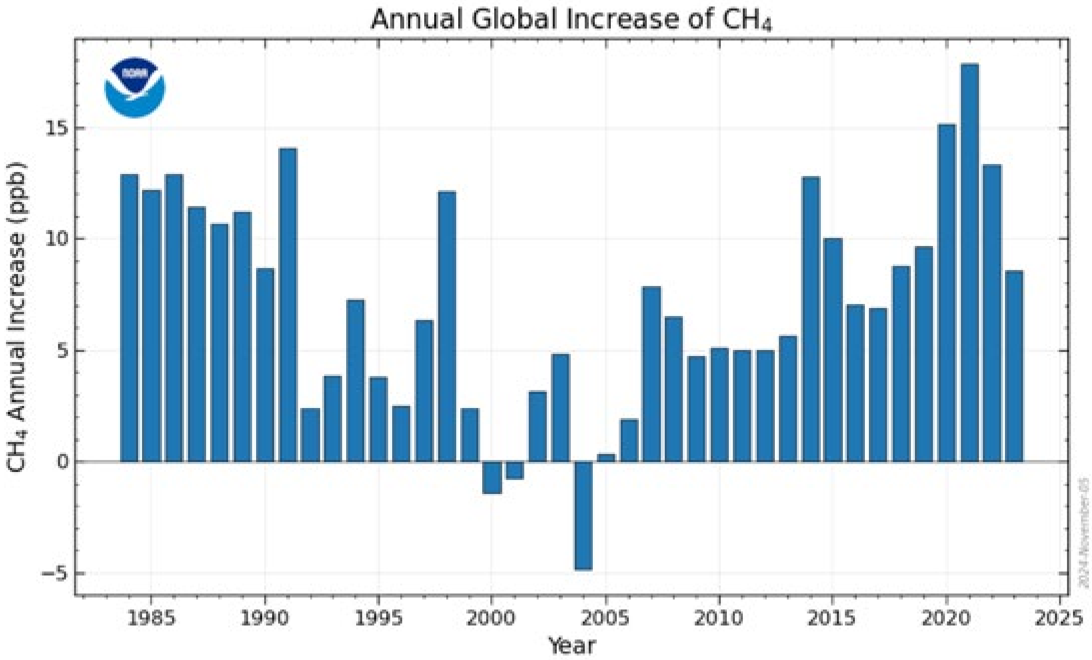
Accumulation of methane in the atmosphere

Methane has an atmospheric lifetime[11] of around 9 years, mainly due to its reaction with hydroxyl, which accounts for approximately 90% of methane loss (Saunios et al., 2024, Szopa et al., 2021). Methane loss via minor sinks is slow. For example, the methane lifetime with respect to loss via soils has been calculated as 135 ± 44 years (Szopa et al., 2021).

The historical imbalance between methane's sources and sinks has caused it to accumulate in the atmosphere. The concentration of methane in the atmosphere has more than doubled since preindustrial times (Gulev et al., 2021), as has the world's population and its need for food.

The accumulation of methane in the atmosphere is well known, due to precise measurements made at atmospheric observing stations both in NZ[12] and around the world. Global average atmospheric methane concentrations rose steeply between the start of the record in the 1980s, then plateaued from the early 1990s until 2007, when methane concentrations began to rise rapidly again (Figure 4). Measurements of isotopes in methane, which are influenced by source and sink processes, reveal that different emission processes were at play in the period prior to 1990 and the period since 1997. The isotopic composition of atmospheric methane prior to the early 1990s suggests a strong role for anthropogenic emissions from fossil fuels and biomass burning (Schaefer et al., 2016). The stabilisation of the methane growth rate during the 1990s is thought to be due to a decrease in fossil emissions due in part to the collapse of the Soviet Union (Dlugokencky et al., 2003), which is consistent with other trace gas observations (Simpson et al., 2012). Isotope data suggests that the renewed growth in 2007 was driven by biogenic processes, such as wetlands or agriculture (Schaefer et al, 2016, Nisbett et al, 2016; Nisbett et al., 2019), with fossil sources playing a smaller role.

Figure 4: **Annual increases in global average methane concentrations in the atmosphere, observed from a network of stations around the world over this period (Lan et al., 2024).**



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[11] Atmospheric lifetimes can generally be thought of as the 'average' time between the emission and removal of a species from the atmosphere. With the exception of CO_2, all greenhouse gases can be characterised using a single atmospheric lifetime.

[12] NIWA measures atmospheric methane at five atmospheric observing sites in New Zealand and Antarctica: Baring Head, near Wellington; Lauder, in Central Otago; Manukau Heads, west of Auckland; Winchmore Farms, in the Canterbury Plains; and Arrival Heights, Antarctica.

Global average methane concentrations in the atmosphere grew more quickly in 2020 and 2021 than at any time since records began in the 1980s (Figure 4; Lan et al., 2024). Three potential mechanisms have been proposed for this striking increase in atmospheric methane. A detailed analysis of both bottom up and top down estimates for 2020 show that at least half of the 2020 growth rate can be explained by vigorous emissions from wetlands due to anomalously warm, wet conditions that year (Peng et al., 2022). Atmospheric chemistry may also be partially responsible. COVID-19 lockdowns lowered emissions of atmospheric pollutants that contribute to the production of methane’s primary chemical sink, which would lead to more rapid accumulation of methane in the atmosphere during 2020 and 2021(Peng et al., 2022; Skeie et al., 2023; Stevenson et al., 2022). Increased emissions from fossil fuels may play a role (Shindell et al., 2024). However, measurements of isotopes reveal that the striking growth in atmospheric methane after 2019 was primarily caused by biological processes such as wetlands, agriculture, or waste (Michel et al., 2024). The growth rate slowed again in 2023 and 2024, yet the 2023 and 2024 growth rates remain the 3rd and 5th highest recorded since methane began to rise again in 2007.

Methane in Context

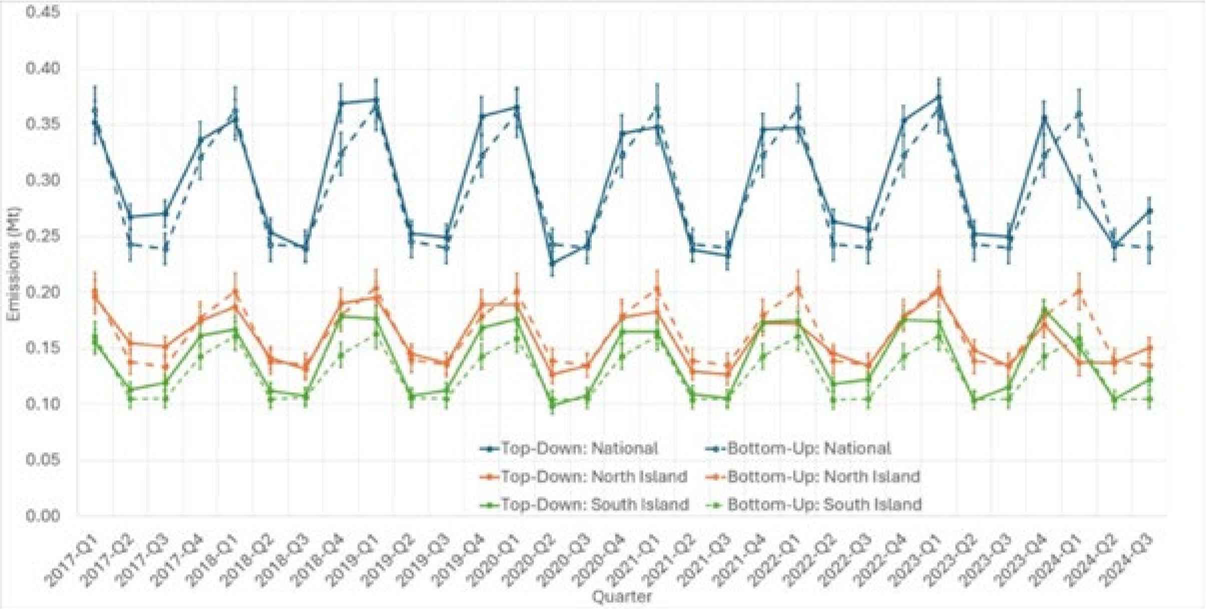
At the global level, as shown in Figure 3, the imbalance of methane sources and sinks is well defined, as is the relative impact of each. This has been well quantified from a network of atmospheric observing stations around the world (Lan et al., 2024). The methane sourced from fossil fuel production differs from other sources in that when it is broken down by atmospheric chemistry, it adds **'new'** carbon (dioxide) to the atmosphere, carbon that had been locked up for many years underground. In contrast the other sources are **'current'** carbon, the result of bacteria in anaerobic environments (wetlands, inland freshwaters, rice paddies, landfills, and the digestive tracts of animals) breaking down plant matter recently formed through photosynthesis. While the source makes no difference to the warming impact of methane once it gets into the atmosphere (refer to Frequently Asked Questions), the additive nature of 'new' carbon in methane from fossil fuels does distinguish it from the recycled carbon in methane from biogenic and other sources in that the fossil fuel methane creates new carbon dioxide once it is broken down.

Each signatory to the Paris Agreement has its own methane profile and NZ is no exception. The NZ Greenhouse Gas Inventory Report (MfE, 2024) shows that most of NZ's gross annual emissions of methane come from food production, the agriculture sector, particularly from ruminant livestock, and the remainder is from the waste sector. With limited fossil fuel production and use, the profile of NZ's methane emissions is dominated by biogenic emissions from 'current' carbon as well as the other natural phenomena of sources and sinks as illustrated in Figure 3.

Methane emissions reported as kt CO_2-e in the NZ Greenhouse Gas Inventory Report, and presented in Figure 2 as Mt CH_4, are calculated using data on animal populations, country-specific emission factors based on measurements made on animals in NZ, production, and other data (MfE, 2024). This approach follows IPCC guidelines established for all nations to follow in international reporting under the Paris Climate Agreement (IPCC, 2006). NZ has invested in research to provide country specific equations and emissions factors that provide a more accurate picture of our emissions than the default values provided by international studies would. The uncertainty of NZ's methane emissions from animals is 16% (Kelliher et al., 2009), and our agricultural emissions from manure management and burning of agricultural residues is 20% (MfE, 2024).

NZ's methane emission estimates (bottom up) are in excellent agreement with independent estimates based on atmospheric measurements (top down) from a network of stations across NZ (Figure 5, Geddes et al., 2020; MfE 2024). As air travels across our landscape, methane concentrations are influenced by emissions or sinks in the landscape it passes over. Atmospheric measurements of methane at observing stations can be combined with models that describe the pathway the air took before arriving at the stations to infer methane emissions (Manning et al., 2011; Geddes et al., 2020; Henne et al., 2016). Emissions estimates from inventories and atmospheric observations both have uncertainties, but these approaches are entirely independent. Thus, atmospheric measurements are recommended to support inventory estimates in the most recent refinement to the IPCC guidelines for national inventory reporting (IPCC, 2019). For NZ, the mean difference between the two estimates is 8.8% for the South Island, 1.5% for the North Island, and 3% for the whole country. The top down estimates were constrained by a larger number of observing sites in the South Island, and therefore we have greater confidence in these estimates. The atmospheric measurements suggest slightly higher methane emissions in the summer compared to inventory data.

Figure 5. **Top-down emissions of methane based on atmospheric observations (solid lines) and bottom up inventory methods (dashed lines) for the North Island (orange) the South Island (green) and nationally (blue). This figure demonstrates the agreement between these two different methods to infer NZ's emissions. The South Island had a larger number of atmospheric methane observations for the study period and therefore we have higher confidence in the top down estimates for the South Island compared to the North Island. (Geddes, A. Personal communication.)**



The inventory analysis is continuously improving. The Ministry for Primary Industries (MPI) has a range of work underway to account for new low emissions technology both at farm and national level when they reach the evidential threshold for inclusion in the National GHG Inventory. This will require field trial data that robustly demonstrates the effectiveness of the mitigations in NZ farm conditions, as well as verifiable and auditable data on their use on farms. As farming practices change and new emission technologies come to market, the inventory will adapt to reflect these changes. Further information can be found from MPI[13].

Figures 2 and 5 provide useful illustrations of NZ emissions and how there has been no increase in emissions in recent years, with a decrease since 2019. Given the short-term nature of methane, it is also useful to examine the estimates of the concentration of methane, the net amount including both sources (emissions) and sinks (its depletion) that come from modelling; these have also indicated a slowing down in the increase of concentrations as emissions have decreased (Figure 6).

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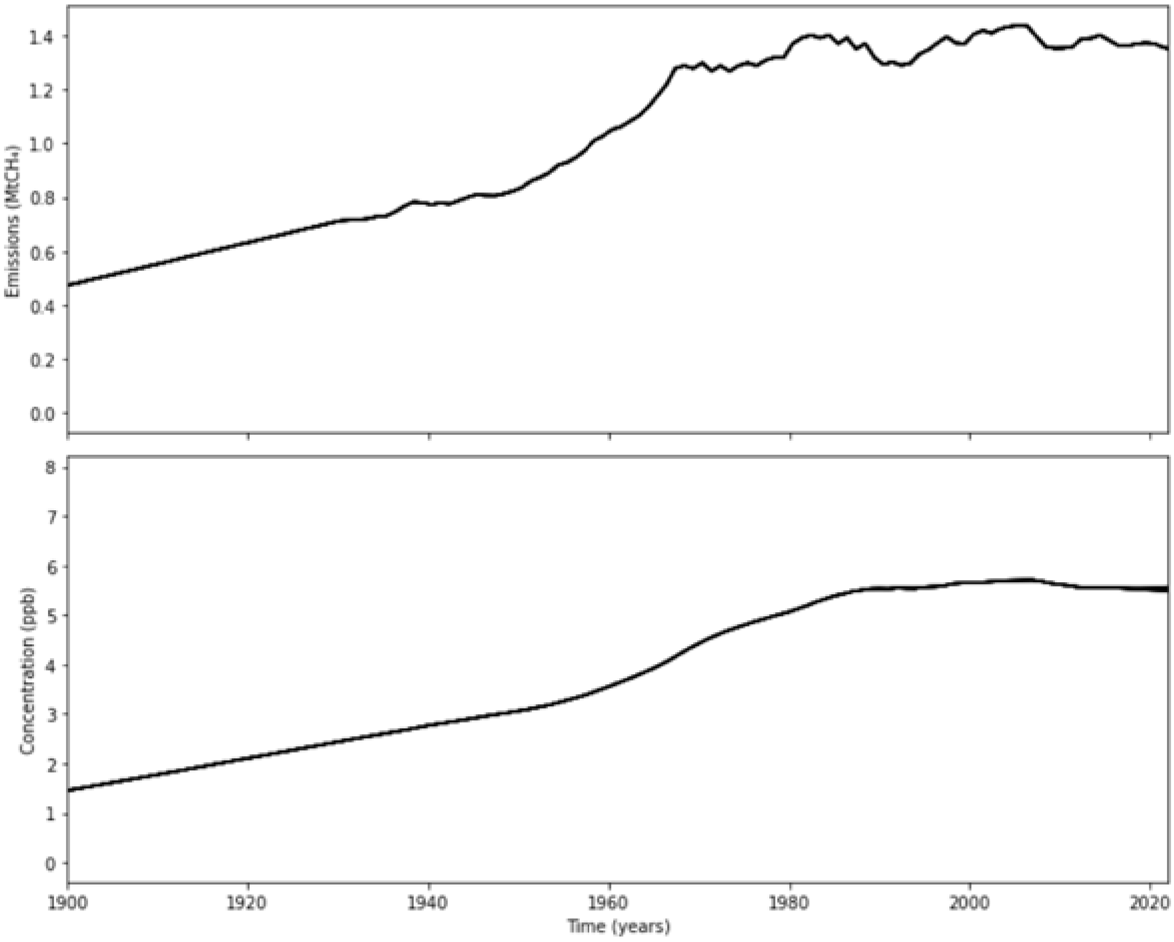
[13] Greenhouse gas reporting | NZ Government

Figure 6: New Zealand’s methane emissions (top, from NZ Greenhouse Gas Inventory, (MfE, 2024)) and contribution to concentrations (bottom, as assessed by the FaIR model, version 2.1)



In summary, despite global trends to the contrary, the evidence to date shows NZ’s methane emissions have been largely stable for some years and decreasing since 2019. The increase in methane concentrations related to NZ’s emissions has slowed over the past decade, reflecting the reduction in emissions and NZ’s contribution to ‘holding the increase in the global average temperature’.

The role of methane as a greenhouse gas

Greenhouse gases and Earth's energy balance

The temperature of the Earth is maintained through an energy balance between the sunlight absorbed and the heat energy lost through terrestrial radiation (Figure 7). Gases that readily absorb terrestrial radiation – greenhouse gases – affect climate by altering the balance between the amount of energy entering and leaving the Earth system (Figure 8). Greenhouse gases trap terrestrial radiation in the lower atmosphere, and this causes the 'global warming' effect.

Figure 7: Normalised intensity of radiation emitted by the Sun and the Earth. Adapted from Revell et al. (2021).

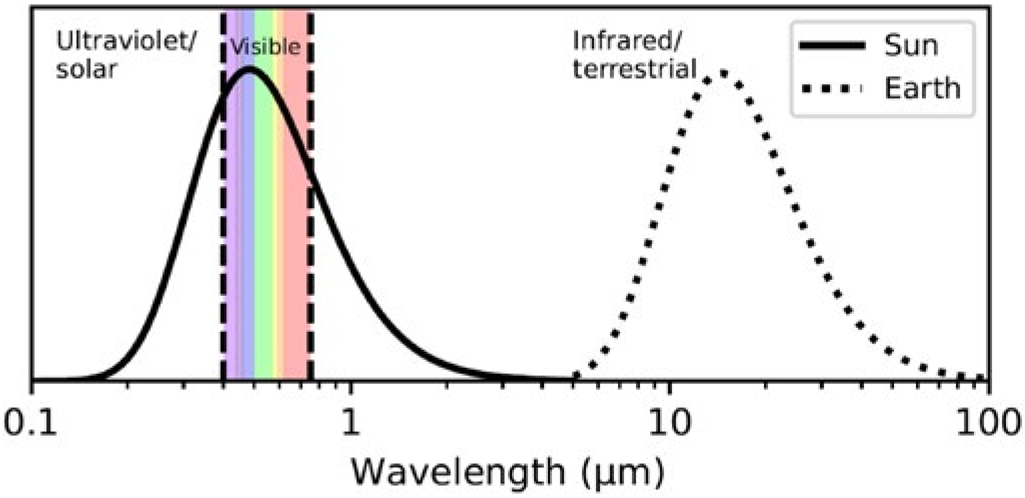
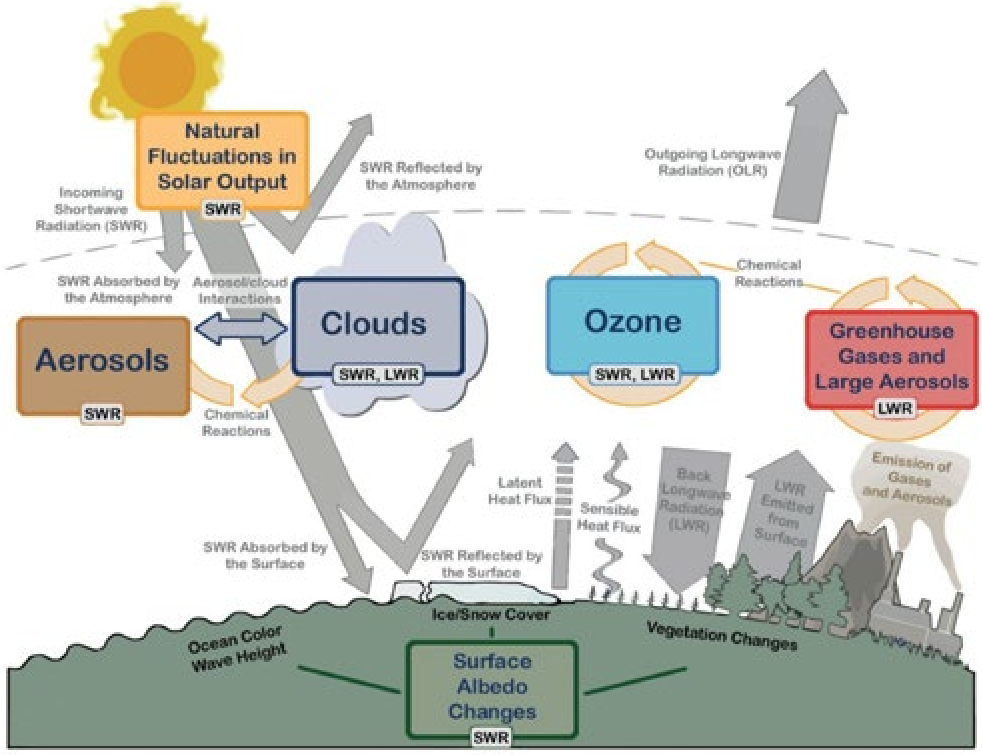


Figure 8: Schematic of the greenhouse effect. From IPCC (2013).



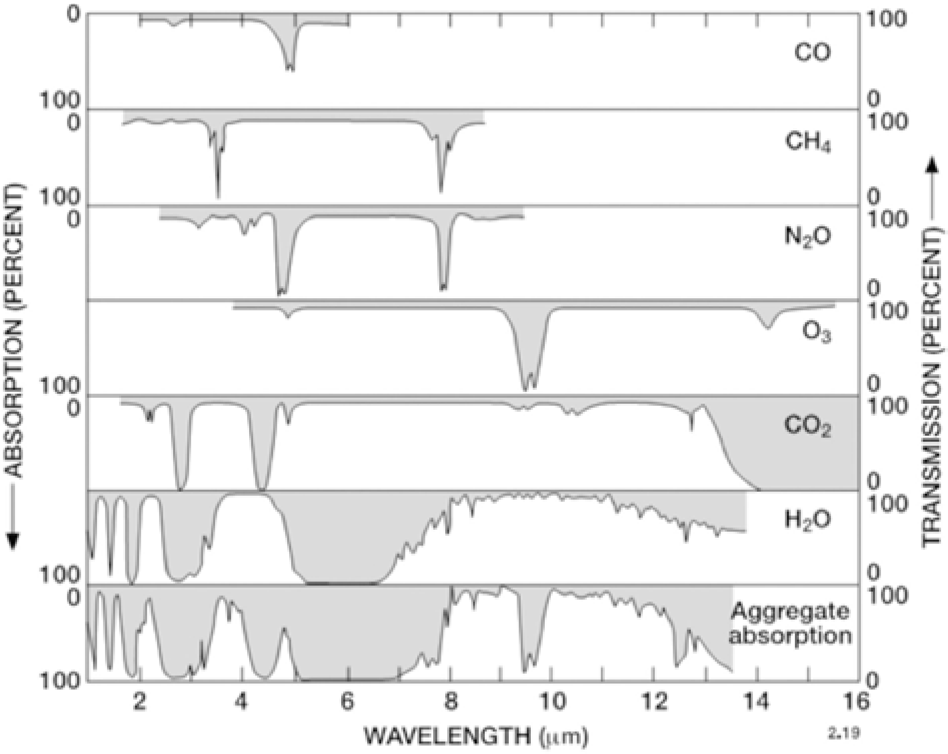
Greenhouse gases and other drivers of climate change alter the Earth's energy balance by changing radiative forcing. A positive radiative forcing means that more energy enters the climate system than leaves it, thus warming occurs. Similarly, a negative radiative forcing means that more energy leaves the Earth system than enters it, thus cooling occurs. Although the radiative forcing is not a climate impact that is experienced directly, the radiative forcing determines how much the Earth warms or cools (Forster et al., 2021).

Greenhouse gases absorb radiation at specific wavelengths with different efficiencies in detailed patterns known as their absorption spectra (Figure 9). Radiative forcing values are determined by sophisticated calculations that account for the fine details of the absorption spectra, the spatial and seasonal variation of surface temperatures, the vertical pattern of temperatures in the atmosphere and the absorption of radiation by other gases in the atmosphere (principally water vapour, carbon dioxide and nitrous oxide).

Radiative forcing of methane

The strongest climate effect of methane is in absorbing terrestrial (thermal infrared) radiation from the Earth's surface and reradiating it out to space at a colder temperature (Collins et al., 2006). Methane also directly absorbs radiation from the Sun (Etminan et al., 2016). Both of these effects warm the climate. Figure 9 shows that below around 7 µm most of the terrestrial radiation absorption is due to water vapour (H2O); between 7 and 8 µm the absorption is due mostly to methane and nitrous oxide (N2O), and beyond 13 µm most is due to CO_2.

Figure 9: Vertical atmospheric absorption and transmission of infrared (terrestrial) radiation from the surface to the top of the atmosphere as a function of wavelength for greenhouse gases in Earth's atmosphere (Brasseur & Jacob, 2017).

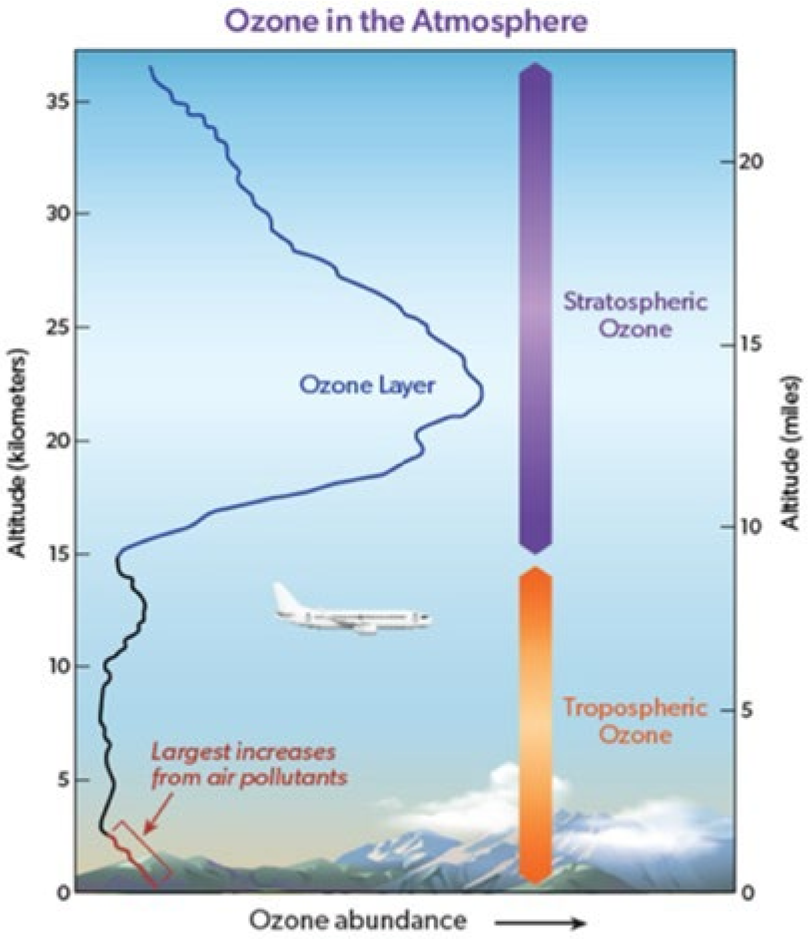


Radiative forcing calculations show that the effectiveness of methane as a greenhouse gas decreases with increasing concentrations of methane as the absorption bands become saturated. Furthermore, some of the methane absorption bands overlap not just with those of nitrous oxide but also carbon dioxide (Etminan et al., 2016). This is important because it means that methane's effectiveness as a greenhouse gas depends on the concentrations of other greenhouse gases in the atmosphere.

Methane also affects atmospheric composition as it is chemically reactive. Chemical reactions involving methane lead to production of ozone, water vapour and carbon dioxide, all of which are also greenhouse gases and so indirectly add to the radiative forcing from methane. For ozone, it is the chemical production in the lowermost layer of the atmosphere the troposphere (surface to approximately 15 km; Figure 10), that is most important[14], whereas for water vapour the production in the stratosphere (15 – 50 km) is most important because the water vapour concentration in the stratosphere is naturally very low. Ozone and water vapour are short-lived in the atmosphere, but contribute to positive radiative forcing, and hence warming, while they exist.

Because methane's radiative efficiency is dependent on atmospheric composition, the climate impact of a specific methane source (e.g. NZ's biogenic emissions) depends on how the overall composition of the atmosphere might evolve in different future scenarios. These will be examined in the next section.

Figure 10: Ozone in the different layers of the atmosphere (Salawitch et al., 2023).



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[14] Ozone in the stratosphere is critical for shielding life on Earth against solar UV-B radiation. However, ozone is present in smaller amounts in the troposphere, where it is a respiratory agent and greenhouse gas.

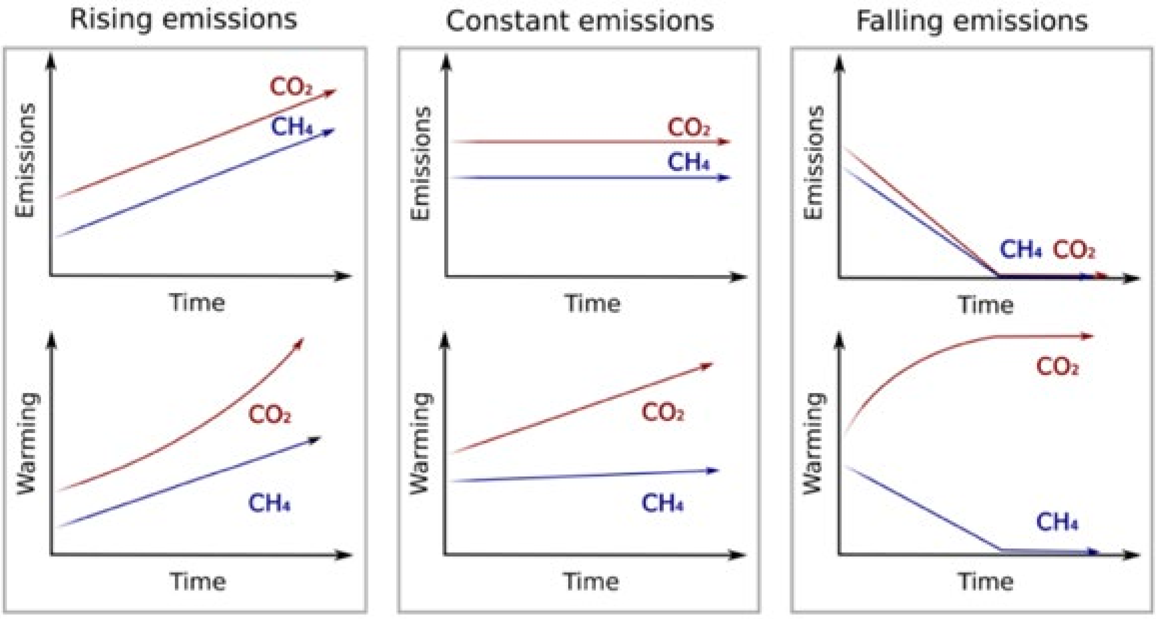
In summary, the key points concerning methane's role as a greenhouse gas are:

- Methane contributes to climate change because it is a greenhouse gas, and absorbs terrestrial radiation (heat) emitted by the Earth.
- Methane also contributes to climate change because it is chemically reactive, leading to the production of other greenhouse gases such as ozone, water vapour and carbon dioxide.
- The effectiveness of methane as a greenhouse gas depends on the concentration of other greenhouse gases in the atmosphere such as nitrous oxide, and the amount of methane itself.

Methane Targets: achieving no additional warming

Additional warming refers to the change in warming relative to a reference year level. Additional warming has been used by the IPCC (e.g. Canadell et al., 2021) mainly in the context of CO_2 budgets. For CO_2 the additional warming compared to a reference year is approximately proportional to the cumulative amount emitted since then. Hence if global CO_2 emissions decline to net zero by a particular year (as in the "falling emissions" scenario sketched in Figure 11), then from then on CO_2 will cause approximately no additional warming compared to that year. This does not apply to short-lived gases. From the "constant emissions" scenario sketched in Figure 11 it can be seen that a relatively small decrease in emissions would be needed to achieve no additional warming.

Figure 11: Relationship between emissions and warming for carbon dioxide and methane (Allen et al., 2022a).



The IPCC stated *"In general, achieving net zero CO_2 emissions and declining non-CO_2 radiative forcing would be sufficient to prevent additional human-caused warming"* (Forster et al., 2021). Since net zero CO_2 emissions are straightforward, we must ask what 'declining non-CO_2 radiative forcing' would look like in terms of methane emissions and previous studies have considered this. Reisinger et al. (2018) suggested that a useful benchmark could be to quantify the reduction in methane emissions needed to result in no additional warming relative to the warming caused by methane emissions already. The IPCC does not specify that any particular year should be used for the base year. The terms of reference for this panel state that this year should be 2017, which is embedded in NZ's Climate Change Response Act (outlined in the Introduction). In 2017, NZ's biogenic methane emissions were 1.361 Mt (Figure 2).

The IPCC report on Global Warming of 1.5 °C defined climate neutrality as the concept of a state in which human activities result in no net effect on the climate system (IPCC, 2018). If this were considered in terms of the effect on global surface temperature, then both net zero CO_2 and no additional warming from methane could be considered to be climate neutral.

Although methane emissions only remain in the atmosphere for around a decade on average, the warming they cause lasts longer as the heat penetrates into the ocean, which can take decades to centuries to heat up or cool down. This means that the amount of warming caused by methane up until the year 2017 is not solely due to methane emitted in recent decades, but has contributions from methane emitted over the 20th century. If the emissions of methane could be fixed at a constant level, warming would continue due to the time lag in the response of the oceans. Hence for no additional warming, the radiative forcing from methane has to decrease. The rate of that decrease depends on how quickly the forcing had increased up to that point, and the timescales for the oceans to respond. This can be calculated using simple climate models which emulate complex Earth system models. The additional warming concept could also be applied with models to national and sectoral emissions of methane rather than the global total (Reisinger, 2018). Here the definition takes the difference between the global warming from total methane excluding NZ biogenic emissions, with that including these emissions.

The concept of no additional warming from previous studies of targets for biogenic methane

The IPCC report 'Global Warming of 1.5 °C' (IPCC, 2018) assessed a range of future greenhouse gas scenarios generated by economic models (IAMs). As discussed in the 'Domestic Targets' section, the scenarios that managed to limit warming to 1.5 °C (or with limited overshoot above this) were deemed to be illustrative, did not indicate requirements and were not country specific. They included a range of agricultural methane emissions in 2050 (i.e. not including biogenic methane from waste) of 24 to 47% (25th to 75th percentiles) below 2010 values.

The IPCC (2018) Summary for Policymakers made the following point about halting anthropogenic warming:

Reaching and sustaining net-zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal timescales (high confidence). The maximum temperature reached is then determined by cumulative net global anthropogenic CO_2 emissions up to the time of net zero CO_2 emissions (high confidence) and the level of non-CO_2 radiative forcing in the decades prior to the time that maximum temperatures are reached (medium confidence).

Essentially, for warming to halt, net emissions of long-lived gases have to decline to zero, while emissions of short-lived gases have to decline slightly for warming to halt on multidecadal timescales (Forster et al., 2021). For global methane emissions, Cain et al. (2019) found that an emission decline of 0.3% per year would yield no further warming. This study assumed no future changes in the radiative efficiency or lifetime of methane.

The conditions for halting warming from long-lived and short-lived gases also generally apply at national scales: stopping net emissions of long-lived gases and reducing the emissions from short-lived forcing sources is usually enough to halt further warming, but the levels of reductions required from non-CO_2 forcings can vary, depending on a country or firm's recent history of emissions of short-lived forcings. Halting further warming – i.e. achieving no additional warming from all sources, fixes the existing warming contributions from all gases. It is sometimes argued that this "grandparents" warming from short-lived gases; but this claim misses the fact that it does exactly the same thing for long-lived gases, too. Net zero CO_2 holds the warming from CO_2 at the level determined by the year at which net zero is achieved. Achieving net zero CO_2 "grandparents" warming from CO_2 in exactly the way that no additional warming "grandparents" warming from short-lived gases. In each case, further emissions reductions (i.e. below net zero, in the CO_2 case) are required to reduce warming.

In NZ's case, the required methane emissions for no additional warming from NZ biogenic methane have been calculated in various studies. Reisinger (2018) found that historical NZ livestock emissions had contributed between 0.0011 and 0.0015 °C of warming by 2016 from 1850. Any reductions in NZ methane depended on the levels of methane emitted by the rest of the world. Hence for a moderate future global methane emissions scenario the necessary NZ reductions were smaller than if global methane concentrations followed a lower emissions scenario, such as limiting warming to 1.5 °C. The reductions necessary for no additional warming after 2016 were 5% (moderate global methane) and 16% (lower global methane) by 2050, but increased to 10% and 22% when the reduced CO_2 uptake was accounted for. Reisinger (2018) concluded that for approximately stable warming from 2016 to 2050, most of these reductions needed to occur before 2030.

A study by Reisinger and Leahy (2019) found that if the rest of the world followed a low emission scenario then a 24% reduction of NZ's methane emissions, below 2010 values by 2050 was sufficient to stabilise NZ's contribution to warming from methane, and a 47% reduction would reduce NZ's contribution to methane's warming below current levels.

A study by Barth et al. (2023) found a similar dependence on greenhouse gas emissions when using a newer set of shared socioeconomic scenarios. The range of reductions needed by 2050 (relative to 2020 values) to achieve no further warming since 2020 was 27% for the low emissions scenario and 8% for the high emissions scenario, with 15% for the middle-of-the-road scenario.

Comparisons between the various studies are complicated by the base year against which reductions are determined. For example, a 24% reduction relative to 2010 values is not always directly comparable with a 27% reduction relative to 2020 values. A further complication is that different models and versions of models have been used in the various studies. Estimates of warming will therefore differ as the models are refined. The base year this review is using is 2017 as that is in the legislation: comparisons between the modelling done in this review and previous studies will need to take this into account.

The finding that higher emissions from the rest of the world means that NZ should reduce emissions less for no additional warming, seems counterintuitive. This is because the calculation is not for the total warming from methane (which would be rising with higher rest of the world emissions), but for the contribution of NZ's methane to this warming. As discussed above, the effectiveness of methane as a greenhouse gas decreases with increasing concentrations of methane as the absorption bands become saturated (Section 'The role of methane as a greenhouse gas'). Another way of describing this situation is that equivalent methane reductions in NZ in higher emission scenarios would contribute less warming (cooling) from NZ's 21st century methane, as opposed to additional warming.

In summary, the key points with respect to how additional warming is defined are:

- Additional warming calculations have been applied to CO_2 budgets. A similar concept of additional warming can be applied to methane, but different calculations are needed because of its short-lived presence in the atmosphere.
- A reference year is needed to define no additional warming relative to a particular point in time. 2017, as stated in the legislation, was specified as the base year for this review[15].
- The warming effect of NZ's methane is not solely dependent on NZ's actions. It is also affected by emissions of methane and other gases from the rest of the world.

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[15] Alternatively, a reference level of warming could be used instead of reference year.

Scenarios: projections of future climate change

Shared Socioeconomic Pathways (SSPs)

Calculating methane emission targets consistent with ‘no additional warming’ requires consideration of longer-term changes in atmospheric composition. Modelling greenhouse gas emissions to the end of the 21st century (and beyond) can inform decision-making. To carry out such modelling, climate models require greenhouse gas and aerosol[16] scenarios. The scenarios developed for the sixth (and most recent) assessment report by the IPCC are called the Shared Socioeconomic Pathways (SSPs). The SSPs represent narratives from 2015 for energy use, land use, air pollution control and greenhouse gas emissions based on evolving socio-economic and technological conditions. These narratives are documented by Riahi et al. (2017) and summarised briefly in Table 1.

Table 1: Summary of SSP narratives, adapted from Riahi et al. (2017).

SSP1	‘Sustainability’ (low challenges to mitigation and adaptation). The world shifts toward a more sustainable path, management of the global commons improves and perceived environmental boundaries are respected.
SSP2	‘Middle of the road’ (medium challenges to mitigation and adaptation). The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Challenges to reducing vulnerability to societal and environmental changes remain.
SSP3	‘Regional rivalry’ (high challenges to mitigation and adaptation). Resurgent nationalism and regional conflicts push countries to focus on domestic issues. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.
SSP4	‘Inequality’ (low challenges to mitigation, high challenges to adaptation). Inequalities increasingly occur across and within countries. Social cohesion degrades while technology development is high in the high-tech economy and sectors. Environmental policies focus on local issues around middle and high income areas.
SSP5	‘Fossil-fueled development’ (high challenges to mitigation, low challenges to adaptation). The push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. The global economy grows rapidly.

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[16] Aerosols, also known as ‘particulate matter’ are tiny droplets or solid particles suspended in air, for example black carbon (soot).

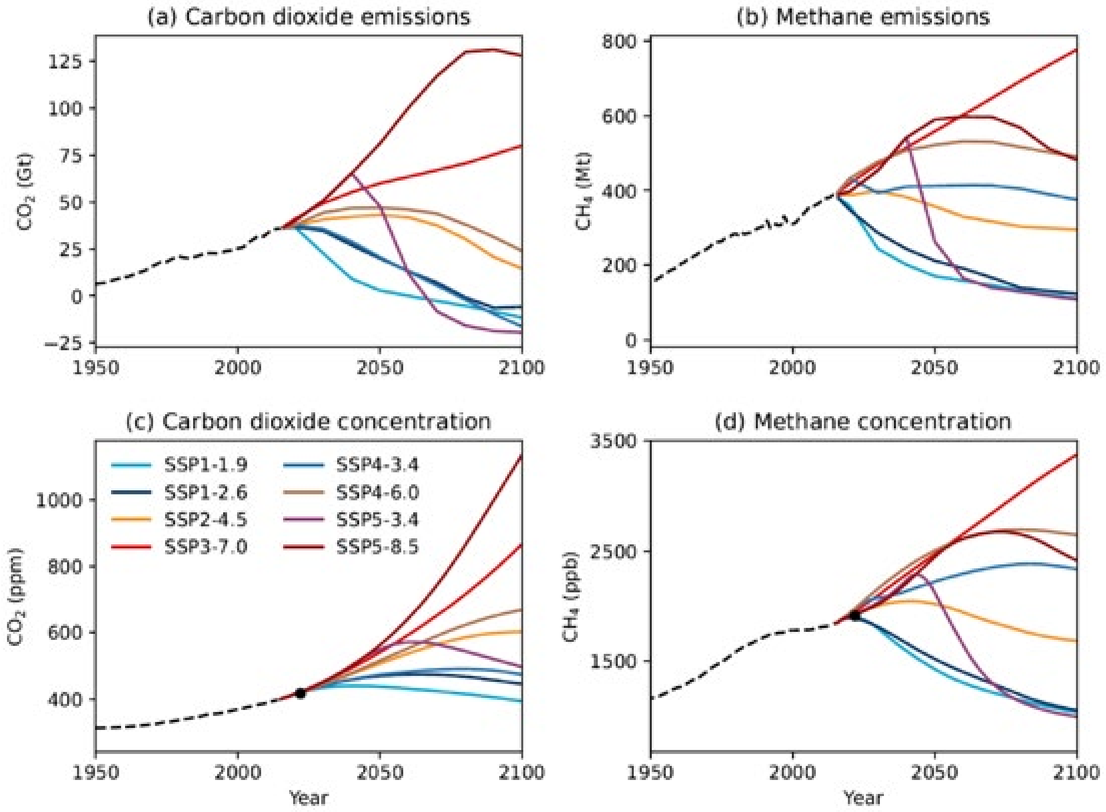
On top of the SSP narratives there are different levels of climate mitigation. The only scenarios widely used which are consistent with the goals of the Paris Agreement are SSP1-1.9 and SSP1-2.6. The ‘1.9’ and ‘2.6’ refer to the increase in radiative forcing between the preindustrial period and the end of the 21st century (i.e. an increase of 1.9 W m-2 and 2.6 W m-2, respectively). These radiative forcing changes span a range of potential values identified via literature and modelling (van Vuuren et al., 2011). The aspirational target of limiting warming to less than 1.5°C above pre-industrial levels is represented by the SSP1-1.9 scenario and the holding to increase to below 2°C is represented by the SSP1-2.6 scenario.

In contrast, for SSP3-7.0 and SSP5-8.5 to occur would require reversal of some current climate policies (Hausfather & Peters, 2020) and lead to ~4-5 °C increases in global-mean temperature by the end of the 21st century (Tebaldi et al., 2021). SSP5-8.5 is considered highly unlikely due to developments in the energy sector (Hausfather & Peters, 2020).

Historical (up until 2014) and projected (following the SSPs) methane emissions and concentrations are shown in Figure 12. Carbon dioxide is also shown, since it is the dominant greenhouse gas emitted from human activities and is long-lived – thus driving most of the global temperature change. Meeting the goals of the Paris Agreement via SSP1-1.9 (for example) would require global emissions of carbon dioxide and methane to follow the SSP1-1.9 pathway illustrated in Figure 12. Emissions of other greenhouse gases (such as nitrous oxide) and aerosols would also have to follow their respective SSP1-1.9 pathways.

When the SSPs were developed, projected methane concentrations for 2022 ranged between 1884 ppb (for SSP1-2.6) and 1980 ppb (for SSP4-6.0; Meinshausen et al., 2020). The actual concentration in 2022 was measured to be 1911 ppb (Lan et al., 2024), i.e. mid-way between these two modelled extremes.

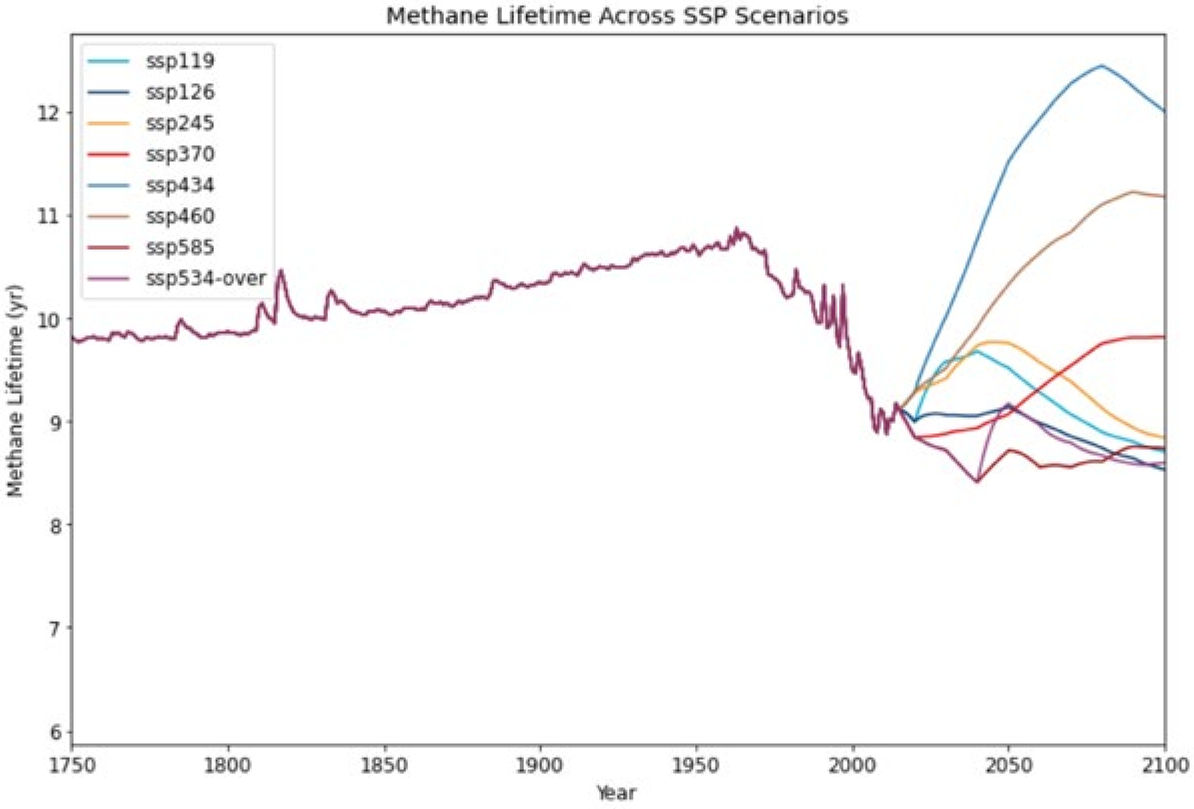
Figure 12. **Top row: Global annual-mean carbon dioxide and methane emissions for the historical period (until 2014; dashed black line) and for future scenarios following the Shared Socioeconomic Pathways (SSPs); Data from Meinshausen et al. (2020). Bottom row: Global annual-mean carbon dioxide and methane concentrations following the SSPs. Black circles on (c) and (d) indicate annual-mean concentrations measured in 2022 (NOAA, 2023).**



Methane Lifetime

Methane's lifetime in the atmosphere has been around nine years in the recent decade (Szopa et al., 2021; Saunois et al., 2024), but can vary from this by more than a year (Stevenson et al., 2020) depending on the atmospheric concentrations of a range of species (CO, CH_4, NOx and volatile organic compounds) which affect the prevalence of the hydroxyl radical, which helps break methane down into CO_2, water vapour, and other trace gases. The SSP scenarios include a range of different possible futures for the composition of the atmosphere, and the FaIR model calculates how these affect methane's atmospheric lifetime as shown in Figure 13.

Figure 13. Methane lifetime as calculated by the FaIR model under historical conditions and the SSP scenarios used in this report.



If the chemical composition of the atmosphere is changed along the lines of the SSP4 'inequality' narrative (Table 1), then the lifetime of methane could be extended by over three years. As methane lasts longer this means that methane concentrations increase, requiring steeper cuts to maintain a constant level of warming. Conversely, if the world follows a high emissions and warming scenario such as SSP5-8.5, then methane lifetimes would reduce (due to the enhanced production of the hydroxyl radical), lowering the level of methane emissions reductions required to satisfy the no additional warming (NAW) condition. Recent versions of FaIR (those subsequent to FaIR2.0) attempt to calculate a dynamic methane lifetime based on interactions with other species. Potentially, this can be an important issue in determining the precise rate of emissions reduction required to stay under a temperature threshold, but it is subject to some uncertainty. IPCC 2021 assessed 2008-2017 methane lifetimes at around 9.1±0.9 years, and pre-industrial lifetimes for atmospheric methane are thought to be closer to 9 years. FaIR offers a number of different ways of calculating methane's radiative forcing. In this study we have chosen to use the Thornhill 2021 approach, though other choices are possible, and also defensible. Continued monitoring will inform scientists and policymakers of both composition and the level of overall warming, and hence of adjustments needed to near-term requirements for emissions reductions consistent with no additional warming.

Key points:

- The Shared Socioeconomic Pathways (SSPs) represent a range of possible climate futures.
- The SSPs were developed for the most recent assessment by the Intergovernmental Panel on Climate Change and are widely used in climate change modelling.
- Methane lifetime in the atmosphere is constantly influenced by different emissions and warming scenarios and therefore continued monitoring is needed to inform emission reduction requirements

In the following section, the SSPs are used to provide possible, plausible scenarios against which to assess NZ methane emissions consistent with no additional warming.

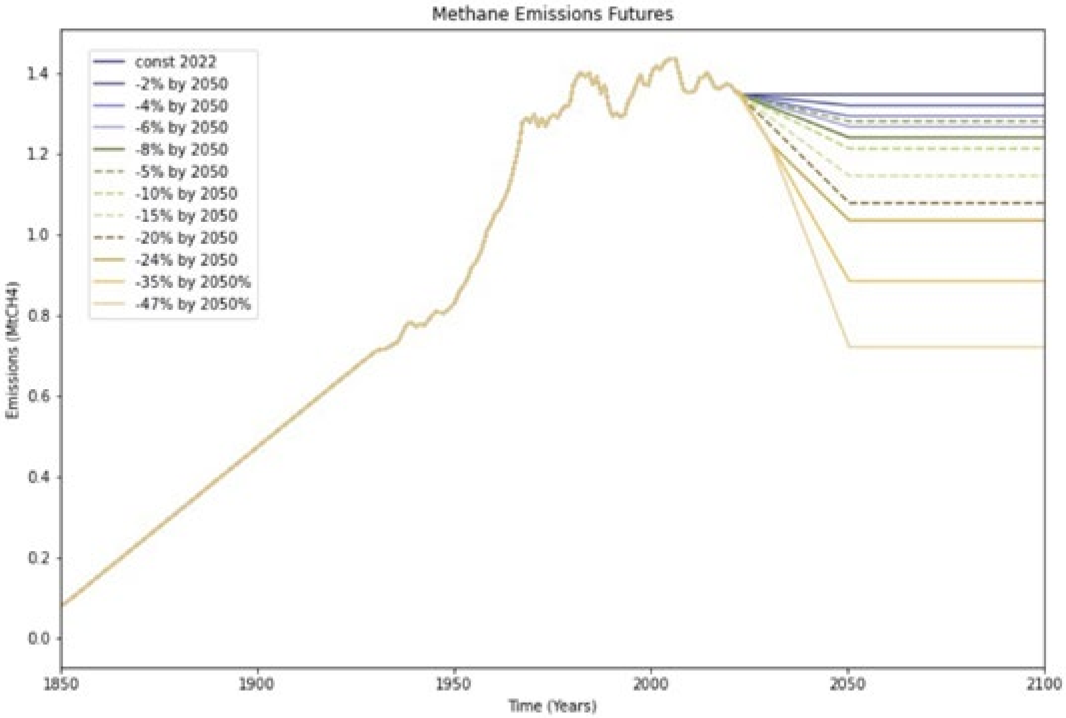
Modelling methane emission futures for New Zealand

To quantify the emissions reductions required to keep NZ's methane-induced warming at or below 2017 levels, FaIR2.1, a simple climate-carbon cycle model, was used. FaIR was chosen because it is an open source model that has been used in a number of studies, including by the IPCC. FaIR2.1 has been developed from previous versions of FaIR developed over the last decade or so (e.g. Smith et al., 2018, Leach et al., 2021). FaIR2.1 adds new complexity, including a dynamic quantification of methane's lifetime based on Thornhill et al. (2021).

A range of different methane emissions futures (MEFs) for NZ were explored to assess conditions under which there may be no additional warming from NZ's biogenic methane. The functional form of emissions reduction was varied to include both per cent per annum emissions reductions (a diminishing curve) and straight-line emissions reductions to 2050. This provided both breadth and depth to the possible ways in which emissions would be reduced. Further details on the modelling methodology using the FaIR2.1 model is provided in Appendix 2.

The MEFs are shown in Figure 14. A number of MEFs were generated that have straight line reductions in methane emissions to 2050 at a specific rate (-2%, -4%, -6%, -8%, -5%, -10%, -15%, -20%, on 2022 levels, and -24%, -35%, -47% on 2017 levels) and then constant emissions afterwards. The three MEFs that start in 2017 do so to make them as consistent as possible with the scenarios outlined in the Climate Change Response Act (2019): these all reduce by 10% by 2030, and then reduce further to fit within the -24% to -47% range in 2050. The other MEFs all begin reductions in 2022 and use it as a baseline in order to start from as recent a point as possible (at the time of writing, NZ methane emissions data past 2022 were unavailable).

Figure 14: **Methane emissions futures (MEFs) used in this study. Historical emissions until 2022 are from the NZ Greenhouse Gas Inventory (MfE, 2024). Emissions futures begin in 2023 and, aside from the last three scenarios which are drawn from the current CCRA, decline linearly until 2050, remaining constant thereafter.**



Temperature responses to these MEFs, as calculated by FaIR2.1, for each of the SSPs considered are presented in time series plots in Appendix 5. The results are summarised in Table 2. In Table 2 if the MEF satisfies the no additional warming relative to 2017 levels in 2050 or 2100, the cell is clear. If the MEF fails the test, i.e. there is warming above 2017 levels under that MEF and SSP scenario, by 2050 or 2100, then the cell is shaded.

Table 2: **Tests for no additional warming (relative to 2017) under 8 SSPs and various future emissions. Shaded means there is additional warming, clear means no additional warming. *percentages changes refer to 2017 emission levels, other percentages changes refer to 2022 emission levels.**

Methane emissions futures involving linear emissions reductions

	SSP1-1.9		**SSP1-2.6**		**SSP2-4.5**		**SSP4-3.4**		**SSP4-6.0**		**SSP3-7.0**		**SSP5-3.4**		**SSP5-8.5**	
	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Constant	■	■	■	■	■	■	■	■	■	■		■				■
-2% by 2050	■	■	■	■	■	■	■	■	■	■		■				■
-4% by 2050	■	■	■	■	■	■	■	■	■	■						■
-6% by 2050	■	■	■	■	■	■	■	■	■	■						■
-8% by 2050	■	■	■		■		■	■		■						■
-10% by 2050	■		■		■		■	■		■						
-15% by 2050	■						■	■		■						
-20% by 2050	■						■	■								
-24% by 2050*								■								
-35% by 2050*																
-47% by 2050*																

The MEFs in Table 2 are straight line decreases to 2050 (the 24%, 35% and 47% MEFs all start with a reduction to 90% of 2017 values by 2030). Additional constant per cent per annum reductions were also evaluated, and results summarised in Appendix 4. These were included to look at how and whether the details of the emissions trajectory between now and 2050 mattered (the results are not particularly sensitive to the functional form), and because some stakeholders tend to express mitigation in a per annum framing, rather than a multidecadal target framing.

Whether or not the MEFs imply warming that stays at or below 2017 temperature levels depends on whether and how much emissions of methane and other GHGs from the rest of the world decline in the coming decades. Global scenarios that are consistent with the aspirational target of limiting warming to less than 1.5 °C above pre-industrial levels are represented by the SSP1-1.9 scenario. This scenario involves rapid reductions in emissions of CO_2 and CH_4, from 2015. Under this scenario, 2023 global emissions of CO_2 were modelled to be 32.3 Gt CO_2, and 324.1 Mt CH_4, respectively (Meinshausen et al., 2020). Actual anthropogenic 2023 emissions of these gases exceeded these estimates: Fossil fuel and industrial CO_2 emissions were 39 Gt, and methane emissions were 350 Mt (UNEP, 2024), illustrating that global emissions now need to drop more rapidly if that aspirational SSP1-1.9 target is to be achieved.

The Panel was asked to consider a scenario consistent with 1.5 °C above pre-industrial levels (e.g. SSP1-1.9) as this is the stated goal of NZ's established legislation. For SSP1-1.9, MEFs fail the no additional warming (NAW) test in 2050 for straight line reductions less than 24% on 2017 levels by 2050, or equivalently for those MEFs with lower than 1.0% per annum reductions (Appendix 4). For this scenario, emissions reductions of 24% on 2017 methane emissions levels by 2050 are sufficient to meet the NAW condition. Because most of the changes in methane's radiative efficiency associated with this scenario occur before 2050, as methane concentrations drop rapidly, and because radiative efficiency remains more constant in the second half of the century, a wider range of MEFs meet the NAW condition under SSP1-1.9 by 2100: emissions reductions of 10% by 2100, or per annum emissions reductions of 0.2% or more across the century, are sufficient to satisfy the NAW condition in 2100 for many MEFs. For the other low emissions scenario, SSP1-2.6, the NAW condition is also met in 2100 from emissions reductions of 10% by 2050 but this is not sufficient to satisfy NAW by 2050. An additional target with a 13% cut by 2050 was explored for this scenario, and this did satisfy the NAW condition by 2050.

At the other end of the global scenario range, scenarios which involve on-going growth in global emissions of GHGs see the NZ MEFs satisfy the NAW condition with low annual rates of reduction. For SSP5, all MEFs, even constant emissions at 2022 levels, satisfy the NAW condition in 2050. In the highest global GHG scenario, SSP5-8.5, reductions of 15% or less by 2050 see additional warming relative to 2017 levels in 2100, while in SSP5-3.4 all MEFs scenarios satisfy the NAW condition in 2100. While SSP5-8.5 is an extreme scenario and one that might be discarded as irrelevant to this analysis, it is of interest to note that it is being used for adaptation advice by government and features prominently in the Ministry for the Environment's (MfE) Coastal hazards and climate change guidance (Ministry for the Environment, 2022).

For a middle of the road scenario SSP2-4.5, which has been the closest scenario to the actual greenhouse gas emission trend since 2015, a 10% cut by 2050 was sufficient to satisfy the NAW condition by 2100 but not sufficient to satisfy the NAW condition by 2050. An additional target with a 14% cut by 2050 was explored for this scenario, and this did satisfy the NAW condition by 2050.

To enable a comparison across all the MEFs that are also comparable to the emission reductions for the current biogenic methane target, the reduction in emissions that was used in each MEF is presented in Table 3 as a percentage of the 2017 levels. So, for those MEFs that are based on 2022 that satisfied the NAW condition the amount of their reduction is expressed in Table 3 as a percentage of the 2017 level. 2022 emission levels are already 1% below 2017 so MEFs with a 0% reduction in the modelling based on 2022 levels require no further decrease.

Table 3: **A summary of the minimum straight line 2050 target) in each scenario that met the requirement for no additional warming (relative to 2017) by 2050 adjusted to a 2017 base year.**

Scenarios	2050 target % decrease for no additional warming adjusted to a 2017 base year
SSP1-1.9	-24
SSP1-2.6	-14
SSP2-4.5	-15
SSP4-3.4	-24
SSP4-6.0	-11
SSP3-7.0	-1
SSP5-3.4	-1
SSP5-8.5	-1

Unless global emissions of GHGs reduce rapidly in the next couple of decades, cuts on 2017 biogenic methane emission levels of around 14-15% by 2050 are sufficient to keep warming from NZ's biogenic methane to levels at or below 2017 levels. The current legislated targets are for cuts between 24% and 47% by 2050 from 2017 emission levels. Cuts amounting to 24% by 2050 are always consistent with the NAW condition to keep or return warming to at or below 2017 levels, even where VOCs rapidly change (SSP4-3.4). For mid-range scenarios and those most like the International Energy Association's emissions scenarios and current NDCs that still are aiming to hold emissions to below 2 °C, cuts of 14-15% by 2050 are consistent with meeting the NAW condition.

Sensitivity analyses

There are a number of factors that could affect the exact level of emissions reductions that are consistent with the NAW criterion. These include the concentration of methane and other GHGs, which determine both the radiative efficiency and lifetime of methane (both discussed above). Climate response parameters, such as the timescales of adjustment and, relatedly, climate sensitivity, and uncertainty in current and historical emissions also influence the level of emissions reductions required. For the current analysis, the details of which depend on balancing reductions in emissions rates with temperature change, the most significant uncertainties concern radiative efficiency and methane lifetime, i.e. aspects of atmospheric chemistry and physics.

Additionally, there is some uncertainty regarding NZ's current methane emissions. To test the sensitivity of results to the amplitude of emissions, we increased and decreased the entire NZ methane emissions data series by 16%. This made no material difference to which scenarios were consistent with the NAW condition. There is also some uncertainty around emissions time-series and although this uncertainty is decreasing as measurement of emissions improves, it provides a factor to which the detailed results presented in Table 2 can be sensitive. Revisions to biogenic emissions during the early years of the inventory period, or revisions to estimates of 20th century methane emissions, could shift the emissions reduction rate required to meet the NAW condition by a few per cent. The more recent the revision, the greater the effect. This is because warming associated with methane is sensitive to recent emission rates and is also sensitive to emissions that occurred earlier.

The sensitivity of warming associated with methane is not because methane is long lasting – it leaves no chemical signal behind after 100 years – but because while it is aloft it traps radiation which warms the planet, especially the ocean, and this warming persists. This is a well-understood phenomenon associated with how the Earth's climate deals with perturbations to its energy budget (Forster et al., 2021, Box 1, Gregory et al., 2004). The ocean dominates the heat capacity of the Earth's climate system, and perturbations to the Earth's energy budget act both to warm the atmosphere and slowly increase ocean heat storage. Methane is short-lived, and acts to warm the atmosphere and surface, and this in turn adds to the ocean's heat storage; the same is true for any source of (positive) radiative forcing. If that source of radiative forcing is turned off, surface temperatures will drop from peak levels, but not return all the way to pre-industrial levels, because the ocean – with its vast heat capacity – has been warmed above pre-industrial levels, and this heat store maintains surface temperatures above pre-industrial levels.

Discussion

NZ's methane emissions are largely sourced from biogenic, i.e. agricultural and waste, activities. Evidence indicates that NZ's methane emissions have been decreasing since 2019 and that NZ's contribution to the increase in methane concentration in the atmosphere is slowing down. Article 2 of the Paris Agreement on climate change "...aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty," by "Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels…'. The subsequent NZ legislation established domestic climate change 2050 targets (reductions of 24-47%) to contribute to the global pursuit of efforts to limit warming to 1.5 °C.

When assessing such targets the dynamics of global atmospheric GHG concentrations and delayed methane-induced warming resulting from oceanic thermal inertia must be taken into consideration, as must global socioeconomic factors evolving over time. These variables can have a significant influence on resultant levels of warming, and the impact of NZ's methane emissions.

Studies designed to predict these variables over a longer time period use sophisticated modelling tools that combine historic and ongoing measures of methane with projected socio-economic developments to calculate what changes to methane profiles could result going forwards – not just to the established 2050 target date but beyond that to the end of the 21st century in order to plan how to meet the no additional warming goal.

As summarised in Table 3 the cuts in NZ's biogenic methane that are necessary to meet the condition of no additional warming are strongly dependent on the path taken by the rest of the world. If the rest of the world were to rapidly increase its climate policies to meet the Paris goal of pursuing efforts towards limiting temperatures to 1.5 °C above pre-industrial levels then NZ's biogenic methane emissions would need to be reduced by 24% by 2050 for no additional warming on 2017 levels by 2050. Exact comparisons with other studies are challenging due to the use of different models or different reference years. This report generally agrees with findings using the same scenario from Barth et al. (2023) who found 27% cuts on 2020 methane levels by 2050 would be sufficient for no additional warming compared to 2020, and Reisinger (2018) using a slightly less stringent greenhouse gas scenario who calculated a required reduction of 22% on 2016 biogenic methane levels was necessary for no additional warming compared to 2020.

The SSP2-4.5 scenario is closest to current global emissions as well as current NDCs, in which case a 15% emissions reduction on 2017 emission levels by 2050, or 0.5% per annum reduction, would meet a target of no further warming from NZ's biogenic methane. This is also in agreement with the studies of Barth et al. (2023) and Reisinger (2018) who calculated necessary reductions by 2050 of 15% or 12% respectively, for the same or similar scenario, and using a 2020 or 2016 reference year. The 0.5% per annum reduction is in line with calculations by Cain et al. (2019) that assumed constant methane radiative efficiency and methane lifetime, which is approximately the case in the middle-of-the-road scenario.

If the world were to reverse some of its climate policies then the global increased methane would reduce the impact of NZ's emissions such that 2022 emission levels by 2050 could potentially be sufficient, for no further warming for the rest of the century.

In conclusion, this report indicates that NZ methane emissions reductions consistent with the NAW criterion could vary between 0% and 24% depending on emissions of GHGs elsewhere.

- If other countries reduce their emissions steeply (i.e. broadly in line with SSP1-1.9), then domestic emissions would have to reduce by around 24% by 2050.
- If countries contributed less in the way of emissions reductions (broadly in line with SSP3-7.0 or SSP5-3.4), then maintaining 2022 domestic emissions levels should be sufficient.
- If other countries' emissions fell between these two extremes, (such as the SSP1-2.6 and SSP2-4.5 scenarios), similar to the current global emissions trajectories and current NDCs, then domestic emission reductions would need to be around 14-15% on 2017 levels.

These conclusions are in very good agreement with previous studies which gives confidence in their robustness and credibility. However, it is acknowledged that their value in policy settings for satisfying a no additional warming criterion is strongly dependent on their sensitivity to changing climate system and socioeconomic parameters around the globe - careful and continued monitoring of such parameters and biogenic methane atmospheric concentrations and emissions will be vital for their successful implementation.

References

Allen, M. et al. Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature 458, 1163–1166 (2009).

Allen, M.R., Shine, K.P., Fuglestvedt, J.S. et al. A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. npj Clim Atmos Sci 1, 16 (2018). https://doi.org/10.1038/s41612-018-0026-8

Allen et al. (2022a), Climate Metrics for Ruminant Livestock, Oxford Martin Programme on Climate Pollutants, ClimateMetricsforRuminentLivestock_Brief_July2022_FINAL.pdf (svdcdn.com), retrieved 22/10/24.

Allen, M. R. et al. Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets. npj Clim. Atmos. Sci. 5, 1–4 (2022b).

Barth, M. et al. (2023) Agriculture emissions and warming in Aotearoa New Zealand to 2050: insights from the science. Report funded by Beef+Lamb NZ, DairyNZ and Federated Farmers, p. 33. Available at: full-report-agriculture-emissions-and-warming-aotearoa-new-zealand-2050-insights

BERG (2018) Report of the Biological Emissions Reference Group (BERG)

Bodeker, G., Cullen, N., Katurji, M., McDonald, A., Morgenstern, O., Noone, D., Renwick, J., Revell, L. and Tait, A. (2022). Aotearoa New Zealand climate change projections guidance: Interpreting the latest IPCC WG1 report findings. Prepared for the Ministry for the Environment, Report number CR 501, 51p.

Brassuer & Jacob (2017), Modeling of Atmospheric Chemistry, Chapter 5: Formulations of radiative, chemical, and aerosol rates, Cambridge University Press, retrieved from: Formulations of Radiative, Chemical, and Aerosol Rates (Chapter 5) - Modeling of Atmospheric Chemistry (cambridge.org), retrieved 4/10/24.

Cain, M., Lynch, J., Allen, M.R. et al. Improved calculation of warming-equivalent emissions for short-lived climate pollutants. npj Clim Atmos Sci 2, 29 (2019). https://doi.org/10.1038/s41612-019-0086-4

Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816, doi:10.1017/9781009157896.007

Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press,

Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi:10.1017/9781009157896.009.

Collins, W. D., et al. (2006). Radiative forcing by well-mixed greenhouse gases: Estimates from climate models in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). Journal of Geophysical Research. https://doi.org/10.1029/2005JD006713

Dlugokencky E. J., et al., Atmospheric methane levels off: Temporary pause or a new steady-state? *Geophys. Res. Lett. 30,* 1992 (2003).

Etminan, M., et al.. (2016). Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. Geophysical Research Letters. https://doi.org/10.1002/2016GL071930

Forster, P., T. Storelvmo, K. Armour, W. Collins, J.-L. Dufresne, D. Frame, D.J. Lunt, T. Mauritsen, M.D. Palmer, M. Watanabe, M. Wild, and H. Zhang, 2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi:10.1017/9781009157896.009.

Fuglestvedt, J. et al. Implications of possible interpretations of 'greenhouse gas balance' in the Paris Agreement. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci 376, 20160445 (2018).

Geddes, A; Mikaloff Fletcher, SE; Schaefer, H; Smale, D; Brailsford, G; Law, R; Ausseil, A-G (2020). Atmospheric Methane Modelling: Evaluating Regional Methane Emission Using Inverse Modelling, Report for Ministry for Primary Industries.

Gregory, J.M. et al., 2004: A new method for diagnosing radiative forcing and climate sensitivity. Geophysical Research Letters, 31(3), L03205, doi:10.1029/ 2003gl018747.

Gulev, S.K., et al., 2021: Changing State of the Climate System. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 287–422, doi:10.1017/9781009157896.004.

Hausfather, Z. and G. P. Peters (2020). "RCP8.5 is a problematic scenario for near-term emissions." Proceedings of the National Academy of Sciences 117(45): 27791-27792.

Henne, S., Brunner, D., Oney, B., Leuenberger, M., Eugster, W., Bamberger, I., Meinhardt, F., Steinbacher, M., and Emmenegger, L.: Validation of the Swiss methane emission inventory by atmospheric observations and inverse modelling, Atmos. Chem. Phys., 16, 3683–3710, https://doi.org/10.5194/acp-16-3683-2016, 2016.

IPCC (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. https://www.ipcc.ch/sr15/

IPCC (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324

Jackson, R. B., M. Saunois, A. Martinez, J. G. Canadell, X. Yu, M. Li, B. Poulter, P. A. Raymond, P. Regnier, P. Ciais, S. J. Davis and P. K. Patra (2024). "Human activities now fuel two-thirds of global methane emissions." Environmental Research Letters 19(10): 101002.

Kelliher FM, Clark H, Smith MH, Lassey KR, Sedcole R. 2009. Reducing Uncertainty of the Enteric Methane Emissions Inventory. Report prepared for the Ministry of Agriculture and Forestry by Lincoln University, National Institute of Water and Atmospheric Research and AgResearch. Wellington: Ministry of Agriculture and Forestry.

Lan, X., K.W. Thoning, and E.J. Dlugokencky: Trends in globally-averaged CH_4, N2O, and SF6 determined from NOAA Global Monitoring Laboratory measurements. Version 2024-10, https://doi.org/10.15138/P8XG-AA10, 2024.

Leach, N. J., S. Jenkins, Z. Nicholls, C. J. Smith, J. Lynch, M. Cain, T. Walsh, B. Wu, J. Tsutsui and M. R. Allen (2021). "FaIRv2.0.0: a generalized impulse response model for climate uncertainty and future scenario exploration." Geosci. Model Dev. 14(5): 3007-3036.

Lynch, J., Cain, M., Frame, D., Pierrehumbert, R. (2021) Agriculture's Contribution to Climate Change and Role in Mitigation Is Distinct From Predominantly Fossil CO_2-Emitting Sectors. Front Sustain Food Syst. ; 4:. doi:10.3389/fsufs.2020.518039.

Manning, A. J., S. O'Doherty, A. R. Jones, P. G. Simmonds, and R. G. Derwent (2011), Estimating UK methane andnitrous oxide emissions from 1990 to 2007 using an inversion modeling approach, J. Geophys. Res., 116, D02305,doi:10.1029/2010JD014763

Meinshausen, M., Z. R. J. Nicholls, J. Lewis, M. J. Gidden, E. Vogel, M. Freund, U. Beyerle, C. Gessner, A. Nauels, N. Bauer, J. G. Canadell, J. S. Daniel, A. John, P. B. Krummel, G. Luderer, N. Meinshausen, S. A. Montzka, P. J. Rayner, S. Reimann, S. J. Smith, M. van den Berg, G. J. M. Velders, M. K. Vollmer and R. H. J. Wang (2020). "The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500." Geosci. Model Dev. 13(8): 3571-3605.

Ministry for the Environment. 2022. *Interim guidance on the use of new sea-level rise projections*. Wellington: Ministry for the Environment.

MfE (2024) Ministry for the Environment: New Zealand's Greenhouse Gas Inventory 1990–2022 https://environment.govt.nz/publications/new-zealands-greenhouse-gas-inventory-1990-2022/

Michel, S.E., Lan, X., Miller, J.B., Tans, P., Clark, J.R., Schaefer, H., Sperlich, P., Brailsford, G., Morimoto, S., Moossen, H., Li, J. (2024). Rapid shift in methane carbon isotopes suggests microbial emissions drove record high atmospheric methane growth in 2020–2022, PNAS, 121 (44) e2411212121 https://doi.org/10.1073/pnas.2411212121

Nisbet, E. G., et al. (2016), Rising atmospheric methane: 2007–2014 growth and isotopic shift, Global Biogeochem. Cycles, 30, 1356–1370, doi:10.1002/2016GB005406.

Nisbet, E. G., Manning, M. R., Dlugokencky, E. J., Fisher, R. E., Lowry, D., Michel, S. E., et al. (2019). Very strong atmospheric methane growth in the 4 years 2014–2017: Implications for the Paris Agreement. *Global Biogeochemical Cycles*, 33, 318–342. https://doi.org/10.1029/2018GB006009

NOAA (2023) National Oceanic and Atmospheric Administration: Greenhouse gases continued to increase rapidly in 2022, https://www.noaa.gov/news-release/greenhouse-gases-continued-to-increase-rapidly-in-2022, retrieved 20/11/24

Peng, S., Lin, X., Thompson, R.L. et al. Wetland emission and atmospheric sink changes explain methane growth in 2020. *Nature* 612, 477–482 (2022). https://doi.org/10.1038/s41586-022-05447-w

O'Neill, B. C., E. Kriegler, K. L. Ebi, E. Kemp-Benedict, K. Riahi, D. S. Rothman, B. J. van Ruijven, D. P. van Vuuren, J. Birkmann, K. Kok, M. Levy and W. Solecki (2017). "The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century." Global Environmental Change 42: 169-180.

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

Reisinger, A. and Leahy, S., 2019. Scientific aspects of New Zealand's 2050 emission targets. Palmerston North: New Zealand Agricultural Greenhouse Gas Research Centre.

Reisinger A, Clark H, Cowie AL, Emmet-Booth J, Gonzalez Fischer C, Herrero M, Howden M, Leahy S. 2021 How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals? Phil. Trans. R. Soc. A 379: 20200452. https://doi.org/10.1098/rsta.2020.0452

Revell, L. E., P. Kuma, E. C. Le Ru, W. R. C. Somerville and S. Gaw (2021). "Direct radiative effects of airborne microplastics." Nature 598(7881): 462-467.

Riahi, K., D. P. van Vuuren, E. Kriegler, J. Edmonds, B. C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J. C. Cuaresma, S. Kc, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L. A. Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J. C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau and M. Tavoni (2017). "The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview." Global Environmental Change 42: 153-168.

Salawitch, R. J., McBride, L. A., Thompson, C. R., Fleming, E. L., McKenzie, R. L., Rosenlof, K. H., Doherty, S. J., & Fahey, D. W.: Twenty Questions and Answers About the Ozone Layer: 2022 Update, Scientific Assessment of Ozone Depletion: 2022, 75 pp., World Meteorological Organization, Geneva, Switzerland, 2023.

Saunois, M., A. Martinez, B. Poulter, Z. Zhang, P. Raymond, P. Regnier, J. G. Canadell, R. B. Jackson, P. K. Patra, P. Bousquet, P. Ciais, E. J. Dlugokencky, X. Lan, G. H. Allen, D. Bastviken, D. J. Beerling, D. A. Belikov, D. R. Blake, S. Castaldi, M. Crippa, B. R. Deemer, F. Dennison, G. Etiope, N. Gedney, L. Höglund-Isaksson, M. A. Holgerson, P. O. Hopcroft, G. Hugelius, A. Ito, A. K. Jain, R. Janardanan, M. S. Johnson, T. Kleinen, P. Krummel, R. Lauerwald, T. Li, X. Liu, K. C. McDonald, J. R. Melton, J. Mühle, J. Müller, F. Murguia-Flores, Y. Niwa, S. Noce, S. Pan, R. J. Parker, C. Peng, M. Ramonet, W. J. Riley, G. Rocher-Ros, J. A. Rosentreter, M. Sasakawa, A. Segers, S. J. Smith, E. H. Stanley, J. Thanwerdas, H. Tian, A. Tsuruta, F. N. Tubiello, T. S. Weber, G. van der Werf, D. E. Worthy, Y. Xi, Y. Yoshida, W. Zhang, B. Zheng, Q. Zhu, Q. Zhu and Q. Zhuang (2024). "Global Methane Budget 2000-2020." Earth Syst. Sci. Data Discuss. 2024: 1-147.

Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., Raymond, P. A., Dlugokencky, E.3501 J., Houweling, S., Patra, P. K., Ciais, P., Arora, V. K., Bastviken, D., Bergamaschi, P., Blake, D. R., Brailsford, G.,3502 Bruhwiler, L., Carlson, K. M., Carrol, M., Castaldi, S., Chandra, N., Crevoisier, C., Crill, P. M., Covey, K., Curry, C. 3503 L., Etiope, G., Frankenberg, C., Gedney, N., Hegglin, M. I., Höglund-Isaksson, L., Hugelius, G., Ishizawa, M., Ito, A.,3504 Janssens-Maenhout, G., Jensen, K. M., Joos, F., Kleinen, T., Krummel, P. B., Langenfelds, R. L., Laruelle, G. G., Liu,3505 L., Machida, T., Maksyutov, S., McDonald, K. C., McNorton, J., Miller, P. A., Melton, J. R., Morino, I., Müller, J.,3506 Murguia-Flores, F., Naik, V., Niwa, Y., Noce, S., O'Doherty, S., Parker, R. J., Peng, C., Peng, S., Peters, G. P., Prigent,3507 C., Prinn, R., Ramonet, M., Regnier, P., Riley, W. J., Rosentreter, J. A., Segers, A., Simpson, I. J., Shi, H., Smith, S.3508 J., Steele, L. P., Thornton, B. F., Tian, H., Tohjima, Y., Tubiello, F. N., Tsuruta, A., Viovy, N., Voulgarakis, A., Weber,3509 T. S., van Weele, M., van der Werf, G. R., Weiss, R. F., Worthy, D., Wunch, D., Yin, Y., Yoshida, Y., Zhang, W.,3510 Zhang, Z., Zhao, Y., Zheng, B., Zhu, Q., Zhu, Q., and Zhuang, Q.: The Global Methane Budget 2000–2017, Earth 3511 Syst. Sci. Data, 12, 1561–1623, https://doi.org/10.5194/essd-12-1561-2020, 2020.

Schaefer, H., S. E. M. Fletcher, C. Veidt, K. R. Lassey, G. W. Brailsford, T. M. Bromley, E. J. Dlugokencky, S. E. Michel, J. B. Miller, I. Levin, D. C. Lowe, R. J. Martin, B. H. Vaughn and J. W. C. White (2016). "A 21st-century shift from fossil-fuel to biogenic methane emissions indicated by $13CH_4$." Science 352(6281): 80-84

Shindell, D., P. Sadavarte, I. Aben, T. d. O. Bredariol, G. Dreyfus, L. Höglund-Isaksson, B. Poulter, M. Saunois, G. A. Schmidt, S. Szopa, K. Rentz, L. Parsons, Z. Qu, G. Faluvegi and J. D. Maasakkers (2024). “The methane imperative.” Frontiers in Science 2.

Simpson I. J., Sulbaek Andersen M. P., Meinardi S., Bruhwiler L., Blake N. J., Helmig D., Rowland F. S., Blake D. R., Long-term decline of global atmospheric ethane concentrations and implications for methane. Nature 488, 490–494 (2012)

Skeie, R. B., Hodnebrog, Ø. & Myhre, G. Trends in atmospheric methane concentrations since 1990 were driven and modified by anthropogenic emissions. *Commun. Earth Environ*. 4, 317 (2023).

Smith, C. J., P. M. Forster, M. Allen, N. Leach, R. J. Millar, G. A. Passerello and L. A. Regayre (2018). “FAIR v1.3: a simple emissions-based impulse response and carbon cycle model.” Geosci. Model Dev. 11(6): 2273-2297.

Stevenson, D. S., Zhao, A., Naik, V., O’Connor, F. M., Tilmes, S., Zeng, G., Murray, L. T., Collins, W. J., Griffiths, P. T., Shim, S., Horowitz, L. W., Sentman, L. T., and Emmons, L.: Trends in global tropospheric hydroxyl radical and methane lifetime since 1850 from AerChemMIP, Atmos. Chem. Phys., 20, 12905–12920, https://doi.org/10.5194/acp-20-12905-2020, 2020

Stevenson, D. S., Derwent, R. G., Wild, O., and Collins, W. J.: COVID-19 lockdown emission reductions have the potential to explain over half of the coincident increase in global atmospheric methane, Atmos. Chem. Phys., 22, 14243–14252, https://doi.org/10.5194/acp-22-14243-2022, 2022

Staniaszek, Z., P. T. Griffiths, G. A. Folberth, F. M. O’Connor, N. L. Abraham and A. T. Archibald (2022). “The role of future anthropogenic methane emissions in air quality and climate.” npj Climate and Atmospheric Science 5(1): 21.

Szopa S, Naik V, Adhikary B, Artaxo P, Berntsen T, Collins WD, Fuzzi S, Gallardo L, Kiendler- Scharr A, Klimont Z, et al. 2021. Short lived climate forcers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Tebaldi, C., K. Debeire, V. Eyring, E. Fischer, J. Fyfe, P. Friedlingstein, R. Knutti, J. Lowe, B. O’Neill, B. Sanderson, D. van Vuuren, K. Riahi, M. Meinshausen, Z. Nicholls, K. B. Tokarska, G. Hurtt, E. Kriegler, J. F. Lamarque, G. Meehl, R. Moss, S. E. Bauer, O. Boucher, V. Brovkin, Y. H. Byun, M. Dix, S. Gualdi, H. Guo, J. G. John, S. Kharin, Y. Kim, T. Koshiro, L. Ma, D. Olivié, S. Panickal, F. Qiao, X. Rong, N. Rosenbloom, M. Schupfner, R. Séférian, A. Sellar, T. Semmler, X. Shi, Z. Song, C. Steger, R. Stouffer, N. Swart, K. Tachiiri, Q. Tang, H. Tatebe, A. Voldoire, E. Volodin, K. Wyser, X. Xin, S. Yang, Y. Yu and T. Ziehn (2021). “Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6.” Earth Syst. Dynam. 12(1): 253-293.

Thornhill, G. D., W. J. Collins, R. J. Kramer, D. Olivié, R. B. Skeie, F. M. O’Connor, N. L. Abraham, R. Checa-Garcia, S. E. Bauer, M. Deushi, L. K. Emmons, P. M. Forster, L. W. Horowitz, B. Johnson, J. Keeble, J. F. Lamarque, M. Michou, M. J. Mills, J. P. Mulcahy, G. Myhre, P. Nabat, V. Naik, N. Oshima, M. Schulz, C. J. Smith, T. Takemura, S. Tilmes, T. Wu, G. Zeng and J. Zhang (2021). “Effective radiative forcing from emissions of reactive gases and aerosols – a multi-model comparison.” Atmos. Chem. Phys. 21(2): 853-874.

United Nations Environment Programme (2024). Emissions Gap Report 2024: No more hot air … please! With a massive gap between rhetoric and reality, countries draft new climate commitments. Nairobi. https://doi.org/10.59117/20.500.11822/46404

van Vuuren, D. P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S. J. Smith and S. K. Rose (2011). “The representative concentration pathways: an overview.” Climatic Change 109(1): 5.

Appendices

1. Terms of Reference

METHANE SCIENCE AND TARGET REVIEW – TERMS OF REFERENCE

Review Title	Review of the methane science and target
Duration	30 June – 29 November 2024
Date issued	24 June 2024

Purpose

1. The purpose of the Advisory Group (referred to as the Panel) is to deliver an independent review of methane science and the 2050 target for consistency with no additional warming from agricultural methane emissions.
2. This should include a scientific understanding of methane and its warming impact in order to provide advice on what a biogenic methane target consistent with the principle of no additional warming would look like for New Zealand.
3. The Panel's review will be independent of the Climate Change Commission's review of the 2050 target this year. It will provide the Government targeted advice to inform its response to the Commission's advice in 2025.

Scope

4. The main output of the Panel will be a report that disseminates the findings of the review to the Government. The report will be made publicly available and should be written in plain language and be accessible to the public.
5. The report should provide the following:
    a. background on New Zealand's climate change targets and legislation;
    b. overview of the concept of no additional warming, including a clear definition of what no additional warming is in the context of a biogenic methane target[17];
    c. a review of previous studies that estimate a no additional warming target for biogenic methane (including any differences between them);
    d. an up-to-date explanation and summary of the warming impact of biogenic methane, specifically including biogenic methane from New Zealand's agricultural sector;
    e. a brief explanation of the global emissions scenarios relevant for determining target ranges for biogenic methane emissions;
    f. consideration of a range of no additional warming biogenic methane emission reductions targets that reflect different background global emissions scenarios, including a scenario that is consistent with limiting global warming to 1.5 degrees Celsius (e.g., Shared Socioeconomic Pathway 1-1.9 from the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6)); and

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[17] For the purposes of this review the biogenic methane target includes all methane greenhouse gases produced from the agriculture and waste sectors (as reported in the New Zealand Greenhouse Gas Inventory).

   g. estimates of biogenic methane emissions reductions needed in 2050 and 2100 to achieve and maintain a state of no additional warming from New Zealand's biogenic methane emissions relative to 2017 levels of warming.

6. In doing so, the review should consider the following:
   a. the limitations and constraints of any advice in relation to target setting;
   b. providing a clear rationale and justification for any methodological choices and an explanation of any assumptions or limitations;
   c. the advancements in methane science and its warming impact since the target was set in 2019;
   d. any relevant science that was not considered during the setting of the methane target in 2019;
   e. the latest published scientific literature, including the IPCC AR6 report;
   f. global scenarios of future greenhouse concentrations and associated emissions; and
   g. what is included as biogenic methane in New Zealand.

7. The following issues are out of scope of the review:
   a. making any conclusions or recommendations that go beyond performing the scientific review and providing the evidence-based advice required by these terms of reference. For example, the advice will not cover implications of any new proposed target on the broader climate strategy. It will not try to make values-based judgements about the burden sharing responsibilities of different sectors or nations; and
   b. reviewing any other aspects of the 2050 Target as set out in s5Q of the Climate Change Response Act 2002.[18]

Approach

8. The review will take place from June to November. Within the four-month period, the Panel will:
   a. engage with relevant experts if they choose to, in the development of the report;
   b. ensure an effective quality assurance process is undertaken, for example, including through an independent external review process;
   c. where possible, provide a consensus view in its report. Where this is not possible, feedback from individual members will be captured, and considered as part of subsequent advice;
   d. provide a process where interested parties, including iwi/Māori, can submit relevant evidence, including mātauranga Māori;
   e. provide a draft report to the Minister of Agriculture and Minister of Climate Change by 1 November 2024; and
   f. provide a final report to the Ministers by Friday 29 November 2024.

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[18] Section 5Q of the CCRA sets out the domestic target for 2050. The 2050 target requires that net accounting emissions of greenhouse gases in a calendar year, other than biogenic methane, are zero by the calendar year beginning on 1 January 2050 and for each subsequent year.

9. The review process should adhere to the following principles:
    a. rigorous - Uses the most up-to-date and comprehensive body of evidence; recognises and minimises bias; is independently reviewed as part of a quality assurance process;
    b. inclusive - Considers many types and sources of evidence; uses a range of skills and people;
    c. transparent - Clearly describes the research question, methods, sources of evidence and quality assurance process; communicates complexities and areas of contention; acknowledges assumptions, limitations and uncertainties, including any evidence gaps; declares personal, political and organisational interests and manages any conflicts; and
    d. accessible - Is written in plain language; is available by 29 November 2024; is freely available online (this will be actioned by Ministers upon receipt of the report).

Context

10. Biogenic methane, a short-lived greenhouse gas (GHG), contributes to ~48% of New Zealand's gross aggregated annual greenhouse gas emissions. Most of New Zealand's gross annual emissions of biogenic methane come from the agriculture sector (~91%), particularly from ruminant livestock. The remainder is from the waste sector (~9%).
11. New Zealand's 2050 target was set as part of the Climate Change Response (Zero Carbon) Amendment Act 2019 which amended the Climate Change Response Act 2002 (CCRA). At the same time the purposes of the CCRA were expanded to include the following purpose – "to provide a framework by which New Zealand can develop and implement clear and stable climate change policies that contribute to the global effort under the Paris Agreement to limit the global average temperature increase to 1.5° Celsius above pre-industrial levels" (see section 3(1)(aa)(i)).
12. Under the CCRA New Zealand adopted a split-gas approach to the 2050 target based on scientific evidence that biogenic methane, as a short-lived gas, does not have to reduce to zero to limit global warming.
13. The legislated 2050 target for biogenic methane requires that New Zealand's gross emissions of biogenic methane in a calendar year are 24 - 47% less than 2017 by the calendar year beginning on 1 January 2050 and for each subsequent calendar year.
14. The Government has committed to "maintain a split-gas approach to methane and carbon dioxide through to 2050 and review the methane science and targets in 2024 for consistency with no additional warming from agricultural methane emissions".
15. The Minister of Climate Change and the Minister of Agriculture are seeking advice on what New Zealand's biogenic methane target should be to ensure no additional warming.
16. Determining an appropriate target for New Zealand is a judgement for the Government based on a range of considerations including equity, responsibility, cost, and economy wide opportunities for emissions reductions.

Skills and experience:

17. To ensure a robust and independent review process, the Panel will need to collectively hold sufficient expertise and capability across the following topics:
    a. climate science – including climate modelling and the warming impact of short and long-lived greenhouse gases;
    b. New Zealand’s greenhouse gas emissions, particularly biogenic methane from the agriculture sector; and
    c. understanding of New Zealand’s climate change targets and budgets under the Climate Change Response Act.

Memberships

18. Four Panel members and a chair will be appointed by the Minister of Agriculture and Minister of Climate Change (Ministers) following approval from APH Committee and Cabinet.
19. A chair will be appointed by Ministers. The chair is expected to:
    a. lead the work programme and ensure effective delivery of the final report;
    b. meet with Ministers to discuss progress of the review;
    c. liaise with the Secretariat on support required for the Panel; and
    d. maintain an effective working relationship with Panel members.

20. A member may resign from the Panel by informing the Ministers in writing.
21. A replacement chair, or new members can be added to or removed from the Panel by Ministers, subject to Cabinet approval.

Fees

22. To be derived from the relevant Cabinet Fees Framework (Category 4).
23. Letters of appointment will detail the remuneration and reimbursement arrangements for the chair and Panel members.

Secretariat / Support:

24. The Panel will be supported by ministry officials (the Secretariat). Full Secretariat support and functions will be confirmed with the chair and Panel member

Deliverables

25. The Panel is to provide a draft report by 1 November 2024 and a final report by 29 November 2024.
26. Additional interim deliverables may be determined in agreement between Panel members, the Secretariat and Ministers as required.

Conflict of interest

27. Group members are expected to disclose any perceived or real conflicts of interest to the chair and Secretariat. A conflict-of-interest register will be maintained by the Secretariat.
28. Where a conflict of interest is declared a management plan will be put in place and monitored by the Chair with the support of the Secretariat.

General confidentiality requirements

29. If the Panel receives an official information request, they must immediately provide it to MfE/MPI via the Secretariat and advise the requester that the request was referred to MfE/MPI.

2. Modelling Methodology

New Zealand's biogenic methane emissions data was taken directly from inventory data supplied by MfE (MfE, 2024), and historical emissions were taken directly from the Climate Change Commission's website[19]. These datasets were combined by scaling the pre-1990 emissions from the Commission's data to match the first five years of the inventory data. We chose the full range of SSP scenarios, from SSP1-1.9 to SSP5-8.5. For each SSP scenario, FaIR was run with and without NZ biogenic methane emissions. Emissions of non-NZ methane emissions and emissions of all other greenhouse gases and reactive species came from Meinshausen et al. (2020). Each simulation ran from 1750 - 2100.

A number of constant per cent per annum reduction curves were also assessed, and these are shown in Appendix 4. These were included to test for path dependence in emissions reductions, and because some people working in agricultural climate mitigation express reductions this way.

All the emissions reductions presented in the figures and in the table are based on emissions reductions to 2050, with constant 2050 emissions afterwards. A set of runs with additional emissions reductions between 2050 and 2100 were also conducted, but these made little difference to most scenarios, since for most SSP scenarios the emissions reductions sufficient to meet the no additional warming (NAW) condition by 2050 are also sufficient to meet the NAW condition in 2100. In some higher emissions SSPs, some MEFs that pass the NAW condition in 2050 fail in 2100, unless further emissions reductions are made, but the extra emissions reductions between 2050 and 2100 to meet the NAW condition are quite similar to the levels of emissions reductions before 2050 that meet the NAW condition. For example, under SSP3-7.0 a 2% emission reduction on 2022 levels meets the NAW in 2050 but fails in 2100. But a 6% emissions reduction on 2022 levels meets the NAW condition in 2100. So, if New Zealand has made a 2% cut in its biogenic methane emissions between 2022 and 2050, it would need to make a further 4% emissions reduction to meet the NAW condition in 2100, if the world followed SSP3-7.0.

3. Further Legislative Information

How NZ achieves its targets

NZ has emissions budgets (EBs) as stepping stones to track towards the 2050 domestic target and there are always three in place. An emissions budget sets the maximum emissions in a 5-year period. The Government published the first three emissions budgets (EB1: 2022–2025, EB2: 2026–2030, EB3: 2031–2035) in May 2022. The Climate Change Commission is due to advise the government on the fourth emissions budget (EB4: 2036 – 2040) and review the first three by the end of 2024.

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[19] https://www.climatecommission.govt.nz/public/Uploads/Targets/supporting-docs/input-data-files-for-temperature-modelling.zip

The emissions budgets include emissions of all the greenhouse gases specified in the Climate Change Response Act: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride.

NZ’s emissions reduction plans (ERPs) set out strategies, actions, and policies for achieving the corresponding EB. The first emissions reduction plan (ERP1) was published in 2022, which sets out policies and strategies for delivering EB1. The second emissions reduction plan (ERP2) is due to be published by the end of 2024.

NDCs

Under the Paris Agreement, every country must set its own nationally determined contribution (NDC). NDCs represent each country’s commitment to delivering on the goals of the Paris Agreement, reducing greenhouse gas emissions, and addressing climate change. These contributions outline the specific targets and actions that nations plan to undertake to limit global warming, typically submitted every five years. NDCs are unique to each country, tailored to their specific circumstances, capabilities, and development priorities.

New Zealand’s first Nationally Determined Contribution (NDC1) under the Paris Agreement is to reduce net GHG emissions to 50 per cent below gross 2005 levels by 2030. It was updated in October 2021.

The NDC1 differs from the domestic target established under the CCRA. It can be achieved through actions taken in Aotearoa to reduce domestic emissions, as well as through purchasing international mitigation.

The NDC1 target is economy-wide, encompassing all sectors and greenhouse gases. This contrasts with Aotearoa’s domestic target, which employs a split-gas approach. As a result, any adjustments to the domestic methane target will necessitate modifications in other sectors to achieve the overall NDC1, or alterations in the use of offshore mitigation.

The Government is to advise the second Nationally Determined Contribution (NDC2) by February 2025.

4. MEFs results of NAW test for constant per cent per annum emissions reductions

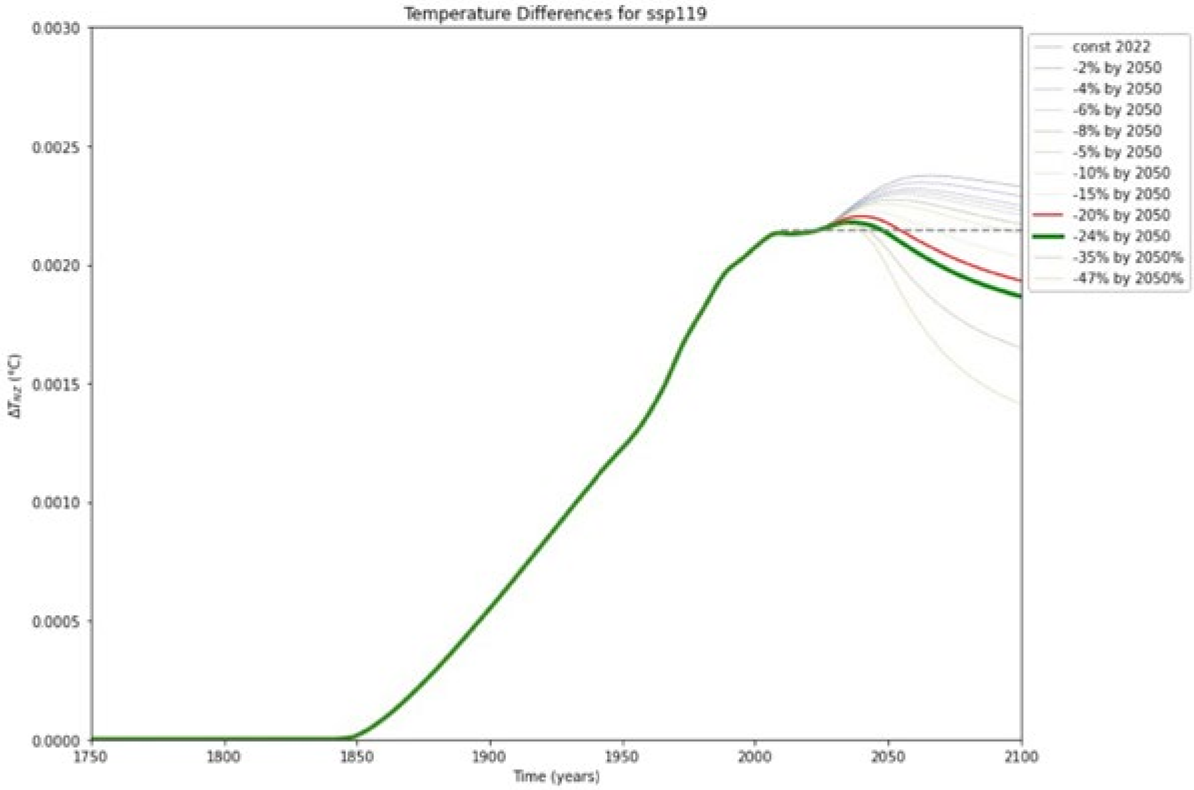
Tests for no additional warming (relative to 2017) under 8 SSPs and constant percent per annum methane emissions reductions from 2022. Shaded means there is additional warming, clear means no additional warming.

Methane emissions futures involving constant per annum per cent emissions reductions																
	SSP1-1.9		**SSP1-2.6**		**SSP2-4.5**		**SSP4-3.4**		**SSP4-6.0**		**SSP3-7.0**		**SSP5-3.4**		**SSP5-8.5**	
	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Constant	■	■	■	■	■	■	■	■	■	■	■	■				■
-0.1%pa	■	■	■	■	■	■	■	■	■	■						
-0.2%pa	■		■		■		■	■	■	■						
-0.3%pa	■		■		■		■	■		■						
-0.4%pa	■						■	■								
-0.5%pa	■						■	■								
-0.75%pa	■						■									
-1.0%pa																
-1.25%pa																
-1.5%pa																
-1.75%pa																
-2.0%pa																
-2.5%pa																

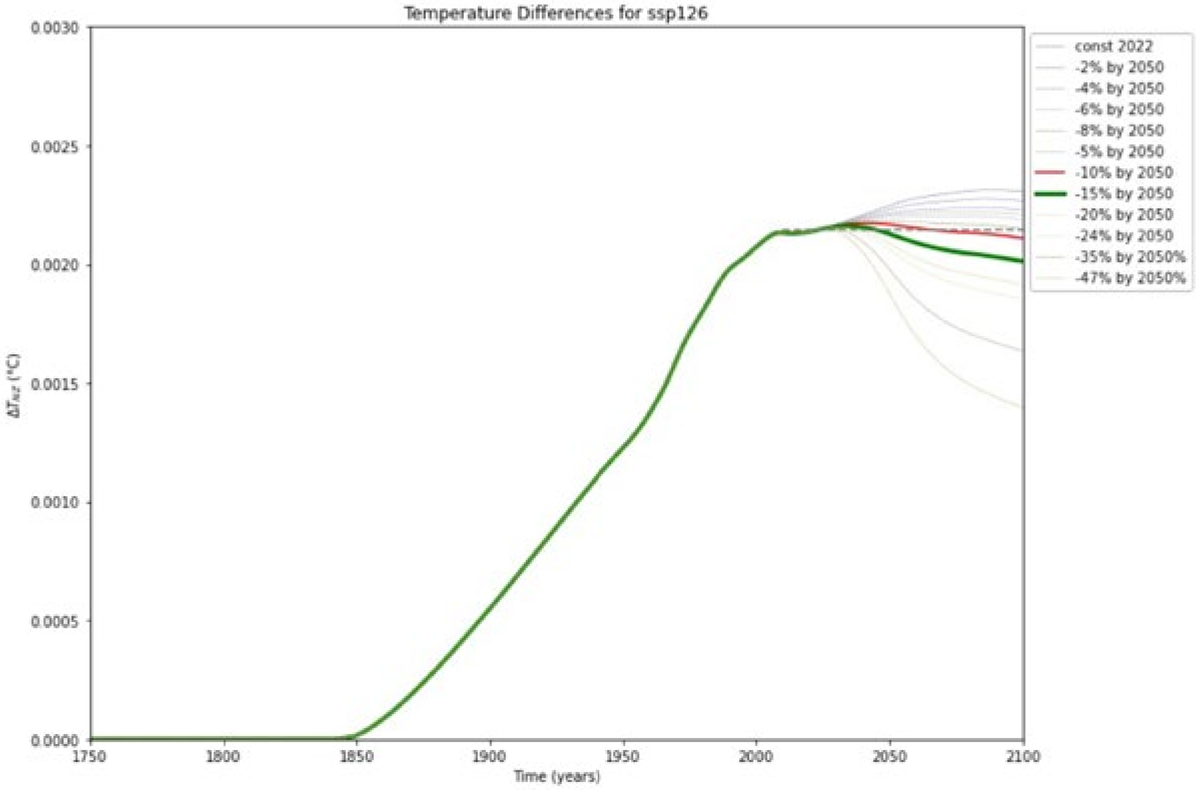
5. Time Series Plots

The following figures show, for each SSP scenario, the temperature response from NZ's methane emissions, calculated by FaIR2.1, for the various MEFs examined. Green lines show the MEF with the smallest methane cut that satisfies the NAW condition.

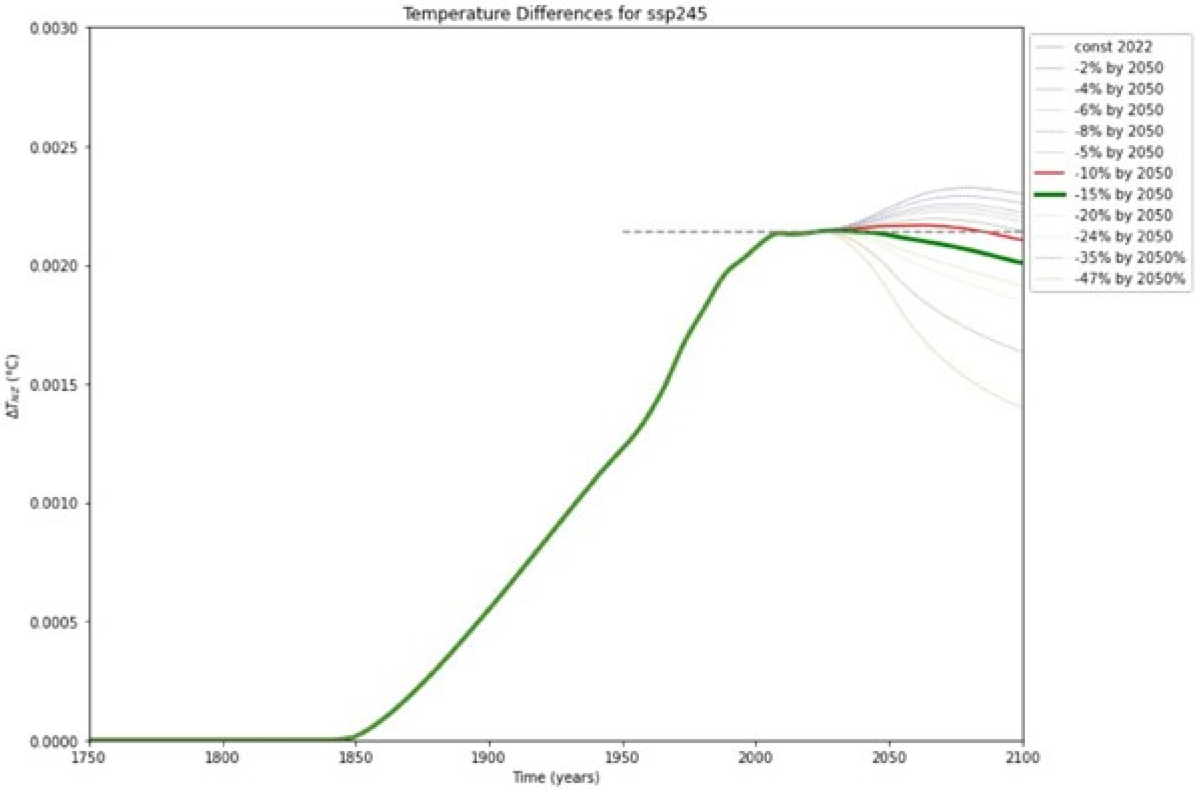
SSP1-1.9



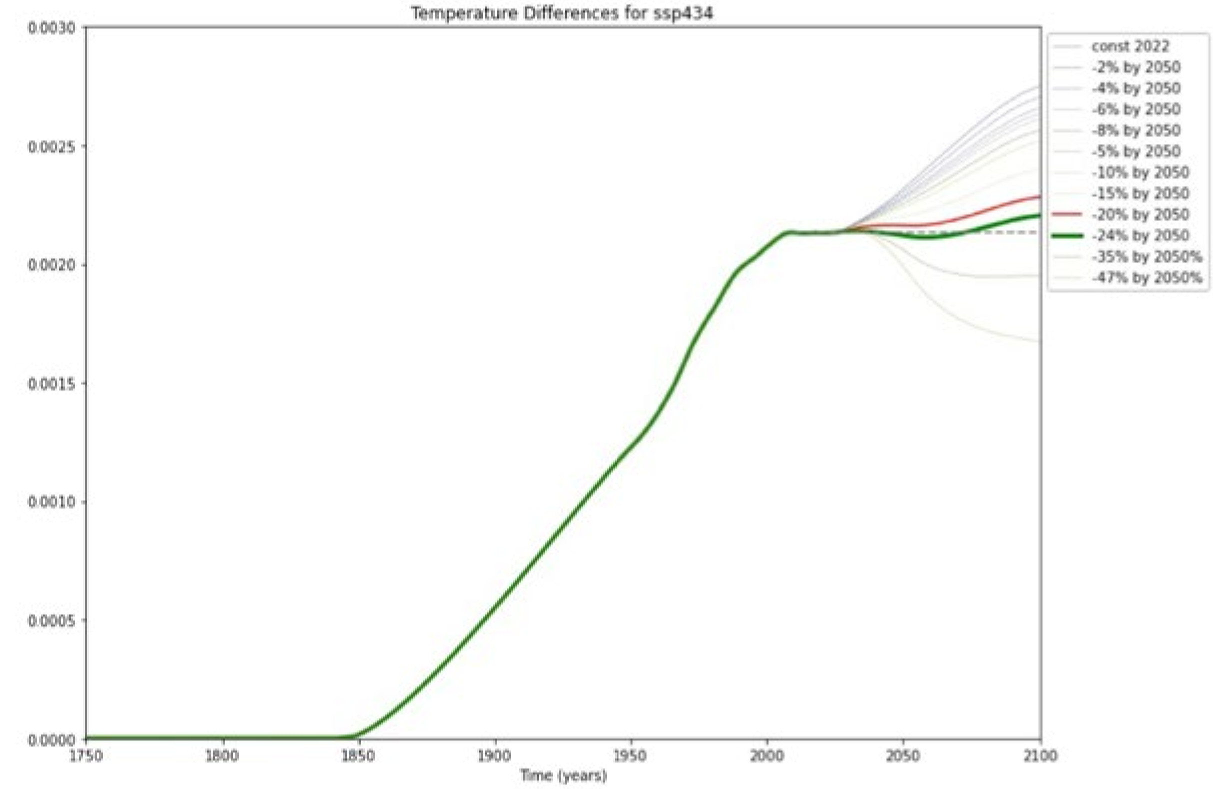
SSP1-2.6



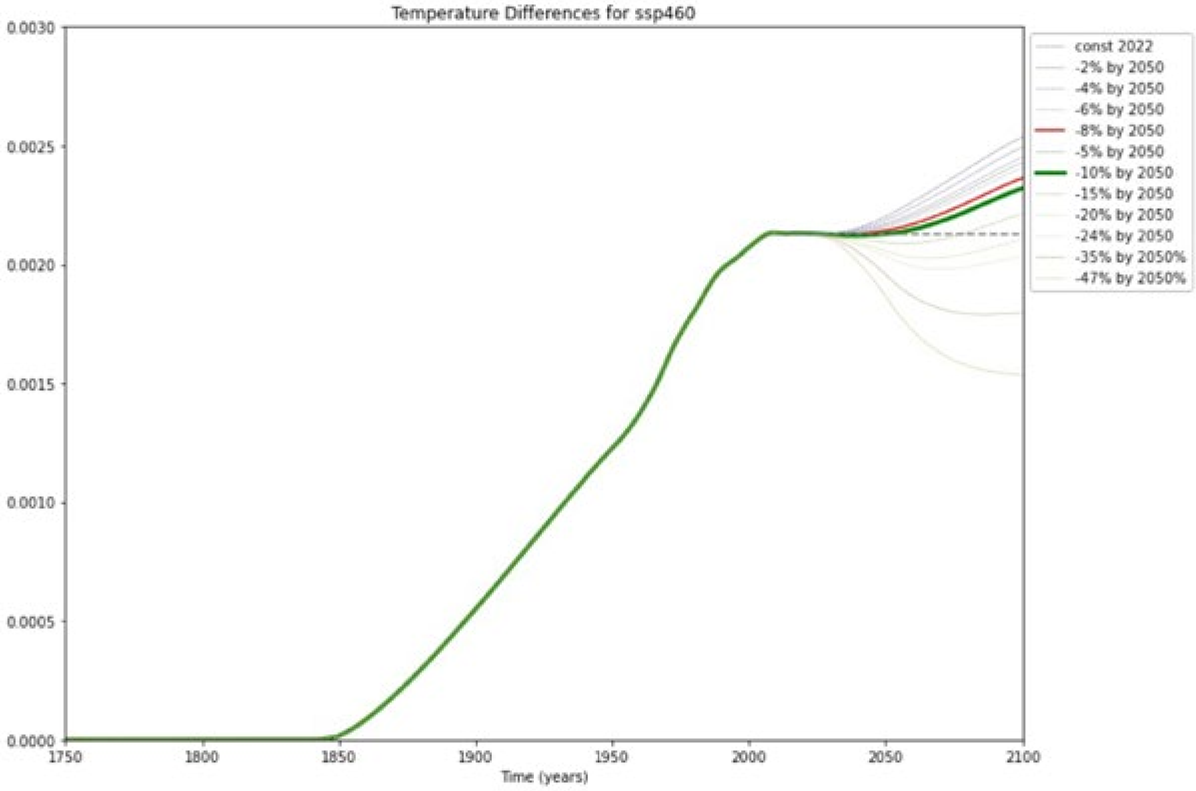
SSP2-4.5



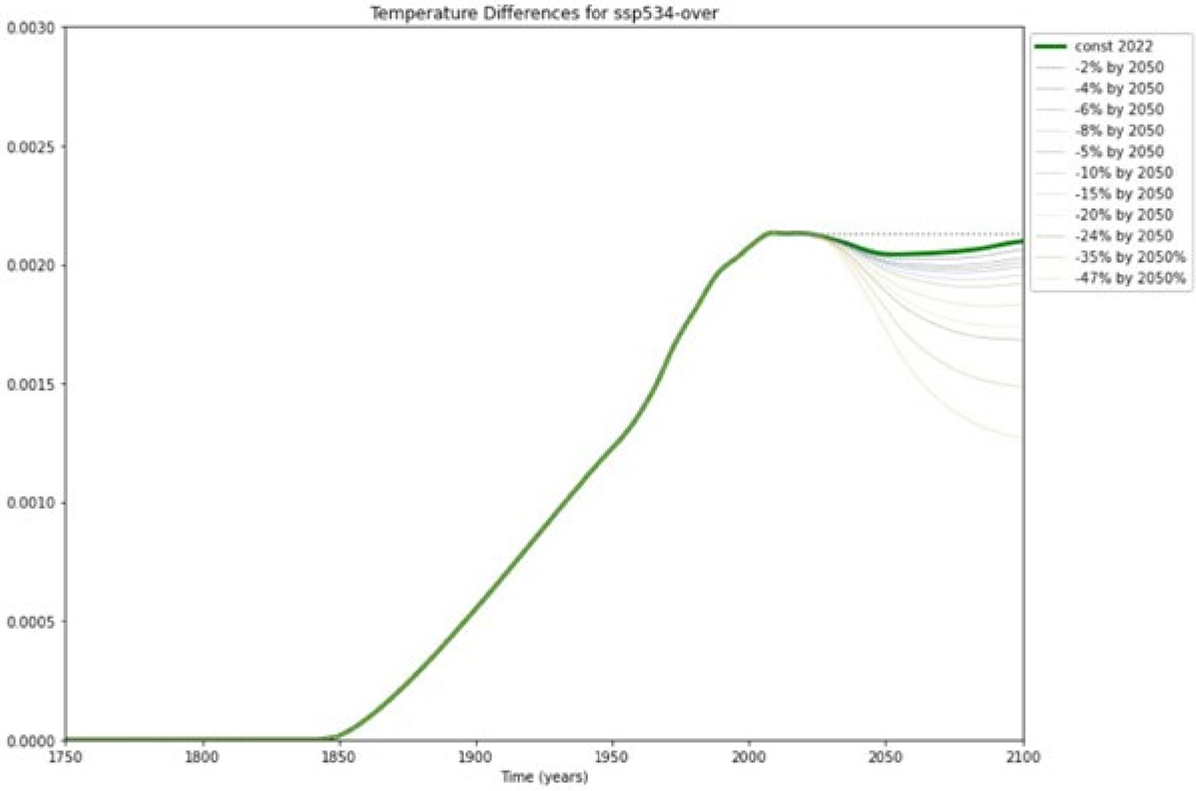
SSP4-3.4



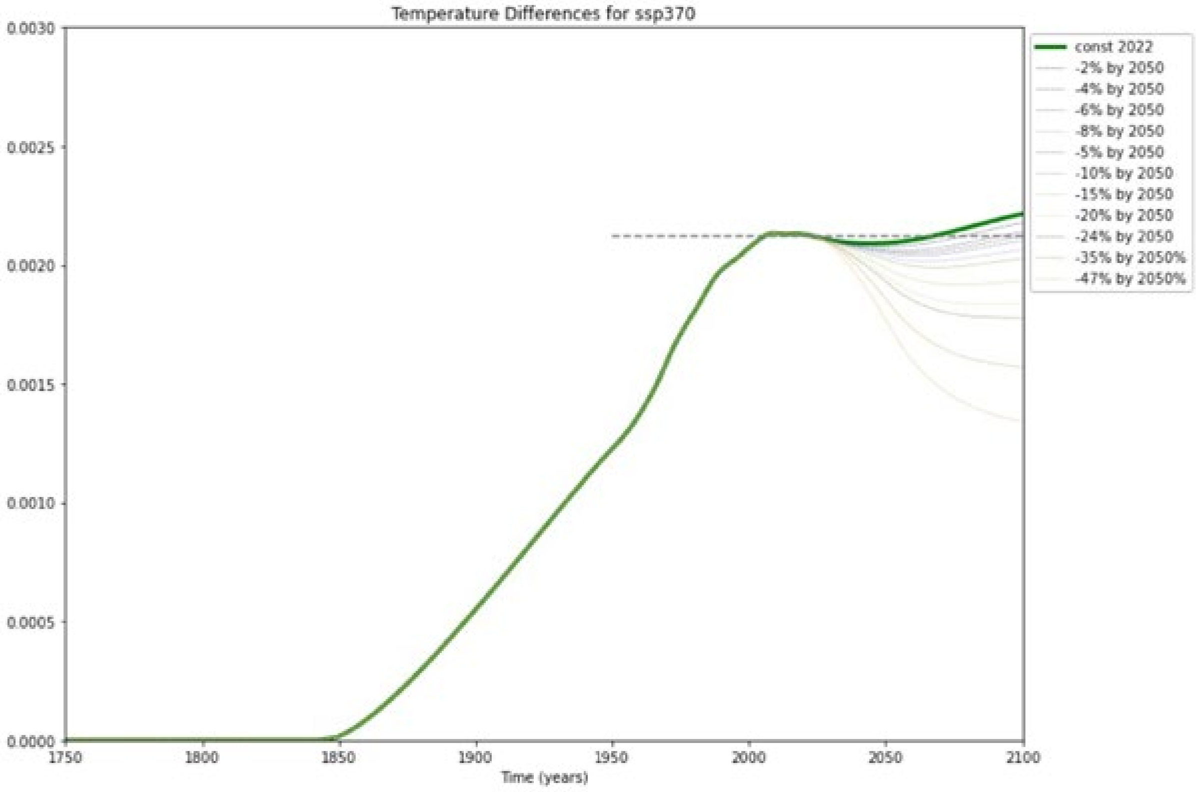
SSP4-6.0



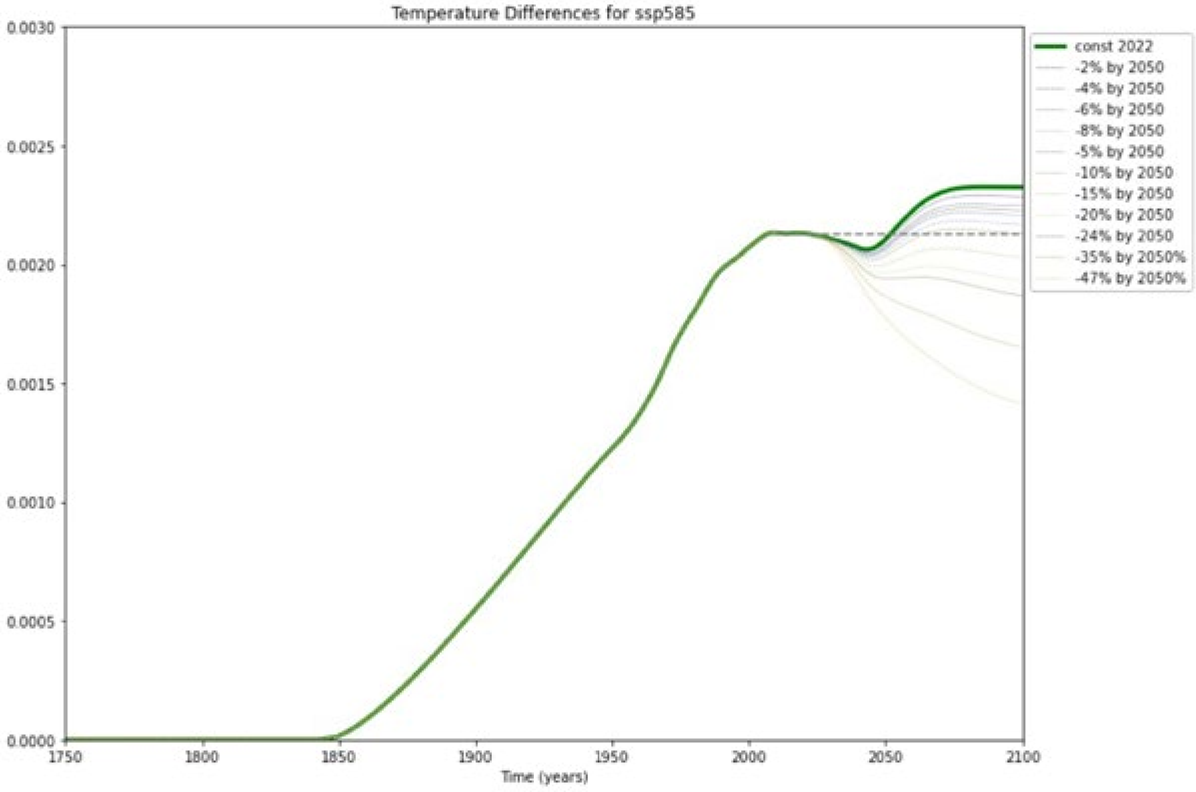
SSP5-3.4



SSP3-7.0



SSP5-8.5



Frequently Asked Questions

What is the global warming potential of methane?

This report does not use climate emission metrics for its calculations, but they are described here for completeness.

Climate metrics were first designed to compare the climate effects of emissions of different greenhouse gases. In the IPCC First Assessment Report (FAR) this was done by comparing the relative radiative effects of a single pulse emission of 1 kg of a gas compared to that of carbon dioxide. (Shine et al. 1990). The radiative effect chosen was the radiative forcing integrated over a number of years (referred to as the "time horizon") following the pulse, and termed the Global Warming Potential (GWP). However the IPCC cautioned: *"It must be stressed that there is no universally accepted methodology for combining all the relevant factors into a single [metric] … A simple approach [i.e. the GWP] has been adopted here to illustrate the difficulties inherent in the concept."* (Shine, 2009). The FAR reported this quantity over three different time horizons, 20, 100 and 500 years. Again a caveat was provided *"These three different time horizons are presented as candidates for discussion and should not be considered as having any special significance"* (Shine 1990).

The GWPs for biogenic methane are 79.7 ± 25.8, 27.0 ± 11 and 7.2 ± 3.8 for 20, 100 and 500 year time horizons. These metrics imply that a 1 kg emission of methane has a "climate effect" that is equivalent to a 79.7 kg emission of carbon dioxide if we are interested in effects over the next 20 years, or equivalent to a 7.2 kg emission of carbon dioxide if we are interested in the effects over the next 500 years[20]. The wide variation is because methane is removed from the atmosphere on a timescale of around a decade. This contrasts with carbon dioxide which accumulates over centuries (Canadell et al. 2021). After a couple of decades the pulse of methane will have mostly decayed and contribute little further radiative forcing whereas the pulse of carbon dioxide will still persist. Hence the climate effect of methane relative to that of carbon dioxide decreases as the time horizon increases.

The GWPs for methane include additions from the chemical production of ozone and stratospheric water vapour. For fossil methane (not considered further in this report) they also include the effect of the carbon dioxide produced.

What is the GWP* metric?

As noted above, this report does not use climate emission metrics for its calculations, but they are described here for completeness.

Since a methane pulse decays within a couple of decades, but a pulse of carbon dioxide persists for centuries the difference in behaviour makes comparisons between the two very sensitive to time horizon. In comparison a step change in methane emissions (i.e. an increase in the rate of emission) leads to a persistent increase in methane concentration that is more similar to the persistence of a pulse of carbon dioxide. A new climate emission metric GWP* was devised (Allen et al., 2018) to compare methane with carbon dioxide that combines 75% of a step with 25% of a pulse (Cain et al., 2019). Under this metric a methane emission that decreases by around 0.3% per year would lead to no additional warming, because the reduction in warming from the short-lived term cancels the extra warming from the long-lived term. Methane emissions that are positive but declining at this rate correspond to a GWP* of 0, i.e. would be equivalent to zero emissions of carbon dioxide.

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[20] Under the "Paris Rulebook" (Decision 18/CMA.1, annex, paragraph 37), parties have agreed to use GWP100 values from the IPCC AR5 or GWP100 values from a subsequent IPCC Assessment Report to report aggregate emissions and removals of GHGs. In addition, parties may use other metrics to report supplemental information on aggregate emissions and removals of GHGs.

The step-pulse (GWP*) metric and the pulse-pulse (GWP) metrics are both physically-based metrics, and GWP* uses GWP in its calculation, but the assessments of climate impacts are different because GWP* matches the temperature effects of a time-series of gases and GWP does not.

The IPCC 6th Assessment Report (AR6) explicitly does not recommend a metric *"this Report does not recommend an emissions metric because the appropriateness of the choice depends on the purposes for which gases or forcing agents are being compared"* (Forster et al. 2021). The causes of controversy with metrics are how they are applied. If the GWP is applied to a methane emission that is changing over time, the climate change resulting from the equivalent carbon dioxide emission can be very different to that resulting from the original methane emissions (Cain et al., 2019). It has been argued that the GWP* should be applied to a baseline of no emissions, rather than starting from the last 20 years (the 20-year timescale is embedded in the GWP* metric) (Reisinger et al., 2021).

It is not necessary to use climate metrics at all if short-lived gases are reported separately to long-lived gases, and if they are treated separately in policy (Allen et al., 2022b). Since the question being addressed in this report is focussed entirely on biogenic methane, no metrics are needed to compare with other gases. Since New Zealand policy envisages separate schemes for methane and carbon dioxide, there is no need for metrics in policy, either.

Do fossil and biogenic methane have different climate effects?

Once aloft in the atmosphere, the climate effects of methane are independent of how it originated, i.e. whether from a recent biological process or from fossil stores. As discussed above, the products of methane chemistry are ozone, water vapour and carbon dioxide. The additional effects of ozone and water vapour have always been included in the climate metrics for methane, but the effect of carbon dioxide is often excluded to avoid double counting. For instance, a carbon budget calculation is often based on how much natural gas is used regardless of whether it is actually combusted or whether it is lost through leaks into the atmosphere. If the carbon has been counted once in the gas usage, it should not be counted again in the climate metric for fugitive methane emissions. Similarly although carbon dioxide is produced in the decomposition of biogenic methane, this carbon will have been removed from the atmosphere previously in growing the animal fodder or producing the organic material that was disposed of in the landfill. Since the uptake of carbon is not included in carbon budgets, the production of carbon dioxide from biogenic methane should not be included either.

There is an allowance in the AR6 assessment (Forster et al. 2021) where some of the carbon is lost through removal of formaldehyde from the atmosphere, and also from delayed emission from the methane oxidation. This is very uncertain, it only contributes a small fraction of the climate metrics for methane and will not be considered in this report.