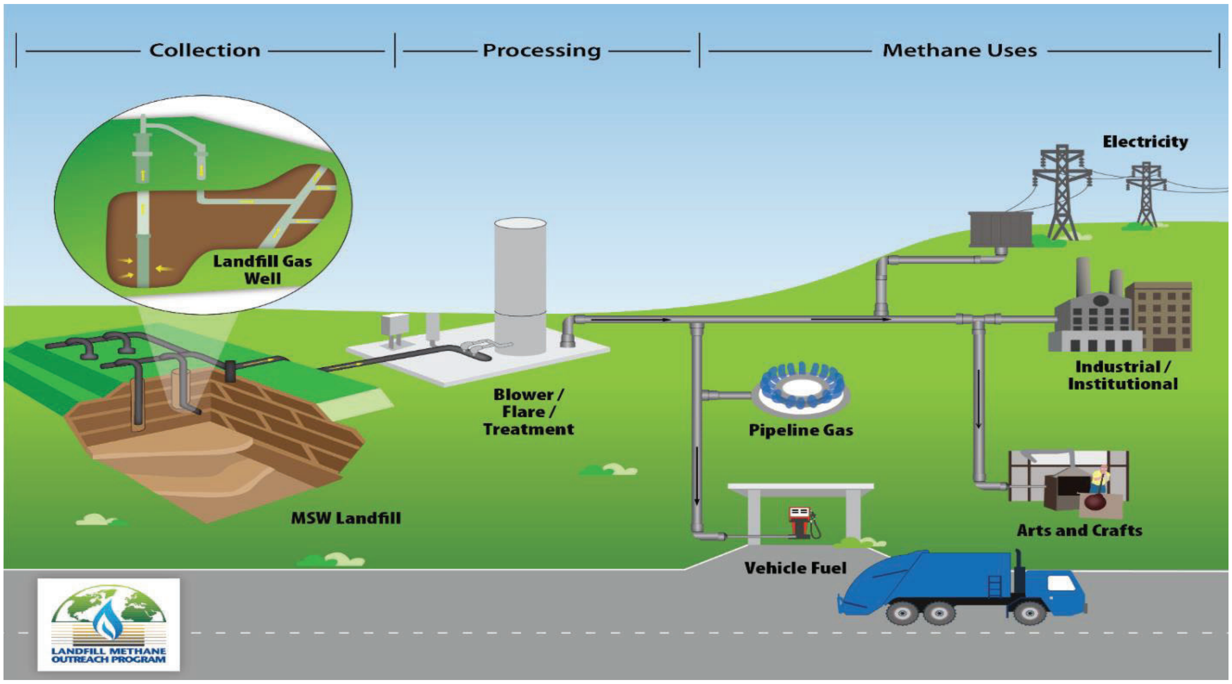
Landfill Gas Methane Capture Information

Landfill gas (LFG) is a natural byproduct of the decomposition of organic material in landfills. LFG is composed of roughly 50 percent methane (the primary component of natural gas), 50 percent carbon dioxide (CO_2) and a small amount of non-methane organic compounds. Methane is at least 28 times more effective than CO_2 at trapping heat in the atmosphere over a 100-year period. Landfills are the third largest source of anthropogenic methane in the United States. According to the EPA, landfill gas (LFG) comprises 17.7 percent of all U.S. methane emissions

Instead of escaping into the air, LFG can be captured, converted, and used as a renewable energy resource. Using LFG helps to reduce odors and other hazards associated with LFG emissions, and prevents methane from migrating into the atmosphere and contributing to local smog and global climate change.

LFG is extracted from landfills using a series of wells and a blower/flare (or vacuum) system. This system directs the collected gas to a central point where it can be processed and treated depending upon the ultimate use for the gas. From this point, the gas can be flared or beneficially used in an LFG energy project.
LFG collection efficiency capture can achieve 85 percent efficiency or more in closed and engineered landfills; it is least effective in open dumps, where the collection efficiency is approximately 10 percent and capture is typically not seen as economically favorable.

Available options to convert LFG into energy include categories such as – Electricity Generation, Direct Use of Medium-Btu Gas, and Renewable Natural Gas.



The cost of an LFG project depends on a number of factors, including the size, location, and layout of the landfill. Typically, one million tons of landfill waste emit approximately 432,000 cubic feet of LFG per day, enough to produce either 0.78 MW of electricity or 216 MMBtu of heat.

Approximately 70 percent of LFG projects generate electricity, primarily via internal combustion engines, gas turbines, and microturbines. Costs vary, but internal combustion engines (ICEs) smaller than 1 MW typically cost $2,300/kW to install, with annual operation and maintenance costs of $210/kW, and ICEs larger than 800 kW typically cost $1,700/kW, with annual operation and maintenance costs of $180/kW. Revenue depends on electricity buy-back rates that are specific to local electric utilities, but typically range between 2.5 and 7 cents/kWh.

Example of current usage of LFG capture for energy:

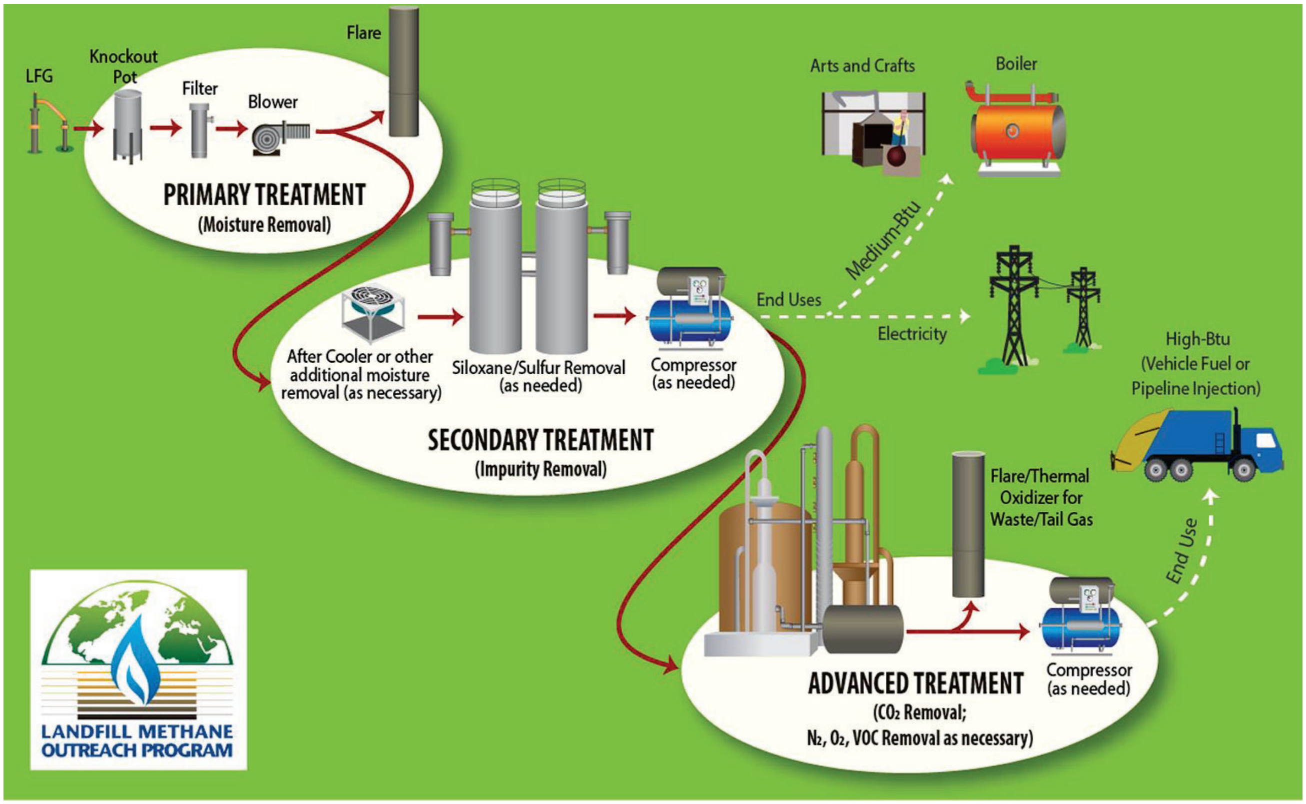
BMW Manufacturing Landfill Gas Energy Project:

Location:	Greer, South Carolina
End User(s):	BMW Manufacturing Co.
Sector(s):	Auto manufacturing

Landfill(s):	Palmetto Landfill
Landfill Size:	22.9 million tons waste-in-place (2015) [closed]
Project Type:	Combined Heat and Power (cogeneration – two gas turbines)
Project Size:	6.5 megawatts (MW) generation [11 MW rated capacity]
Savings:	$1 million/year
LMOP Partners Involved:	Ameresco, BMW Manufacturing Co., Durr Systems, South Carolina Energy Office, Waste Management

At its South Carolina assembly plant, BMW began using landfill gas (LFG) from Waste Management's Palmetto Landfill in 2003 to fuel four gas turbine cogeneration units (4.8 MW rated capacity) and recover 72 MMBtu per hour of hot water. The turbines fulfilled about 25 percent of the plant's electrical needs and nearly all of its thermal needs.

Three stages of LFG Treatment



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Methane emissions: choosing the right climate metric and time horizon

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Methane is a more potent greenhouse gas (GHG) than CO_2, but it has a shorter atmospheric lifespan, thus its relative climate impact reduces significantly over time. Different GHGs are often conflated into a single metric to compare technologies and supply chains, such as the global warming potential (GWP). However, the use of GWP is criticised, regarding: (1) the need to select a timeframe; (2) its physical basis on radiative forcing; and (3) the fact that it measures the average forcing of a pulse over time rather than a sustained emission at a specific end-point in time. Many alternative metrics have been proposed which tackle different aspects of these limitations and this paper assesses them by their key attributes and limitations, with respect to methane emissions. A case study application of various metrics is produced and recommendations are made for the use of climate metrics for different categories of applications. Across metrics, CO_2 equivalences for methane range from 4–199 $gCO_{2eq.}/gCH_4$, although most estimates fall between 20 and 80 $gCO_{2eq.}/gCH_4$. Therefore the selection of metric and time horizon for technology evaluations is likely to change the rank order of preference, as demonstrated herein with the use of natural gas as a shipping fuel *versus* alternatives. It is not advisable or conservative to use only a short time horizon, *e.g.* 20 years, which disregards the long-term impacts of CO_2 emissions and is thus detrimental to achieving eventual climate stabilisation. Recommendations are made for the use of metrics in 3 categories of applications. Short-term emissions estimates of facilities or regions should be transparent and use a single metric and include the separated contribution from each GHG. Multi-year technology assessments should use both short and long term static metrics (*e.g.* GWP) to test robustness of results. Longer term energy assessments or decarbonisation pathways must use both short and long-term metrics and where this has a large impact on results, climate models should be incorporated. Dynamic metrics offer insight into the timing of emissions, but may be of only marginal benefit given uncertainties in methodological assumptions.

Environmental significance

Methane emissions are a key contributor to climate change but have a substantially different impact on global warming than carbon dioxide: methane has a much high radiative efficiency but is relatively short-lived. Consequently, the use of Global Warming Potentials over a single 100 year time frame has been frequently called into question as it hides the substantial variation in impact over time. This study compares a comprehensive range of different climate metrics and their key qualities to provide an insight on which metric and time horizon is most appropriate for use in different applications.

1. Introduction

Methane emissions are the second largest contributor to climate change next to carbon dioxide, with its direct impact representing around 20% of additional climate forcing since 1750 according to the Saunois *et al.*[1] Further, the estimated direct and indirect forcing effects of methane (including oxidation to CO_2 and impact on ozone creation) is estimated to be 58% of the value of CO_2 (0.97 W m^{-2} for methane compared to 1.68 W m^{-2} for CO_2).[2] Annual emissions are only 3% w/w of those associated with CO_2 (0.56 $GtCH_4$/year *vs.* 14.5 $GtCO_2$/year for methane and CO_2 respectively),[1,3] but methane has a radiative forcing approximately 120 times more than CO_2 immediately after it is emitted. On the other hand, methane has a perturbation life of only 12.4 years,[2] whereas CO_2 lasts in the atmosphere for much longer: 50% of an emission is removed from the atmosphere within 37 years, whilst 22% of the emission effectively remains indefinitely.[4] Consequently, the relative impact of methane compared to CO_2 changes over time.

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Global warming potentials (GWP) are used to compare the relative impact of different greenhouse gases (GHGs) on climate forcing, by converting emissions into 'CO_2 equivalents'. It is defined as the average (time-integrated) radiative forcing of a pulse emission over a defined time horizon, compared to CO_2. GWP is used widely across industrial, regulatory and academic applications to compare the effect of a change in product or process. The 100 year time horizon is most common, giving a CO_2 equivalent value of 28–36 for methane (depending on whether various indirect climate effects are included).[2] However, there is much criticism about the use of GWP, because:

- The selected time horizon has a large impact on the value of the metric;
- Despite its name, it does not compare gases against their effect on global temperature;
- Measures an average climate forcing effect of a single pulse emission over time but gives no indication of the climate impact at an end-point in time, or that of a sustained emission.

Increasingly there are calls for the use of different time horizons (*e.g.* 20 years) or even different metrics that better reflect climate change or align with climate targets (*e.g.* the global temperature change potential as described in the IPPC AR5 [2]). But which metric is most appropriate for different applications and over what time horizon?

Previous studies have assessed the impacts of a small selection of alternative metrics on natural gas *versus* coal for electricity[5] and the climate impacts of transportation.[6] Deuber *et al.*[7] and Johansson[8] examine the physical basis and relationship between some metrics, whilst others assess the cost of emissions mitigation using different metrics.[9,10] Mallapragada and Mignone[11] classify a selection of metrics based on some key characteristics and apply metrics to a case study of natural gas *versus* gasoline-fuelled vehicles.

This paper goes further by assessing a large suite of climate metrics regarding their key differentiating characteristics and applies a case study technology assessment to demonstrate the impact of metric selection on technology preference. The study makes recommendations for which metrics and time horizons are most appropriate for different applications, including short term regional emissions estimates, life cycle technology assessments and energy systems pathways.

The contribution this paper makes is to provide insight for industry, policy makers and academics to ensure the appropriate use of metrics. A range of metric values and methods are presented and synthesised, and clear guidelines are given for the use of metrics across different applications.

First, the report describes the procedure for assessment for the climate metrics. Section 3 gives a summary of the climate impact of GHGs and methane in the atmosphere. Section 4 describes the global warming potential metric, including its history and limitations. Alternative metrics are defined in the following Section 5 and key differences and factors that affect the choice of metrics are outlined in Section 6. Evidence around the impact of using the various metrics are described in Section 7, before recommendations and conclusions are made.

2. Assessment methods

Given the purpose of this study is to assess the impact of using different climate metrics and to make recommendations for their use in different applications, the following stages of assessment are undertaken:

- Contextualising the climate cause–effect chain.
- Assessing climate metrics and key characterising factors.
- Applying a case study.

To place the analysis of different climate metrics in context, the study first describes the climate cause–effect chain, against which metrics will be categorised and assessed. Methane is the focus of this study and is explained in this context, but it should be noted that the assessment is applicable for the study of other emissions and environmental impacts.

A review of a full suite of proposed climate change metrics is then carried out. Firstly, the standard GWP metric is defined and characterised relating to its physical basis, methodological construction and associated uncertainty. Alternative metrics are synthesised from a wide body of literature and compared against GWP and each other, relating to their 'CO_2 equivalent' quantities as well as their basis for construction, intuitiveness and associated uncertainty. Key characteristics are developed and analysed against typical applications of each metric. Characteristics considered are:

- The time horizon or associated discount rates;
- The physical/economic basis of the metric;
- Static *versus* dynamic metrics;
- The level of uncertainty *versus* tangibility; and
- The suitability of metrics for different applications.

To demonstrate the impact of the broad range of metrics and CO_2 equivalent values, a case study is given: a climate assessment of the use of LNG as a shipping fuel, against alternative fuels. The case study is based on the outputs of a full environmental assessment, but focuses on the change in rank preference of fuel based on different CO_2 equivalents, as well as the use of dynamic *versus* static metrics.

Different applications of metrics from industry, policy and academic are characterised in terms of factors such as their required simplicity and their time-frames of consideration. From this, a series of recommendations for the use of metrics are made, which may serve as guidelines for further discussion.

3. Greenhouse gases and the climate cause–effect chain

The link between GHG emissions, climate change and damage to human health and ecosystems is multifaceted. Fig. 1 illustrates a simplified cause–effect chain linking emissions with climate change-related damage, and later in this report the metrics will be placed in this context. Firstly, a GHG is emitted, which increases the concentration of this GHG in the atmosphere. Each GHG has a radiative efficiency, which is the capacity of an atmospheric concentration of gas to trap and re-radiate heat downwards, measured in W m^{-2} ppb^{-1}.[2] When multiplied by the atmospheric concentration, this gives the

Fig. 1 The cause–effect chain linking greenhouse gas emissions to climate change-related damage.

total radiative forcing attributed to the GHG. Thus, radiative forcing is the total change in heat balance in the atmosphere from the increase in concentration of a greenhouse gas,[5] measured in W m^{-1}.[12]

An increase in radiative forcing results in a temperature increase, where the degree of temperature rise is governed by the magnitude of emission and radiative efficiency, as well as the existing atmospheric concentration of the GHG and the concentrations of other gases in the atmosphere. The increase in global average temperature causes damage *via* increased extreme weather events, sea level rise, oceanic circulation changes, species extinction and more. This damage is likely to increase faster than the rate of change in global temperature.[13]

Two important points require emphasis. First, increased radiative forcing is not the same as temperature increase. Temperature change is a result of increased forcing, but the value of temperature change is governed by other factors as well. There is also a lag between radiative forcing and temperature change of approximately 15–20 years,[14] as shown in Fig. 2. Second, global average temperature change is not the only indicator that may describe climate change. Other important factors describe climate change, including the rate of temperature rise and the cumulative temperature rise. Each of these climate change attributes are interrelated but cause damage to health and ecosystems in different ways, examples of which are described in Table 1. The global average temperature rise increases the variation and volatility of temperatures and results in more extreme weather events. The rate of temperature increase governs how much time species may take to adapt to new conditions and so a fast rate will cause more species extinction. The cumulative temperature rise (*i.e.* prolonged increases) strongly affects longer term changes such as glacial melt and seal level rise. Emissions of GHGs affect each of these climate attributes differently, depending on: emission quantity; existing concentration of pollutant in the atmosphere; residence time of emission in the atmosphere; and the concentration of other molecules in atmosphere (*e.g.* OH^- and O_3).

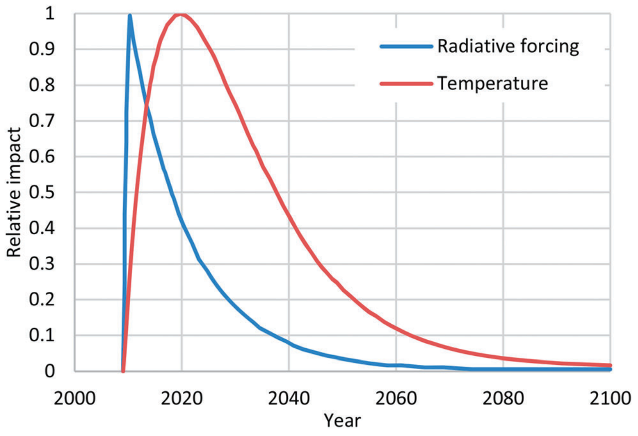

Fig. 2 The relative impact of a pulse emission of methane on radiative forcing and subsequent impact on temperature change. Source: ref. 14.

For methane, an emission has a much larger radiative forcing effect than CO_2 given the difference in radiative efficiency and indirect impacts.[4] However, methane is a short-lived climate pollutant (SLCP) and has an atmospheric lifetime of 8.4 years, defined as the atmospheric burden divided by the sink strength.[15]

Methane comes out of the atmosphere and troposphere by typically reacting with hydroxyl radicals, oxidising to form CO_2 and water (which are also both greenhouse gases). 88% of the methane reacts this way, meaning that one gram of methane will form 2.4 grams of CO_2.[13] The other 12% of the methane forms molecules such as methanal (formaldehyde) and methyl hydroperoxide. The increasing concentration of methane in the atmosphere reduces the availability of the hydroxyl radicals for further reactions which in turn would increase the lifespan of methane. Thus, the perturbation lifetime of methane, which allows for the gases influence on other atmospheric species during its life, is 12.4 years.[2]

In comparison, the lifespan of CO_2 is more complicated due to the different mechanisms that take CO_2 out of the atmosphere, but 50% of a pulse emission is removed from the atmosphere within 37 years, whilst 22% of the emission effectively remains indefinitely.[4] Thus, whilst the initial radiative forcing is low compared to methane, the lasting and cumulative effects are large. The change in radiative forcing over time is shown in Fig. 3 for methane and CO_2.

The effect of GHG emissions on the climate is multifaceted and detailed climate models are required to understand the effects of changing emissions and the environment over time. Such models as MAGICC6 [17] are used in integrated assessment projects to estimate the impacts. However, these are detailed

Table 1 Climate change attributes and resultant damage. Sources: ref. 5 and 14

Climate change measure	Damage
Temperature increase	Extreme weather events Heat waves Coral bleaching
Rate of temperature rise	Species extinction
Cumulative temperature rise	Sea level rise Glacial melt Ocean circulation change

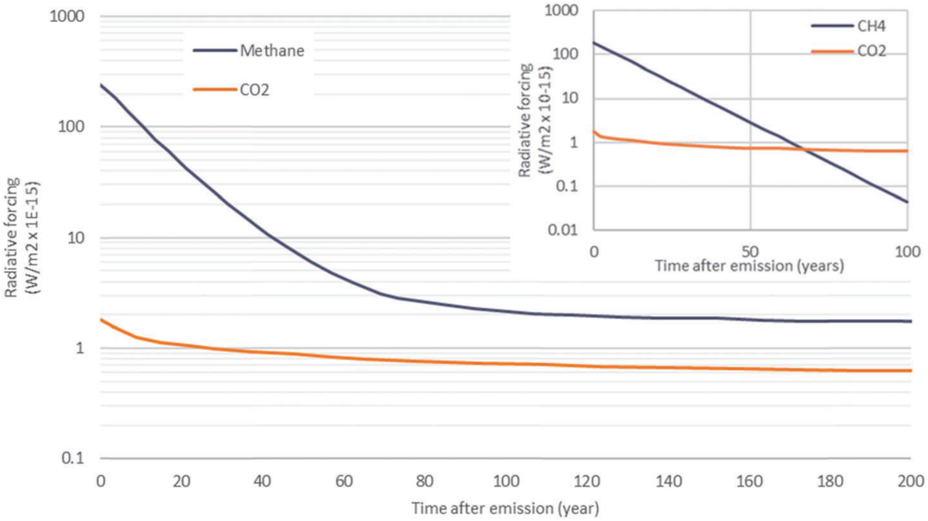

Fig. 3 Radiative forcing of a 1 kg pulse emission of methane and carbon dioxide over time, including the eventual oxidation of methane into CO_2. Graph inset is the radiative forcing of methane without the inclusion of methane oxidation into CO_2. Source: ref. 4 and 16.

global models that require many environment-related assumptions. Simpler, faster approaches are often required to compare the effect of changing processes or technologies in studies such as industrial emissions measurements, policy-related emissions strategies and environmental life cycle assessments. This is the role of climate metrics, to compare technologies, products and policy pathways simply and effectively.

4. Global warming potential

Global warming potential (GWP) is the standard metric used to compare GHGs emitted from different products and services. The metric was developed for use following the Kyoto Protocol and adapted by the Intergovernmental Panel on Climate Change[18] to help in the design of emissions strategies, accounting for the trade-offs between different types of GHG.[19] It is defined as the time-integrated radiative forcing of an emission pulse of a gas, relative to that of CO_2, over a defined time horizon.

For a 100 year time horizon, methane GWP is 36 $gCO_{2eq.}/gCH_4$, meaning that the average radiative forcing of a methane emission over 100 years after the emission is 36 times that of an equivalent mass of CO_2. The IPCC have typically given estimates of GWP for time horizons of 20, 100 and 500 years (although the most recent 5th assessment report excluded 500 years) and the 100 year GWP (GWP100) remains the most common metric used.

With a high radiative efficiency and short lifetime compared to CO_2, methane has a much higher GWP over short timescales: GWP20 is 87 $gCO_{2eq.}/gCH_4$. Fig. 4 shows the GWP of methane over different timescales, but not including the effect of climate-carbon feedback (CCFB), resulting in slightly lower numbers than those expressed within this paragraph (*e.g.* a GWP100 of 30 rather than 36).

The values of GWP for each GHG have been developed over each IPCC assessment report, to account for better understanding of radiative forcing and the various indirect radiative forcing effects, such as cloud albedo and CCFB.[2,21] CCFB is a broad term that encompasses both negative and positive feedback effects associated with increased forcing or temperature. For example, a positive feedback is an increase in temperature causing greater concentrations of water vapour, which itself results in further radiative forcing. The cloud albedo effect is the impact of clouds reflecting radiation and contributing to climate cooling. The concentration of GHGs in the atmosphere and troposphere has an impact on cloud formation and consequently the cloud albedo effect. Additionally, most atmospheric methane eventually oxidises into CO_2, which raises the total GWP values by 1 and 2 for 20 and 100 year time horizons, respectively. This is summarised in Table 2, presenting the change in GWP for methane across IPCC publications.

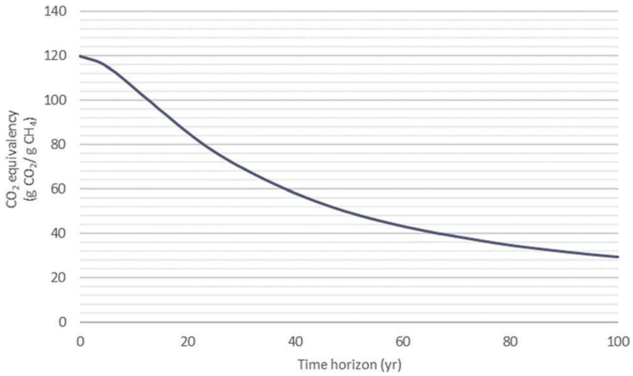

Fig. 4 Illustration of the changing GWP of methane over time. Sources: ref. 20 and 12, using GWP factors without climate-carbon feedback effects.

Table 2 Changes to GWP and perturbation lifetime of methane in IPCC assessment reports. Source: ref. 2, 18, 19, 22 and 23

					Effect included[c]		
Publication	Year	Lifetime (years)	GWP (20 year)	GWP (100 year)	T-O_3	S-H_2O	CCFB
1st AR	1990	10	63	21	✗	✗	
2nd AR	1995	12.2 ± 3	56	21	✗	✗	
3rd AR[a]	2001	12	62	23	✗	✗	
4th AR[b]	2007	12	72	25	✗	✗	
5th AR without CCFB	2013	12.4	84	28	✗	✗	
5th AR with CCFB	2013	12.4	86	34	✗	✗	✗
5th AR with CCFB and oxidation	2013	12.4	87	36	✗	✗	✗

[a] CO_2 AGWP revised down in AR3 leading to relative increase in GWP for other gasses including methane. [b] CCFB included for calculation of CO_2 AGWP. [c] T-O_3 – tropospheric ozone. S-H_2O – stratospheric water vapour. CCFB – climate-carbon feedbacks.

Additionally, indirect effects have been inconsistently included in historical IPCC publications. In the second and third assessment reports calculations of GWP did not include CCFB. In the fourth assessment report, CCFB were included in the calculation of CO_2 absolute global warming potential (AGWP), the baseline against which the GWP for other gases is based. However, while CCFB also impacts on the radiative forcing of other gasses, these impacts were not included in the GWP calculations until AR5, which results in a large increase, especially for the 100 year horizon GWP, as shown in Table 2.

4.1 Criticism of GWP

There are a number of criticisms levelled at the use of GWPs relating to the three key aspects of this metric: a time horizon must be set; it is modelled on a single pulse emission; and it measures time-integrated radiative forcing.

First, the need to select a time horizon requires the metric user to decide a timeframe that is important. This is a particular issue for methane given that the GWP values change so significantly over time. The selection of a single time horizon is arbitrary and means that other timeframes are disregarded: selection of a short timeframe for methane will ignore the long-term impacts of CO_2, whereas selection of a long timeframe for methane will largely ignore the short term forcing of methane. Indeed, the fact that any time horizon is set means that longer term impacts are systematically underrepresented.

Second, the GWP was designed to equate pulse emissions, *i.e.* one-off emissions, rather than sustained or developing emissions, such as those modelled using life cycle assessment methods. This does not generally reflect the consequences of real-world investment or policy decisions.[12]

Last, the physical basis of the GWP is the integrated radiative forcing and does not represent the temperature (or other climate) impact. As described in Section 3, radiative forcing is a precursor to temperature change, but they are not synonymous. Additionally, the fact that GWP is based on an integrated measure means that the GWP indicates the average impact over a time horizon rather than the impact at the end-point of the time horizon (both are useful in estimating the impacts of climate change).

The limitations associated with GWP have given rise to the creation of alternative climate metrics over the last 20 years. These metrics are defined in the following section, after which their key differentiating factors are discussed in Section 6, including time horizons and physical basis.

5. Alternative metrics

The many climate metrics that have been proposed in the last few decades can be categorised in a number of ways, which are summarised in Table 3. Table 3 lists the most cited metrics and categorises them based on key factors: CO_2 equivalency value, their physical basis, whether they are static or dynamic metrics, cumulative or end-point estimates, and their level of uncertainty. The following section firstly describes the most used alternative, GTP, before outlining the characteristics of each other metric in order that they appear in the table.

5.1 GTP – global temperature change potential

Global temperature change potential (GTP) is the most popular and most researched alternative climate metric to GWP.[2] It was developed by Shine *et al.*[24,32] and is included in the IPCC Assessment Reports. It is defined as the change in mean surface temperature after a specified time due to a pulse emission, relative to the effect from an equivalent pulse emission of CO_2. The key differences compared to the GWP are:

- It is an end-point metric,[11] measuring the impact at the end of a time period, rather than a cumulative effect within a time period; and
- It estimates the effect on temperature, rather than radiative forcing (which gives rise to temperature but the relationship is not linear).

Values of GTP for methane are currently estimated as 13 $gCO_{2eq.}/gCH_4$ (GTP100) and 71 (GTP20) including an allowance for CCFB and the eventual oxidation of methane into CO_2. Whilst the GTP20 is around 20% lower than the equivalent GWP20 (87), the 100 year time horizon differs greatly, over 60% lower than GWP, as shown in Fig. 5. This is because the GTP figure measures at the end-point and does not account for the strong forcing prior to this time. At 100 years the proportion of the pulse emission remaining in the atmosphere is

Table 3 Climate metrics relating to methane and their key attributes. Source: ref. 2, 4, 12, 14, 16 and 24–30

			Time horizon/end-point value							
Metric	Full name	Source	20	100	500	Indicator type	Static/dynamic	Emission type	Time frame	Uncertainty
GWP	Global warming potential[a]	IPCC 2014 (ref. 31)	84–87	28–36	8–11[b]	Radiative forcing	Static	Pulse	Cumulative	Lowest
SGWP	Sustained-flux global warming potential	Neubauer 2015 (ref. 4)	96	45	14	Radiative forcing	Static	Sustained	Cumulative	Lowest
ICI	Instantaneous climate impact	Edwards 2014 (ref. 16)	43	0.1	—	Radiative forcing	Dynamic	Sustained	End-point	Low
CCI	Cumulative climate impact	Edwards 2014 (ref. 16)	86	34	—	Radiative forcing	Dynamic	Sustained	Cumulative	Low
TWP	Technology warming potential	Alvarez 2012 (ref. 12)	—	—	—	Radiative forcing	Dynamic	Sustained	Cumulative	Low
GTP	Global temperature change potential	Myhre 2013 (ref. 2)	71	13	—	Temperature change	Static	Pulse	End-point	Low
IGTP	Integrated global temperature change potential[c]	Peters 2011 (ref. 6)	96	38	12	Temperature change	Static	Pulse	Cumulative	Low
TEMP	Temperature proxy index	Tanaka 2009 (ref. 29)	—	39	—	Temperature change	Static	Pulse	Cumulative	Low
CCIP	Climate change impact potential	Kirschbaum 2014 (ref. 14)	—	32	—	Temperature change; rate of change; cumulative change	Static			Medium
GSP	Global sea level rise potential	Sterner 2014 (ref. 28)	78	18	3.8	Sea level rise	Static	Pulse	End-point	High
IGSP	Integrated global seal level rise potential	Sterner 2014 (ref. 28)	95	39	11	Sea level rise	Static	Pulse	Cumulative	High
GPP	Global precipitation change potential	Shine 2015 (ref. 30)	120	8.1	—	Precipitation	Static	Pulse	End-point	High
GDP	Global damage potential	Kandlikar 1995 (ref. 25)	—	—	—	Economic	Static	Pulse	Cumulative	Highest
GCP	Global cost potential	Manne 2001 (ref. 27)	—	—	—	Economic	Static	Pulse	End-point	Highest
SCM	Social cost of methane	Shindell 2017 (ref. 13)	—	—	—	Economic	Static	Pulse	Cumulative	Highest

[a] Range of values for GWP represents various additional inclusions for carbon climate feedback and oxidation of methane into CO_2. [b] The 500 year value is not given in the most recent IPCC assessment report, so the figure presented is from the 4th assessment report. [c] The IGTP metric values are estimated to be 12% higher than equivalence GWP values and are thus calculated. The original estimation was based on the 4th assessment report values of the GWP.

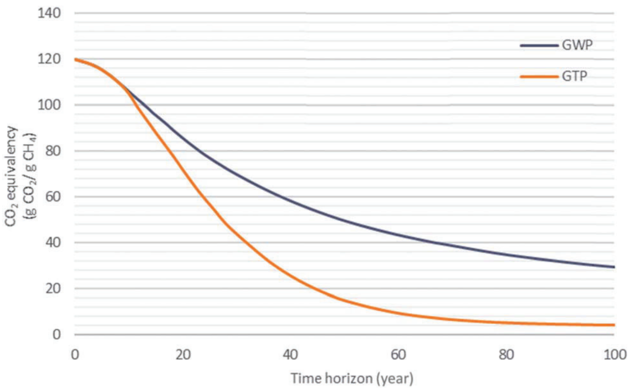

Fig. 5 The global temperature change potential of methane compared to the global warming potential, CO_2 equivalencies across different time horizons. Note, indirect carbon climate feedback and methane oxidation effects are not included within these estimates. Source: ref. 33.

relatively small. Indeed, at this time after the emission, the dominant force is from only the indirect effects such as CCFB and methane oxidation (without which the GTP100 would be only 4).

The GTP goes one step further down the cause–effect chain (see Fig. 8) than GWP by estimating the relative temperature change resulting from the increased radiative forcing. This brings more clarity when using the metric for temperature-based analyses (*e.g.* keeping global temperatures below 2 °C). However, the estimation of GTP incorporates additional assumptions about physical processes, such as climate sensitivity and the exchange of heat between the atmosphere and the ocean.[2,24] This consequently brings more uncertainty compared to GWP.[4] The IPCC estimate an uncertainty of GTP100 of ±75% (with a 90% confidence), compared to ±30% and ±40% for GWP20 and GWP100, respectively.[2]

5.2 SGWP – sustained-flux global warming potential

The sustained-flux global warming potential (SGWP) has been previously called the step-change global warming potential[4,34] and is designed to eliminate the dependence of the GWP metric on the single 'pulse' emission. This metric measures the relative radiative forcing of a sustained emission of a GHG relative to that of CO_2. This metric is otherwise the same as GWP, but the sustained emission measurement results in a larger CO_2 equivalence and is 40% higher than GWP for the 100 year horizon.[4]

5.3 ICI and CCI – instantaneous and cumulative climate impact

Edwards and Trancik[16] developed a new set of metrics in 2014, intended to be a simplified dynamic method to account for changing emissions profiles over time, in order to assist with development of effective emissions pathways. Instantaneous climate impact (ICI) measures the radiative forcing associated with emissions at a specific time point, similar to an instantaneous version of GWP. It is dynamic in that the time horizon end-point is fixed, rather than the time period after an emission (further explained in Section 6). Consequently, in a multi-year emissions assessment (*e.g.* a life cycle assessment), as the year of emission increases, the time period decreases until the end time point is reached. The result is that any methane emissions incurred at the start of the time frame contributes relatively little, but the values increase significantly as the emissions approach the end-point.

The second of the set of impacts developed by Edwards and Trancik[16] is a cumulative version of the ICI, the CCI. As such, it measures the cumulative radiative forcing of an emission or emission profile. It is similar to the GWP in that it measures cumulative radiative forcing, but whereas the time horizon is fixed with GWP (*e.g.* 100 years), the end point is fixed with CCI (*e.g.* 2080). In other words, the CCI is a dynamic version of GWP.[11]

5.4 TWP – technology warming potential

Technology warming potential (TWP) is designed specifically for comparing technologies or products over variable time and is classed as a dynamic metric.[12] TWP does not produce a CO_2 equivalency metric as such, but produces a 'technology equivalency', as it gives relative improvements (or otherwise) associated with technology switching over a time frame. It is defined as the relative proportional change in cumulative radiative forcing over different timescales and may be as a result of a pulse or sustained emission.[5] The effect is broadly similar to the ratio of GWPs associated with two different technologies, but the initial set-up of TWP did not allow for climate carbon feedbacks, suggesting that the methane impact may be underestimated in this metric.[5]

5.5 IGTP – integrated global temperature change potential

The integrated global temperature change potential (IGTP) is a cumulative version of the GTP. Unlike the GTP which estimates the temperature impact of a pulse emission at a specific time, the IGTP estimates the cumulative temperature impact from the time of a pulse emission to a specific time horizon, relative to CO_2.[6] In this respect, it is a temperature equivalent of the global warming potential. This means that IGTP values are higher than GTP, as the initial high radiative (and temperature) forcing is effectively 'remembered' in the cumulative time horizon estimates.[26,28] Values are approximately 12% higher than the GWP for the 20, 50, 100 and 500 year time horizons.

5.6 TEMP – temperature proxy index

The temperature proxy index (TEMP) was developed by Tanaka *et al.*[29] in 2009 to provide a temperature based equivalency metric similar to the GTP but integrated over a specific time horizon (similar to the IGTP). Instead of a projected impact metric derivation such as the GWP, TEMP values are numerically estimated based on the historical contribution of different GHGs over the post-industrial time period.[30] The TEMP metrics and analysis suggest that GWP100 underestimates the contribution from methane and that a value of 39 would be most appropriate (which is not dissimilar to the current GWP100 value of 36 including carbon climate feedbacks and oxidation to CO_2).

5.7 CCIP – climate change impact potential

The climate change impact potential (CCIP) metric was created by Kirschbaum[14] in 2014 and is the only mid-point type metric that combines the effects of temperature rise with cumulative warming as well as rate of warming. Key assumptions associated with this metric are that each impact (temperature, cumulative temperature and rate of rise) are weighted equally in importance and the values are only available for 100 year time horizon, which is similar to the GWP100 at 32 $gCO_{2eq.}/gCH_4$.

This is a unique metric in its attempt to incorporate the different types of climate impact. If there were a specific calculator that allowed the selection of weighting and time horizon to generate the appropriate CO_2 equivalence, this would be a useful bridge between simple static metrics and more complicated climate models.

5.8 GSP and IGSP – global sea level rise potential

The global sea level rise potential was developed in 2014 and goes a step further than the temperature impacts of emission by estimating the specific impact on sea level rise.[28] It is a static metric based on a set time horizon, estimating the relative change in sea level at the end of the time horizon. The values for 20, 100 and 500 year time horizons lie between those associated with GWP and GTP for methane, at 78, 18, 3.8 $gCO_{2eq.}/gCH_4$ respectively.[28] The relative uncertainty associated with GSP is likely to be higher than GWP or GTP as it is further in the line of damage estimation (see Fig. 8). However, this is still a physical metric with no required socio-economic evaluation, unlike the GDP and GCP.

The IGSP is a cumulative version of the GSP, similar to the GWP but estimating average sea level impacts. The metric values for IGSP are slightly higher than those of GWP at 95, 39 and 11 $gCO_{2eq.}/gCH_4$ for 20, 100 and 500 year horizons respectively.

5.9 GPP – global precipitation change potential

Global precipitation change potential is a static equivalency metric created in 2015 that compares GHGs against their effect on global average change in precipitation, due to a pulse or a sustained emission.[30] The precipitation estimate over time uses both a radiative forcing element (GWP) and a temperature change element (GTP) and their relative impact changes over time.[26] Similar to the sea level rise metric, this metric goes further along the cause and effect chain, whilst still being physically based (rather than socio-economic). The metric values are higher than GWP and GTP values for the 20 year horizon (120) and slightly lower for the 100 year (8.1). This indicates that the effect of methane on global precipitation change is large in the short term, much larger than the temperature change impact.

5.10 GDP – global damage potential

Global damage potential (GDP) goes beyond mid-point physical impacts to estimate the end-point damages caused by climate change, relating to human health, increased rates of mortality and ecosystem losses, which are aggregated using an economic value.[7] It is still an equivalency metric in that it estimates the relative damage impact of an emission compared to CO_2 and is based on the cumulative impact over time. The end-point economics-based metric removes the requirement to specify a timeframe by setting an infinite horizon and setting a discount rate at which future emissions are discounted against near term emissions. Recently estimated GDP equivalences for methane are between 19 and 100 with a base case of 50 (with an additional outlier of 420, associated with high discount rate).[35] The estimation of an economic value on damage represents significantly higher uncertainty than other mid-point metrics, owing to the additional assumptions that must be made to estimate:

- The damage caused by an increase in concentration (*e.g.* number of extreme weather events, sea level rise, extinction events); and
- The economic value placed on such damage.

The GDP is an intuitively useful method to determine the least-cost mitigation strategy.[25] However, the move from a physical to economic basis and the high uncertainty reduces the transparency and useability of such a metric for many applications and it is typically utilised within an integrated climate-cost model framework.[2]

5.11 GCP – global cost potential

Global cost potential (GCP) is also an end-point economic metric and defines price ratios between GHGs and CO_2 that deliver the least-cost mitigation solutions to meet a specific climate target at a specific time.[2,27] Similar to the GDP, this metric is typically an output from a climate-economic model generating price ratios for different GHG mitigation options using an optimisation model[36] and are not normally used in carbon equivalency-related studies due to their complexity and dependence on system assumptions. Tanaka *et al.*[36] recently estimated GCP values that fit with a 2 °C climate target, resulting in a range of values from 5 to 65 $gCO_{2eq.}/gCH_4$, with a peak at the time of stabilisation around 2060.

5.12 SCM – social cost of methane

The social cost of methane (SCM) is another estimator of the economic costs of damage associated with methane. As indicated by the name, the damages focus on methane rather than the climate effect, as it includes damages associated with air quality and tropospheric ozone creation which has a large impact on crop yield and premature deaths.[13] Impacts are monetised and levelized per tonne of emission, and subsequently compared to the social cost of carbon. Instead of using specific time horizons, the time horizon is infinite and a discount rate is set. Thus, instead of varying values over time horizons, they vary significantly over discount rate: 10% discount rate equates to a CO_2 equivalency of 199; 5–102%; 4–76%; 2.5–42%; 1.4–26%. These values are higher than most other equivalency metrics, partly due to the incorporation of the damage effect of ozone creation.

6. The key factors that differentiate climate metrics

There are many important differentiating factors associated with the climate metrics, which are analysed below to inform recommendations for metric selection. The following section assesses metric in relation to: selecting the timeframe; static *vs.* dynamic metrics; the physical basis; level of uncertainty; simplicity *vs.* tangibility; and suitability for the application.

6.1 Selecting the timeframe

The need to select an appropriate timeframe is the most common criticism of the GWP and has the largest impact on metric value. This variation is shown in Fig. 6, giving equivalencies for different metrics for methane over different time horizons.

There is no single correct time horizon to use: it depends on the perspective and reason for which the estimation is being carried out.[11,26,37–39] The IPCC typically uses a 100 year time horizon (GWP100), being commensurate with the scenario timescales used in its modelling work. However, 20 year time horizons are increasingly used, which can significantly alter results, often leading to disagreement and conflicting conclusions in the literature.[12,40] Using a short-term metric inherently ignores the impact of long term, long-lived forcers (CO_2) and on a systems scale this means prolonging the point at which the globe reaches climate stabilisation. Conversely, a long-term metric inherently ignores the large impact of short-lived forcers (methane), which may cause more rapid temperature increases require more drastic emission reduction measures earlier to meet temperature targets.

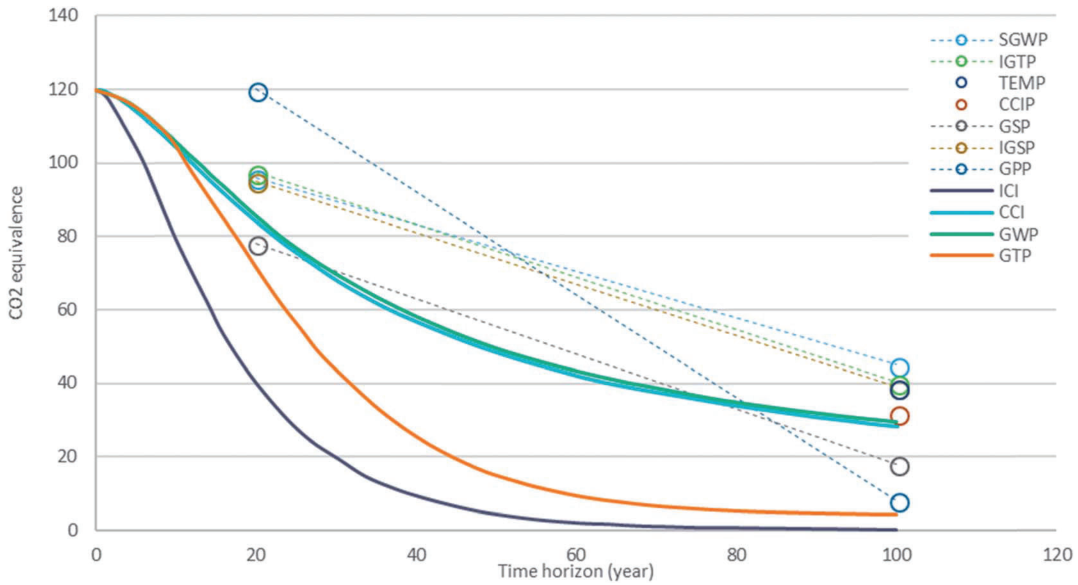

Fig. 6 The CO_2 equivalence of methane using different climate metrics, against the time horizon. Dotted lines are placed between paired values of the same metric where only two points are known. Note, for static metrics the *x* axis denotes the time since the emission and for dynamic metrics CCI and ICI, the *x* axis represents the time away from the end-point stabilisation year (*e.g.* 40 years on the *x* axis means this value is associated with a time horizon of 40 years before the stabilisation period).

Using a GWP100 gives the average radiative forcing occurring over the 100 years after an emission. But why is the average effect over the next 100 years important and are there other important time horizons? The selection of time horizon is a policy decision: are there concerns about short-term or long-term global temperatures? Many countries have committed to reducing GHG emissions by 2030 or 2050, but these are interim targets with the aim of long term decarbonisation. There is an argument to suggest that an appropriate time horizon should be in accordance with 1.5 or 2 °C decarbonisation pathways that require stabilisation of GHG concentrations by 2050–2100 : 30–80 years.[41–43] However, the GWP metric does not measure the impact at a specific time, but the average effect over a period. When concerned with a specific time for stabilisation, an instantaneous metric (such as GTP) may be more appropriate.

As the time of required climate stabilisation grows closer, the importance of methane mitigation grows stronger. Conversely, in 2100, an emission of methane from 2015 will be seen as relatively unimportant. The timeframe after a stabilisation year will also be extremely important in maintaining a stabilised climate, whilst the application of a short time horizon effectively reduces the importance of longer term emissions to zero, which may be inappropriate.

Alvarez *et al.*[12] suggest that for technological environmental analyses, it is most appropriate and transparent to plot estimated GHG emissions over different time horizons. Other studies suggest that a comparison should span a flexible range of time horizons, *e.g.*[12,16] Ocko *et al.*[65] suggest simply presenting GWP from both a 20 and 100 year time horizon. For larger-scale integrated assessment models which project emissions up-to, and beyond, climate stabilisation periods, the use of a single GWP value such as the GWP100 would significantly undervalue the impact of methane emissions. Thus the inclusion of both short and long-term metrics is imperative to assess the robustness of any projections, especially where the contribution of methane emissions is significant.

From the development of metrics that analyse impacts on sea level and precipitation,[28,30] it is clear that potent short lived pollutants like methane may play a strong role in climate change in both the shorter (20 years) and longer (100+ years) time horizons. Both the short term and longer term effects of emissions must be understood and thus the inclusion of multiple time horizons help to prevent any unintended consequences associated with a technology or product switch.

As described in Section 5, there are three metrics described here that do not require the setting of a time horizon, but instead use a discount rate to estimate impacts over an infinite time: the GDP, GCP and SCM metrics. Whilst the avoidance of a time horizon is beneficial, the need to apply a discount rate represents a similar arbitrary weighting of preference for shorter (or longer) time horizons and so there is little advantage from this perspective. The numerical values are even more wide ranging as shown in Fig. 7, perhaps due to the compounding of assumptions relating to discount rates and the cost of damages.

6.2 Physical basis of the metric

The various metrics differ with respect to their physical or socio-economic basis, and are primarily categorised as: radiative forcing; temperature; economic; or a mix of the aforementioned. They can also be categorised in relation to their position along the climate cause–effect chain as shown in Fig. 8. Metrics sitting closer to the end-point effects are more intuitively useful and understandable. As described, GWP is based on radiative forcing, but there is suggestion that a switch from GWP to

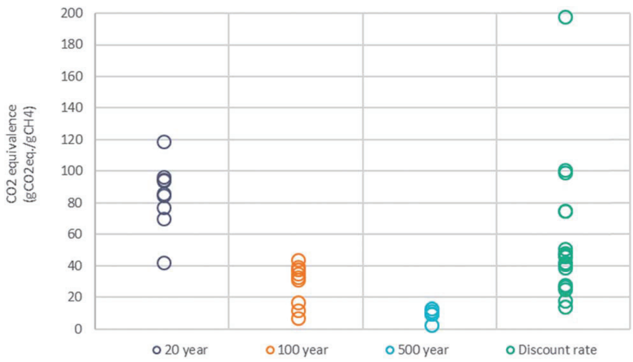

Fig. 7 CO_2 equivalence of methane for different time horizons and compared to metrics which use discount rates instead of time horizons.

a temperature-based metric such as GTP is more appropriate given that our climate targets revolve around global mean temperature changes.[2]

However, at the point in the cause–effect chain where metrics estimate end-point damage, they convert from a physical basis to socio-economic and this carries additional uncertainty. These damage indicators may be extremely useful for broader studies into decarbonisation pathways, but typically require energy/climate/economic system models and are a step away from a simple metric design. The use of simpler physical metrics is preferable for such uses as annual emission inventories from a company or national perspective, or for simpler technological evaluations.

More recent metrics estimating contribution to sea level rise, the GSP, and to precipitation change, GPP, are very useful in improving our understanding of the physical effects of emissions across different timeframes and will help to inform the appropriate CO_2 equivalencies. It is notable that these metrics are broadly within ranges bounded by the GWP and GTP for equivalent time horizons.

6.3 Static *vs.* dynamic metrics

The way that GWP (and GTP) is used in most abatement studies does not take into account the timing of emissions. Typically, one metric (*e.g.* GWP100) is used to estimate emissions, for example from a natural gas well, over the lifetime of the well. However, as a well may be active and emitting for 30 years or more, this means that the end-point of the time horizon is not fixed. For example, if a well emits within the first year of operation, say 2015, the GWP100 would consider the impact up to 2115. If the well still operates and emits at 2045, the GWP100 estimation would consider the impact up to 2145.

Static metrics like the GWP and the GTP use fixed time horizons. This means that the time horizon (*e.g.* 100 years) stays the same length, even when emissions studies may span multiple years (*e.g.* life cycle assessments). However, these metrics may also be used dynamically instead, using a fixed end-point in time rather than a fixed time horizon. This means that for multiple year studies, the end-point (*e.g.* the year 2100) stays the same and the horizon reduces as the year of emission advances. For example, a GWP100 may be used with an emission in 2015, a GWP99 in 2016 and GWP98 in 2017 *etc.*[44] Fig. 9 shows the difference between static (GWP and GTP) and dynamic (ICI and CCI) metrics by defining the CO_2 equivalency value over time.

To use a dynamic approach in a technology assessment, first an end-point must be selected (*e.g.* 100 years from the start of the assessment time). Estimations of emissions must be made for each year of the assessment period (*e.g.* over a 30 year lifetime of a technology). Additionally, a different metric value for each year must be estimated. For example, emissions at year zero will be multiplied by the 100 year metric value, whilst emissions at year one will be multiplied by the 99 year metric value, and so on until the end of the assessment period (*e.g.* emissions at year 30 multiplied by the 70 year metric value). Thus, the use of dynamic metrics adds significant complexity to

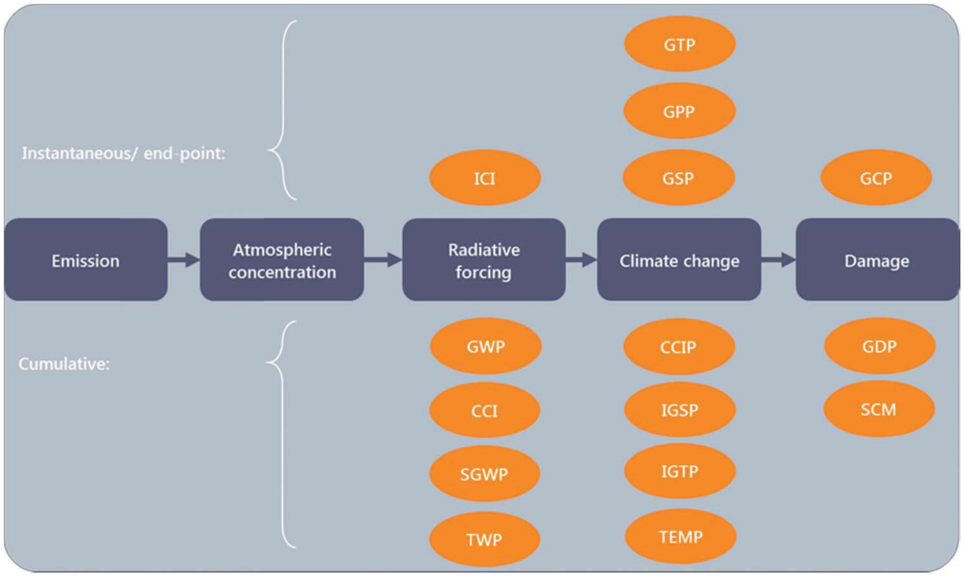

Fig. 8 Climate metrics categorised by: stage in cause–effect chain; whether they indicate instantaneous or cumulative impacts.

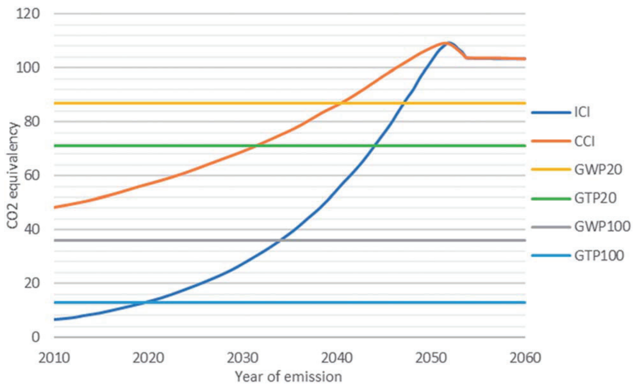

Fig. 9 Comparing GWP, GTP, ICI and CCI metric values over time. ICI and CCI values are dynamic and are set to an end-point of 2059, as per Edwards and Trancik,[16] giving an equivalent initial time horizon of 49 years.

the calculation relative to static metrics. Applications of the use of dynamic metrics in environmental studies include Levasseur *et al.*[44] and Edwards and Trancik.[16]

The use of static metrics must be carried out with care for emissions scenarios over long timeframes, for example with life cycle assessments. When doing so, the definition of the metric changes from its original meaning, for instance with GWP, which is intended to measure the average effect of a single pulse emission over a specific time horizon. Both the pulse and specific time horizon aspects are no longer applicable as there may be sustained emissions over many years.

The use of a dynamic metric may result in significantly different results compared to the use of static metrics.[16] Using the example above, the methane emissions during the first year would have a significantly lower impact on global warming than equivalent methane emissions during the 30th year. Such metrics are the ICI[16] or a dynamic version of the GTP.[2]

Whilst the use of dynamic metrics may be preferable when comparing technologies over long timescales, static metrics are most appropriate for emissions estimates based on shorter timescales, for example annual emissions estimates. Additionally, the projection of a specific stabilisation year for use with a dynamic metric is an assumption, with atmospheric GHG concentration stabilisation years spanning 40 years or more across different emission pathways, as mentioned in Section 6.1. Thus, the use of a simpler static GWP for an LCA that spans 30 years would fall within this uncertainty range. Thus, there may be only marginal benefit in applying a dynamic metric methodology, which may be outweighed by the relative increase in complexity of calculation.

6.4 Simplicity *vs.* tangibility

As metrics move along the cause–effect chain, they become more policy relevant[2] and relatable as an output. For example, temperature change may be a more tangible measure than radiative forcing, whereas damage estimates as a result of climate change are even more so. However, with greater tangibility comes more assumptions, uncertainty and complexity. For example, moving from a physical temperature change to estimating the socio-economic damage caused by that temperature change requires the modelling of climate impacts, population and demand projections, as well as technological resilience and innovation. Thus, there is a trade-off between simplicity, uncertainty and tangibility.

Myhre *et al.*[2] show that uncertainty is higher for GTP than for GWP for example: ±40% for GWP100 compared to ±75% for GTP100 (with a 90% confidence interval). However, the impact of different time horizons gives even more variation in results than this uncertainty. Further, the uncertainty in estimates of methane emissions in the first place have relatively high uncertainties in some cases *e.g.*,[51] which are likely to be of similar order of magnitude to those from GWP or GTP. Some uncertainty is to be expected, which is why sensitivity analyses should be carried out wherever an investment or policy decision is marginal or at risk. It is the authors' opinion that for technology assessments and annual emission inventory estimates, physical climate metrics that enable CO_2 equivalency over a broad range of values best serve the purpose of understanding the range of potential climate impacts.

6.5 Suitability for application

Perhaps most importantly, the chosen metric must be appropriate for the application. Different applications require different levels of complexity and span different time scales as shown in Table 4. Typical uses of climate metrics are:

- Emissions inventories from industry operations.
- National/regional emissions contributions.
- Technology assessments *e.g.* LCA for policy planning.
- Energy system mitigation pathways.

When the result will inform a long-term investment decision or policy, it is imperative that the impacts of using different metrics and time horizons on the result are explored.

Broadly, estimates of emissions over a short timeframe, *e.g.* annual emissions estimated from a company or national perspective, are likely to require a simple and static metric, given the lack of time variation and the requirement for fast and repeated estimation. For a technology assessment or a life cycle assessment that spans multiple years, a suitable metric may be:

Table 4 Categories of applications for the use of climate metrics, with associated qualities and requirements

Application	Timeframe	Calculation complexity	Static/dynamic	Suitable metrics
Annual estimate: facility/region	∼1 year	Low	Static	GWP/GTP/similar
Technology assessments	∼20 years	Medium	Static or dynamic	GWP/ICI/CCI/GSLP *etc.*
Decarbonisation pathways	∼100 years	High	Dynamic	End-point metrics

a dynamic metric which accounts for the longer time frame considered; and a simple metric, given that the scope boundary is small and does not consider wider global implications. Estimates of emissions pathways to meet climate targets over longer time scales and multiple technologies may require metrics that: estimate the effects of climate change, either physical or economic damage; and may utilise more complex approaches such as climate models or end-point metrics.

7. The impact of different metrics on emissions results

As seen in the summary Table 3, the CO_2 equivalency values of methane range from 4 to 120 across metrics and time horizons. Additionally, the end-point metrics SCM and GDP have even higher values associated with the highest discount rates (for example the SCM estimates an equivalency of 199 at 10% discount rate[13]). It is clear that the time horizon (or discount rate) has the largest impact on variation, more so than the metric type. Given that these are static multipliers in emission estimates, the impact of using different static values is large and linear.

To determine the impact of using different static and dynamic metrics and time horizons, this study applies the various metrics and equivalency values to an emissions case study: an estimate of greenhouse gas emissions associated with the production and consumption of various shipping fuels, including liquefied natural gas (LNG), heavy fuel oil (HFO) and methanol. Multi-year technology or fuel assessments typically use a single metric (*e.g.* the GWP100), but this assessment shows that the use of a singly metric inappropriately ignores the importance of timing of emissions and of the differences between short-term and long-term climate impact.

LNG exhibits 25–30% lower CO_2 emissions than liquid fossil fuels such as HFO upon combustion on an energy output basis, but typically has greater methane emissions.[45–48] Total methane emissions are governed by both the upstream supply chain and the engine type: this study investigates the use of a lean-burn spark ignition (LBSI) and a high-pressure dual fuel (HPDF) engine.[45] HFO and methanol are both used within diesel engines, where methanol also has lower CO_2 emissions due to its relatively higher H–C ratio.[48–50] A full environmental assessment has been conducted and is presented in a parallel paper to this, but a summary of the life cycle CO_2 and methane emissions are given in Fig. 10.

For the natural gas supply chain, upstream methane emissions arise from extraction, gathering and processing, liquefaction, storage and bunkering. Median estimates from Balcombe *et al.*[51] were used for production, gathering and processing. Liquefaction figures were estimated based on mean values derived from 6 studies[52–57] and synthesised in Balcombe *et al.*[58] For LNG storage the study uses assumptions made in Lowell *et al.*,[53] whereas for bunkering, it is assumed that 0.22% of LNG is boiled off or displaced as vapour during fuelling, with a 50% capture resulting in 0.11% emission.[53,59]

For methanol, the production and processing of natural gas is the same as included for the LNG supply chain. The inventory for gas reforming and methanol synthesis is derived from the NREL database,[60] using the Ecoinvent 3.3 database for the ancillary impacts.[61] The upstream allocated impacts to heavy fuel oil and marine diesel oil are taken from the Ecoinvent 3.3 database. For HFO, bunker oil with an average sulphur content of 3.5% w/w is assumed. For diesel, the production of low sulphur light fuel oil is used, with a sulphur content of 0.005% w/w. For upstream carbon dioxide emissions, 440 gCO_2/kg HFO and 524 gCO_2/kg diesel is associated with the production up to point of use.[61]

Engine efficiencies, total methane emissions and total CO_2 emissions are given for each fuel/engine option in Table 5. For engine efficiencies, average values from various sources: ref. 45–48, 53, 62 and 63 were taken and emissions are expressed per kWh of power output considering the average efficiency.

As can be seen in Fig. 10, large differences exist across the options in methane emissions both upstream and at end-use, as

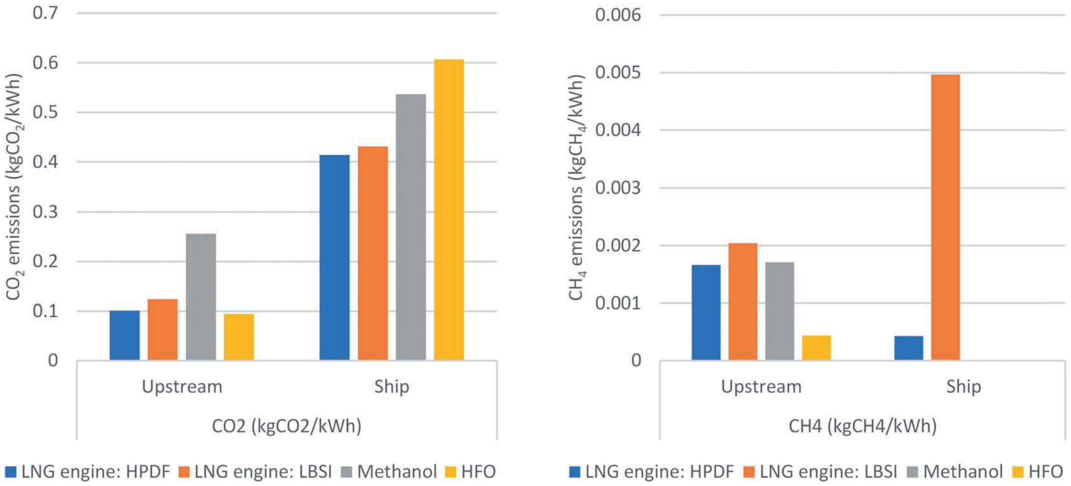

Fig. 10 CO_2 and methane emissions associated with the supply and use of 4 different fuels and engines for ships. Emissions are divided into upstream supply chain and ship usage. Source: ref. 51–61.

Table 5 Summary of inventory of engine efficiencies, methane and CO_2 emissions. Data averages from various sources: ref. 45–48, 53, 62 and 63

	LBSI	HPDF 2-stroke	HFO	MDO	Methanol
Efficiency (% LHV)	45%	51%	45%	45%	45%
Methane (gCH_4/kW h)	4.8	0.3	0.011	0.01	0
CO_2 (gCO_2/kW h)	462.3	427	593.0	524	536.4

well as some moderate variation in CO_2 emissions. Combined life cycle GHG emissions are represented in Fig. 11 for different CO_2 equivalency values assumed. Given the different emission profiles, there exist some crossover points where the rank order of fuels change. Under low equivalency values of less than 20 $gCO_{2eq.}/gCH_4$, both LNG fuelled engines exhibit the lowest GHG emissions. Putting this in context, CO_2 equivalence values of less than 20 are those associated with longer time horizons and end-point metrics which do not account for the high initial forcing impacts. Such metrics with less than 20 $gCO_{2eq.}/gCH_4$ are the GTP at timeframes greater than 45 years, the ICI at timeframes greater than 30 years and the global sea-level rise potential (GSP) and global precipitation change potential (GPP) at 100 year time horizon.

As CO_2 equivalency value increases, the higher methane emissions associated with LBSI LNG engine result in this fuel/engine option exhibiting the highest GHG emissions. Conversely, the LNG fuelled HPDF engine exhibits the lowest impacts across all equivalency values beside the highest at 120 $gCO_{2eq.}/gCH_4$, due to its significantly lower methane slip rates. It should be noted that methanol fuelled engines exhibit higher GHG emissions than HFO across all time horizons due to the high CO_2 emissions associated with methanol production from natural gas, as well as the moderate upstream methane emissions.

To understand the time dependence of emissions, we employ dynamic versions of the GTP and GWP for the above case study. The climate impact of the different fuels varies over time significantly, as shown in Fig. 12. When long time horizons are considered, LNG engines perform favourably, especially in the case of GTP. For GTP and time horizons greater than 40 years, LNG presents a reduced climate impact by 10–20%. However, the LBSI engine with high levels of methane slip performs very poorly with respect to short term climate forcing. With respect to GWP, the integrated nature of the metric means that the initial high climate forcing of LNG engines maintains its impact for the LBSI engine across all timeframes considered, resulting in a higher climate impact than HFO. The HPDF with lower methane slip and low CO_2 emissions has the lowest climate impact across all time horizons.

Two implications arise from this assessment. Firstly, short-term impacts are substantially different to long-term impacts across different technologies and the selection of timeframe may change the rank order of preference. It is imperative that both short and long-term climate impacts are accounted for when considering industrial investment or policy decisions. Secondly, for LNG fuelled engines to reduce GHG emissions compared to HFO, both upstream and end-use methane emissions must be constrained. Engines which inherently exhibit high methane slip are inappropriate for reduction of climate impacts. It should be noted however that LNG offers other benefits than just climate impact, including reduced NO_x, SO_x, particulates as well as cost improvements.

The effect of changing equivalency value on the climate impact of other technology groups is also noticeable. For example, Edwards and Trancik[16] compare the operation of a CNG passenger vehicle *versus* one fuelled with petrol. Using a GWP100 results in the CNG vehicle improving GHG emissions by 10–15%, but with a GWP20 the CNG vehicle exhibits 20% higher emissions than for petrol. Producing a dynamic assessment using ICI and CCI

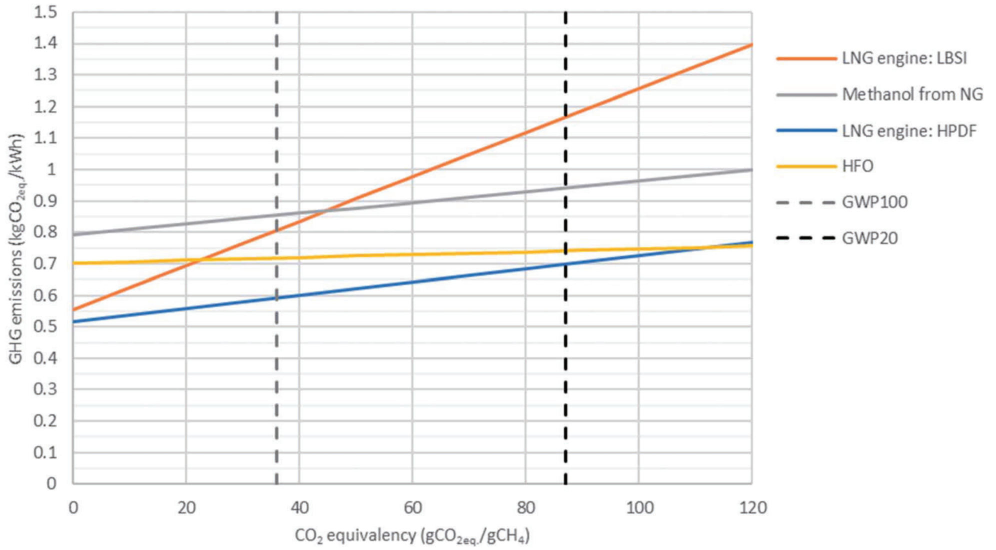

Fig. 11 Estimates of total CO_2 equivalent GHG emissions for different shipping fuels and engines.

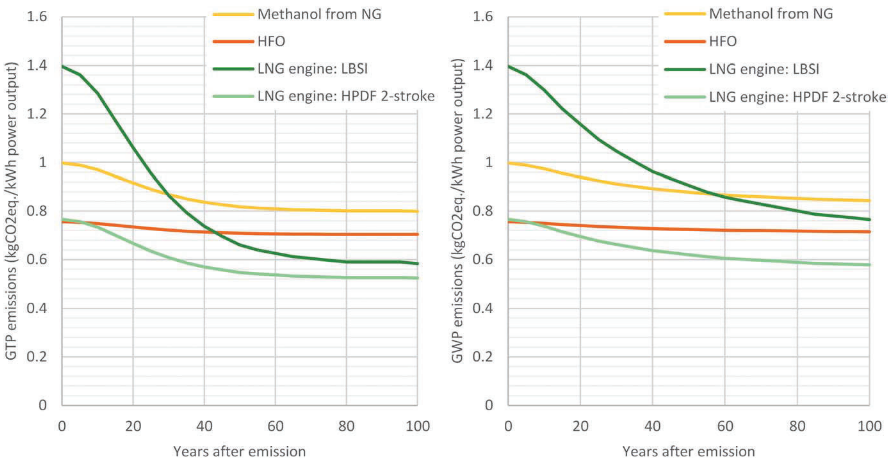

Fig. 12 Life cycle GHG emissions associated with a selection of fuels and marine engine types, expressed for each year after emissions using GTP (left) and GWP (right) metrics.

metrics shows that CNG passenger vehicles offer a climate benefit only over timeframes longer than 20 years.

The comparison of natural gas against coal for power generation is robust in favour of natural gas and shows preference in all but the most conservative of assumptions about GWP values and methane emissions.[64] However, for estimates where carbon capture and storage is used to reduce combustion emissions by up to 90%, the impact of methane emissions proportionally increases. In this case, the choice of metric and time horizon is likely to have a large impact on the relative benefit.

Thus, the selection of metric, and more importantly, time horizon, has a large impact on the ranking of these fuels and technologies, as well as the magnitude of estimates. Investment or policy decisions that trade-off different greenhouse gases like above must ensure that both short-term and long-term climate impacts are taken into consideration.

8. Conclusions and recommendations

This report has investigated the use of various climate metrics and analysed their key attributes and limitations, with respect to methane emissions. There is no single metric or time horizon that is appropriate for all applications and situations. One key point is that methane emissions for the most part are transitory,[33] whereas CO_2 emissions are persistent. Consequently, when considering time horizons the emphasis must not be lost on eliminating CO_2 emissions as, if they are not largely eliminated, the climate will not stabilise. Therefore, any adoption of a shorter time horizon should be tempered with a comparatively longer one.

Given the requirement to stabilise GHG concentrations and to ensure there is no long-term climate change beyond a 2 °C limit, it is inadvisable to use only a 20 year time horizon. A 20 year horizon effectively disregards the impact of emissions after this point, which in the context of comparing methane to CO_2 emissions, dangerously undervalues the long term impact of CO_2. A two-value approach, which indicates the effect over two different time horizons, is suggested by a number of studies.[65]

In selecting an appropriate metric, there is a trade-off between simplicity and transparency.[66] The most appropriate metric depends on the application and which aspect of climate change is most pertinent to the study.[2] Using a single value equivalency such as the GWP100 or GTP100, is the simplest option but hides much information which may be needed to make an investment decision or a policy recommendation. For example, a GHG with a short life but strong radiative forcing may have the same GWP value over a set time horizon as a GHG with a long life but weak forcing effect: the impact of each GHG on climate change may be significantly different but this is lost with such a simplification.[32]

A temperature-based metric such as GTP fits well with a temperature based climate target, but it is suggested that the damage caused by climate change will increase faster than the temperature increase.[13] Consequently, reducing our CO_2 equivalencies from GWP values to GTP values may cause an underestimation of the impact of methane. Even the use of GWP100 may cause an underestimation of the contribution of methane,[16] for example to impacts relating to sea level rise.[28]

The overarching recommendation from this study is to present emissions results with transparency. It is prudent to report methane and CO_2 emissions separately and where climate metrics are used, a summary of the magnitude and type of metric should be given. If the equivalency value has a large impact on results, both low and high values should be used to assess the impact.

Broadly, metric applications can be placed into three categories: short-term (*e.g.* annual) emissions estimates of processes, facilities or regions; multi-year technology assessments or life cycle assessments; and long-term modelling of energy systems and decarbonisation pathways. Recommendations are made for each category.

Estimates of emissions on a short timescale in the order of 1 year typically involve aggregating estimates for a facility or region and require simple static metrics such as GWP or GTP.

Two recommendation options are to: present emissions using a single GWP or GTP metric (50 or 100 year), and include the separated contribution from both methane and CO_2; present two time horizons, a short term (*e.g.* 20 or 50) and a longer term (*e.g.* 100 or more), such that any comparative arguments for technology change holds in both the short term or the long term, or at least that a detriment to either short or long term has been considered.

For technology assessments or life cycle assessments that span 20 or 30 years, suitable metrics could be static (GWP or GTP) or dynamic (*e.g.* ICI or TWP) to account for the emissions timing. However, given the uncertainty associated with a projected stabilisation year, this report considers dynamic metrics to be of only marginal benefit. Additionally, given the increase in complexity associated with using a dynamic metric, the selection of a static metric and incorporating two (or more) time horizons would be appropriate.

For longer term analyses of multiple energy systems over long timeframes, higher levels of complexity are acceptable and application of climate models is most suitable. Where this is not feasible, the application of dynamic metrics or the assessment of both short and long-term time horizons is imperative, especially under scenarios where methane emissions are significant.

In summary, the use of climate metrics in GHG estimation must be carried out with great care and the standard usage of a single global warming potential is not acceptable as it may hide key trade-offs between short and long-term climate impacts. To counter this, transparent reporting of methane and CO_2 emissions is required. It is vital to test any GHG estimates with high and low equivalency values to ensure that we are not simply replacing long-term climate forcing with short-term, or *vice versa*.

Conflicts of interest

There are no conflicts to declare.

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European Commission

Energy, Climate change, Environment

Energy

Methane emissions

The EU methane strategy aims to reduce methane emissions, improve air quality and reinforce the EU’s global leadership in the fight against climate change.

Methane is the second most important greenhouse gas contributor to climate change following carbon dioxide. In fact, methane’s ability to trap heat in the atmosphere is even stronger than that of carbon dioxide.

On a 100-year timescale, methane has 28 times greater global warming potential than carbon dioxide and is 84 times more potent on a 20-year timescale.

According to the International Energy Agency, the annual increase in methane concentration from 2020 to 2021 was the highest on record and real-time data shows that levels continued to increase in 2022. When using fossil gas for electricity generation, lifecycle methane emissions must not exceed 3% of delivered volumes, because in climate terms, it would then be better to use coal for electricity generation. Abating methane emissions is therefore highly relevant to achieving the 2050 climate objectives. Moreover, methane is a potent local air pollutant and contributor to ozone formation, which causes serious health problems.

Key figures on methane

2nd

most important GHG contributor to climate change

60%

of the global methane emissions result from human activity

1/3

of this comes from the energy sector

According to the Climate and Clean Air Coalition (CCAC) Scientific Advisory Panel, reducing methane emissions associated with human activity by 50% over the next 30 years would mitigate against global temperature change by 0.2°C, a significant step towards keeping the overall temperature increase below 2°C.

The International Energy Agency estimates that more than 260 bcm of gas was wasted worldwide in 2021 *(https://www.iea.org/reports/global-methane-tracker-2023/overview)* due to flaring, venting and leaking and that 47% of those emissions can be mitigated with existing technology through measures, such as leak detection and repair. That gas could contribute to the EU security of supply, greater liquidity and help lower prices. It could also mean that new reserves would not be needed to take us to 2050. Given the market value of the additional gas captured through such measures, 40% of these mitigations would have no net-cost.

EU methane strategy

©European Union

Tackling greenhouse gas emissions is a priority of the European Green Deal.

The EU's methane strategy (COM2020/663), published in October 2020, sets Europe's ambition and aims to curb temperature increases, improve air quality and reinforce the EU's global leadership in the fight against climate change.

It focuses on reducing methane emissions in the energy, agriculture and waste sectors, which account for almost all human-related methane emissions.

This cross-sectoral approach takes targeted action in each area while also promoting synergies across sectors, for example through the production of biomethane.

Regulation on methane emissions reduction in the energy sector

As announced in the EU methane strategy, the Commission adopted on 15 December 2021 a proposal for a regulation aimed at reducing methane emissions in the energy sector.

The provisional agreement was reached *(https://ec.europa.eu/commission/presscorner/detail/en/IP_23_5776)* between the European Parliament and the Council on 15 November 2023. After its formal adoption, it will be published in the EU Official Journal and enter into force 20 days later.

The new legal act will provide for reducing energy sector methane emissions in Europe and in our global supply chains. It aims to stop the avoidable release of methane into the atmosphere and to minimise leaks of methane by fossil energy companies operating in the EU. The new regulation covers

- improved measurement, reporting and verification of energy sector methane emissions
- an immediate reduction in emissions through mandatory leak detection and repair and a ban on venting and flaring practices, which involve the release of methane directly into the atmosphere
- a methane transparency requirement on imports, collecting information on whether and how exporter countries/companies are measuring, reporting and abating methane emissions, with a view to establish a methane intensity profile of those entities

The Commission proposals on measurement and reporting of methane emissions, which build on the Oil and Gas Methane Partnership 2.0 (OGMP 2.0) framework, will help understand the exact locations and volumes of methane emitted, allowing a shift from estimates to direct measurements of methane emissions, checked by independent verifiers. The urgency to tackle methane emissions is reflected in the proposals on mitigation that aim to deliver reductions soon after the legislation will enter into force.

For **oil and gas**, companies would need to frequently survey their equipment to detect leaks. If found, they would need to be repaired immediately, mostly within 5 or 15 working days and monitored to ensure that repairs were successful. The proposal also bans venting and routine flaring, allowing venting only in exceptional or unavoidable circumstances for safety reasons. It allows flaring only if re-injection, utilisation on-site or transport of the methane to a market are not technically feasible, with more restrictive rules for how it can be carried out.

For **coal**, the proposal envisages a phase out of venting and flaring of methane, ensuring that safety aspects in coal mines are accounted for. The proposal also obligates EU countries to establish mitigation plans in the case of abandoned coal mines and inactive oil and fossil gas wells.

Partners and initiatives

As methane emissions transcend national borders, the European Green Deal stresses the need for international collaboration.

Global Methane Pledge

President von der Leyen and President Biden launched the Global Methane Pledge (GMP) at COP26 in Glasgow 2021 to slash methane emissions by 30% by 2030. Since its launch, the GMP has generated unprecedented momentum for methane action. Country endorsements have grown from just over 100 in 2021 to over 150 representing 80% of the global economy, and more than 50 countries have developed national methane action plans or are in the process of doing so.

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At the COP28 Global Methane Pledge Summit in December 2023, President von der Leyen presented the first ever EU methane regulation for the energy sector and announced €175 million in funding to methane actions *(https://ec.europa.eu/commission/presscorner/detail/en/ip_23_6057)*. Moreover, she committed to developing a roadmap for COP29 for the global rollout of the "You Collect, We Buy" scheme, whereby the EU incentivises companies to commercialise gas that would otherwise go to waste, announcing that the EU and Algeria would be the first to pilot the scheme.

This video is also available on the EC AV portal. It was produced for COP28 December 2023, and explains the objectives of the Global Methane Pledge.

At the Major Economies Forum in April 2023, the EU joined the **Methane Finance Sprint**, launched by President Biden asking governments to contribute to the goal of mobilising at least $200 million in new methane finance for projects by COP28.

In September 2023, at the occasion of the UN General Assembly in New York, Canada, the Federated States of Micronesia, Germany, Japan, and Nigeria joined the EU and the US as Champions of the Global Methane Pledge.

In June 2022, a **GMP Energy Pathway** was launched at the Major Economies Forum on Energy and Climate to accelerate methane emissions reductions in the fossil energy sector. A **GMP Food and Agriculture Pathway** and **GMP Waste Pathway** were launched in the margins of COP27, where the EU and the US convened a Methane Ministerial to highlight the progress and discuss further implementation steps, including enhanced efforts leading up to COP28.

Joint declaration on reducing GHG emissions from fossil fuels

At COP27 in 2022, the EU also confirmed its commitment on methane emission reduction by endorsing a 'Joint declaration on reducing greenhouse gas emissions from fossil fuels *(https://ec.europa.eu/commission/presscorner/detail/en/statement_22_6827)*', together with the United States, Japan, Canada, Norway, Singapore, and the United Kingdom**.**

Together they represent 50% of global gas import volumes and over 30% of global gas production. And they aim to take steps to reduce the methane emissions associated with their energy consumption, which can spur emissions reductions across the value chain.

MMRV Working Group

The new International Working Group on measurement, monitoring, reporting and verification (MMRV) was publicly announced on 15 November 2023. It's a follow up action to the Joint Declaration on reducing greenhouse gas emissions from fossil fuels adopted at COP27, where the importance of adopting robust measurement, monitoring, reporting, and verification frameworks at international level was highighted.

The Working Group members include 12 countries, the European Commission and the East Mediterranean Gas Forum (as observer): Australia, Brazil, Canada, Colombia, France, Germany, Italy, Japan, Norway, Republic of Korea, United Kingdom and the United States of America.

It aims to develop a consensus-based approach for the MMRV of greenhouse gas (GHG) emissions across the international supply chain of natural gas, from pre-production through final delivery, to enable the provision of comparable and reliable information as well as to better equip companies with tools to rapidly reduce their GHG emissions.

The Working Group will also advance data accuracy and comparability by building upon well-established and globally recognised frameworks, particularly OGMP 2.0, which today includes over 115 companies with assets in more than 60 countries, representing over 35% of the world's oil and gas production and over 70% of LNG flows.

International Methane Emission Observatory

To help take the issue forward, the Commission supported in 2021 the establishment of the International Methane Emission Observatory (IMEO) together with the UNEP, the Climate and Clean Air Coalition and the International Energy Agency.

Funding from EU Horizon 2020 kick-started the development of the observatory, followed by further contributions from the EU through the Neighbourhood, Development and International Cooperation Instrument (NDICI) and from other partners, such as the Global Methane Hub and Bezos Earth Fund.

The IMEO collects and verifies methane emissions data to provide the international community with an improved understanding of global emissions and where abatement action should be focused. It provides a sound scientific basis for the implementation of the Global Methane Pledge. Its collected data help to prioritize actions and monitor results against commitments made by state actors as well as oil and gas companies.

The IMEO also coordinates the Oil and Gas Methane Partnership 2.0 (OGMP 2.0), the flagship oil and gas reporting and mitigation programme of UNEP. It is the only comprehensive, measurement-based international reporting framework for the sector, which today covers 35% of oil and gas producers and 70% of LNG flows.

In November 2022, at the COP27 in Sharm El-Sheikh, IMEO announced the Methane Alert and Response System (MARS), a satellite-based system to detect methane emissions. It has started through pilots to detect major emissions from the energy sector, and in the future, it will expand to cover other methane emitting sectors, such as waste and livestock.

Climate and Clean Air Coalition

The EU is actively involved in several international initiatives on reducing methane emissions, including through the Climate and Clean Air Coalition (CCAC) ↗, established under the United Nations Environment Programme (UNEP). The CCAC works to tackle short-lived climate pollutants such as methane and black carbon in an effort to combat climate change and improve local air quality. In this context, the Commission submitted an EU methane action plan in November 2022 to appear alongside other national plans.

Documents

- Factsheet: Global Methane Pledge: From Moment to Momentum (November 2022)
- EU Methane Action Plan (November 2022)
- Report: An Eye on Methane: International Methane Emissions Observatory 2023 Report *(https://www.unep.org/resources/report/eye-methane-international-methane-emissions-observatory-2023-report)* (December, 2023)
- Report: Climate change 2013: The physical science basis (Intergovernmental Panel on Climate Change, 2013)

Related links

Press material and news

- EU announces €175m financial support to reduce methane emissions at COP28 *(https://ec.europa.eu/commission/presscorner/detail/en/ip_23_6057)* (02/12/2023)
- Commission steps up ambition to agree on a global framework for the measurement, monitoring, reporting and verification of greenhouse gas emissions *(/news/commission-steps-ambition-agree-global-framework-measurement-monitoring-reporting-and-verification-2023-11-15_en)* (15/11/2023)
- Deal on first-ever EU law to curb methane emissions (15/11/2023)
- Proposal of a new EU framework to decarbonise gas markets, promote hydrogen and reduce methane emissions (15/12/2021)

- Methane tracker 2023, International Energy Agency
- Proposal for a Regulation on methane emissions reduction in the energy sector (COM (2021)805)
- Impact assessment report (SWD/2021/459)
- Executive summary of the impact assessment report (SWD/2021/460)
- Study: Assistance to assessing options improving market conditions for bio-methane and gas market rules (December 2021)
- An EU strategy to reduce methane emissions (COM(2020)663 final)
- Workshop: Strategic plan to reduce methane emissions in the energy sector (20/03/2020)
- International Methane Emissions Observatory *(https://www.unep.org/explore-topics/energy/what-we-do/methane/imeo)*
- Global Methane Pledge
- Climate and Clean Air Coalition (CCAC)

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Delaying methane mitigation increases the risk of breaching the 2 °C warming limit

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Atmospheric methane levels are growing rapidly, raising concerns that sustained methane growth could constitute a challenge for limiting global warming to 2 °C above pre-industrial levels, even under stringent CO_2 mitigation. Here we use an Earth system model to investigate the importance of immediate versus delayed methane mitigation to comply with the 2 °C limit under a future scenario of low CO_2 emissions. Our results suggest that methane mitigation initiated before 2030, alongside stringent CO_2 mitigation, could enable to limit global warming to well below 2 °C over the next three centuries. However, delaying methane mitigation to 2040 or beyond increases the risk of breaching the 2 °C limit, with every 10-year delay resulting in an additional peak warming of ~0.1 °C. The peak warming is amplified by the carbon-climate feedback whose strength increases with delayed methane mitigation. We conclude that urgent methane mitigation is needed to increase the likelihood of achieving the 2 °C goal.

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Methane (CH_4) is a potent greenhouse gas, second only to CO_2 in the contribution to global temperature increase relative to pre-industrial levels[1]. Atmospheric CH_4 levels have grown rapidly since the year 2007[2,3]. The mean atmospheric CH_4 concentration ([CH_4]) currently exceeds 1900 parts per billion (ppb), which is >2.5 times larger than the pre-industrial average[4]. Recent trends of observed CH_4 levels are tracking future scenarios of unmitigated emissions[5,6]. For more than three decades, global CH_4 emissions have been dominated by anthropogenic sources mostly related to fossil fuel exploitation, livestock production, waste and agriculture[2,3,7]. Several studies have highlighted the importance of CH_4 mitigation for tackling climate change in the current century, in parallel with efforts to decarbonize the world economy[8–10].

A salient outcome of the 2015 Paris Agreement is the international commitment to keep global warming to well below 2 °C above pre-industrial levels, and pursue efforts to limit the mean global temperature increase to 1.5 °C above pre-industrial levels[11]. Achieving these temperate goals will require reaching net-zero CO_2 emissions alongside deep reductions in CH_4 and other non-CO_2 emissions by or around mid-century[12]. While the need for urgent CH_4 mitigation is now recognized (e.g. the Global Methane Pledge following COP26[13]), it is necessary to assess the importance of immediate versus delayed CH_4 mitigation to comply with the temperature goals in the Paris Agreement—particularly taking into account potential Earth system feedbacks. There is still limited knowledge about (i) the importance of biogeochemical feedbacks[14,15] in the context of CH_4 mitigation for achieving the Paris temperature goals[16,17], and (ii) long-term (i.e. multi-century) climate impacts of delaying or failing to mitigate CH_4 in the current century[18,19].

In this study, we use an Earth system model with an interactive CH_4 cycle to investigate the importance of immediate versus delayed CH_4 mitigation to comply with stringent warming limits in the Paris Agreement. It is important to note that: (i) currently, there are very few Earth system models driven by CH_4 emissions in their representation of the global CH_4 cycle[17,20]; and (ii) previous research applying an Earth system modeling approach to investigate CH_4 mitigation and its implication for meeting stringent temperature goals have relied on scenarios of prescribed [CH_4] without considering explicit changes in anthropogenic CH_4 emissions, potential climate-CH_4 feedbacks, and climate impacts of CH_4 mitigation beyond the 21st century[16]. We use version 2.10 of the University of Victoria Earth System Climate Model (UVic ESCM)[21], into which we implemented a simplified representation of the global CH_4 cycle—featuring simulated wetland CH_4 emissions (including CH_4 emissions from previously frozen soil carbon upon permafrost thaw)[22] and atmospheric CH_4 decay (See Methods). We validate the model against historical [CH_4] data and estimations of the global CH_4 budget in recent decades (See Supplementary Notes 1 & 2).

To assess the importance of timing for CH_4 mitigation to achieve the 2 °C temperature goal, we prescribe anthropogenic CH_4 emissions according to two Shared Socioeconomic Pathways (SSPs)[23,24]: (i) SSP1-2.6, a scenario featuring immediate CH_4 mitigation; and (ii) SSP3-7.0, a scenario without CH_4 mitigation throughout the 21st century. We design four additional scenarios of anthropogenic CH_4 emissions by assuming different initiation of CH_4 mitigation over the next few decades. These scenarios follow the SSP3-7.0 trajectory up to a specific year (2020, 2030, 2040 and 2050) and decline linearly to reach the same amount of CH_4 emissions as SSP1-2.6 in 2100, and then evolve according to the SSP1-2.6 extension beyond the 21st century (Fig. 1). These mitigation scenarios assume deep reductions in anthropogenic CH_4 emissions, corresponding to 69–78% of emission reductions between the year of peak emissions and the year 2100 (Supplementary Table 1). CH_4 mitigation approaches that are currently achievable with existing strategies and technologies (i.e. technically feasible solutions) could– once deployed– lead to the elimination of >50% of global anthropogenic CH_4 emissions by the year 2050, with large contributions from cutting fossil fuel and solid waste emissions[25]. By design, our idealized mitigation scenarios allow us to compare the effect of immediate versus delayed CH_4 mitigation on the global climate at the end of the 21st century and beyond. We further assume that all other future anthropogenic forcings (including CO_2 emissions) evolve according to SSP1-2.6, which is a scenario aimed at limiting global warming to below 2 °C throughout the 21st century[26].

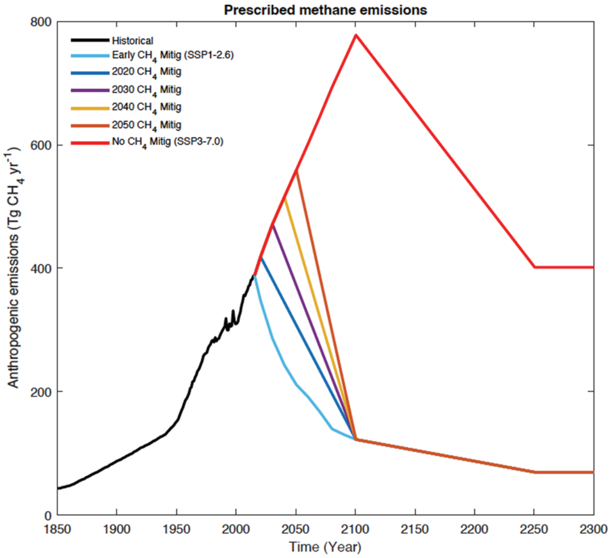

Fig. 1 Anthropogenic CH_4 emissions prescribed to the UVic ESCM in this study. Emissions in the early mitigation scenario ("Early Mitig") correspond to SSP1-2.6, whereas emissions without mitigation ("No Mitig") correspond to SSP3-7.0. Immediate and delayed mitigation scenarios follow the SSP3-7.0 CH_4 emission trajectory to the specified point in time and decline linearly to reach the same amount of CH_4 emissions as SSP1-2.6 in 2100, and evolve according to the SSP1-2.6 extension beyond the 21st century.

Results

Delaying CH_4 mitigation results in higher peak warming. The timing of CH_4 mitigation affects peak levels of [CH_4], [CO_2], and surface air temperature (SAT) in the future. According to our model, every 10-year delay in CH_4 mitigation increases the [CH_4] peak by 150-180 ppb (Fig. 2b). As such, delaying CH_4 mitigation to the 2040-2050 decade will increase the [CH_4] peak by 450–540 ppb relative to CH_4 mitigation initiated at or around 2020. The [CH_4] increase has a direct effect on global mean surface air temperature (SAT). For every 10-year delay in CH_4 mitigation, our model simulates an additional peak warming of ~0.1 °C (Fig. 2d). Delaying CH_4 mitigation to or around mid-century will increase the peak warming by 0.2–0.3 °C relative to a CH_4 mitigation initiated at present-day. Through feedback mechanisms operating in the Earth system (discussed below), one indirect effect of delaying CH_4 mitigation manifests with atmospheric CO_2 concentration ([CO_2]). Our model suggests that every 10-year delay in CH_4 mitigation implies an increase in the [CO_2] peak by 2-3 ppm (Fig. 2c). Consequently, delaying CH_4 mitigation to the 2040-2050 decade will increase the [CO_2] peak by 6-9 ppm relative to CH_4 mitigation at present-day. Relative to the early mitigation scenario (SSP1-2.6), delaying CH_4 mitigation to the 2040-2050 decade implies more [CH_4]

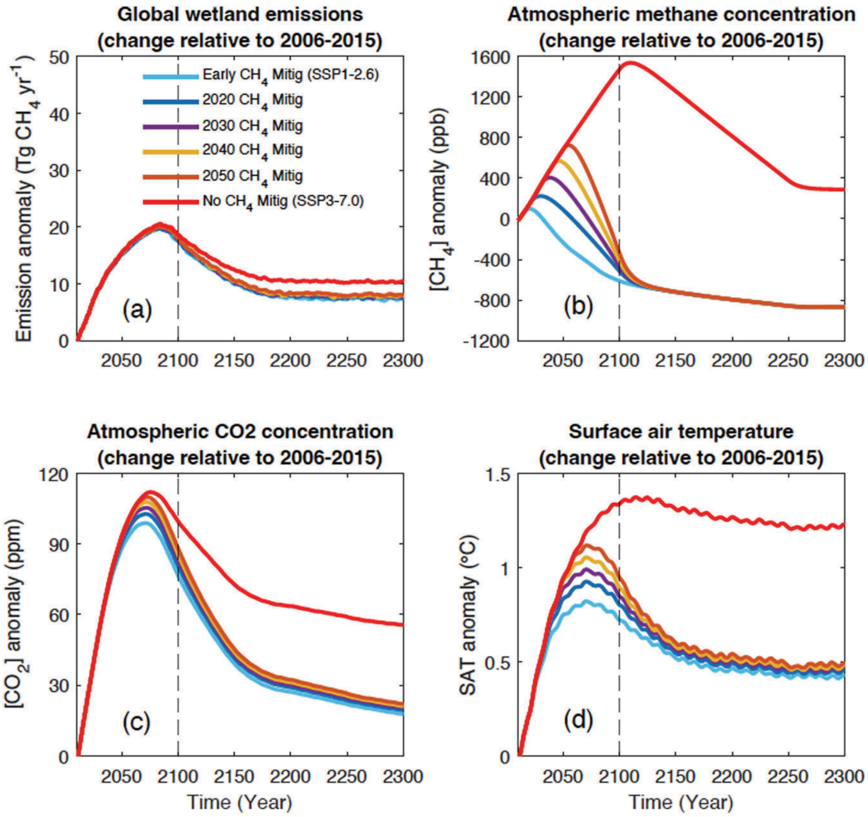

Fig. 2 Projected changes in atmospheric composition and temperature relative to present-day conditions under the mitigation scenarios explored in this study. Changes are shown for (**a**) global wetland CH_4 emissions, (**b**) atmospheric CH_4 concentration, (**c**) atmospheric CO_2 concentration, and (**d**) surface air temperature (SAT) relative to 2006-2015 for different initiation of CH_4 mitigation under the assumption that all non-CH_4 forcing agents (including CO_2) from anthropogenic sources evolve according to SSP1-2.6. The variability in the SAT curves is associated with the solar cycle.

(~200 ppb) and warming (~0.2 °C) at the year 2100 (Fig. 2b, d and Supplementary Note 3).

The decline in [CH_4] in response to CH_4 mitigation depends on the balance between CH_4 sources and sinks (Supplementary Fig. 1). CH_4 sources are dominated by anthropogenic CH_4 emissions (Fig. 1 and S1a), whereas CH_4 sinks in our model are proportional to the atmospheric CH_4 burden (Methods and Supplementary Fig. 1b, c). A delayed CH_4 mitigation results in a higher atmospheric CH_4 burden and [CH_4] than for an early mitigation, which implies a lag in the decline of CH_4 sinks and [CH_4] for the delayed mitigation in comparison to the early mitigation. Implications of this lag are most noticeable towards the end of the 21st century: while total CH_4 emissions converge in 2100 for all mitigation scenarios, the atmospheric CH_4 burden around the year 2100 remains high for delayed CH_4 mitigation relative to early CH_4 mitigation owing to a lag in CH_4 sinks (Supplementary Fig. 2). Overall, relative to the early CH_4 mitigation (SSP1-2.6), simulated CH_4 sinks in 2100 are ~65 Tg CH_4 yr^{-1} higher for CH_4 mitigation delayed to 2040-2050 (See Supplementary Note 4).

The peak warming is amplified by biogeochemical feedbacks. In our model simulations, SAT changes are influenced by biogeochemical feedbacks in addition to the timing of CH_4 mitigation. In particular, we find that the feedback of SAT changes on the atmospheric CO_2 concentration (referred to as the carbon-climate feedback) contributes to increasing peak SAT differences between early and delayed CH_4 mitigation. While we prescribe the same anthropogenic CO_2 emissions in all our model simulations (See Methods), atmospheric CO_2 levels are projected to be higher for delayed CH_4 mitigation scenarios than for early CH_4 mitigation scenarios (Fig. 2c). In comparison to early CH_4 mitigation, delayed CH_4 mitigation results in high [CH_4] levels that lead to high SAT levels. Enhanced global warming results in high [CO_2] levels, which in turn contribute to increase the SAT differences between early and delayed CH_4 mitigation scenarios. Such feedbacks between SAT and [CO_2] involve the response of natural CO_2 sinks to global warming and climate change. For instance, increased SAT enhances the release of CO_2 through soil respiration and weakens the uptake of atmospheric CO_2 by oceans through the solubility pump, resulting in enhanced [CO_2] and an amplification of global warming[14]. Overall, we deduce that the carbon-climate feedback amplifies the SAT response in late versus early CH_4 mitigation scenarios (Fig. 2d and Fig. 3). To quantify the contribution of the carbon-climate feedback to additional peak warming from delayed CH_4 mitigation, we performed additional model simulations with prescribed CO_2 concentration from the early mitigation scenario (i.e. Early CH_4 Mitig SSP1-2.6). These model simulations suppress the warming signal from delayed CH_4 mitigation that is due to the carbon-climate feedback, and their difference with our standard model simulations allows to quantify the magnitude of the feedback. According to our results, the contribution of the carbon-climate feedback to the peak warming increases for every 10-year delay in CH_4 mitigation (Fig. 3). The peak warming attributable to the feedback ranges from ~0.03 °C for CH_4 mitigation initiated in 2020 to ~0.06 °C for CH_4 mitigation initiated in 2050 (Fig. 3).

In contrast, we do not detect a strong feedback between global warming and wetland CH_4 emissions in our model simulations–despite changes in precipitation patterns and wetland areal extents between the different mitigation scenarios explored in this study (Supplementary Fig. 3). Differences in projected wetland CH_4

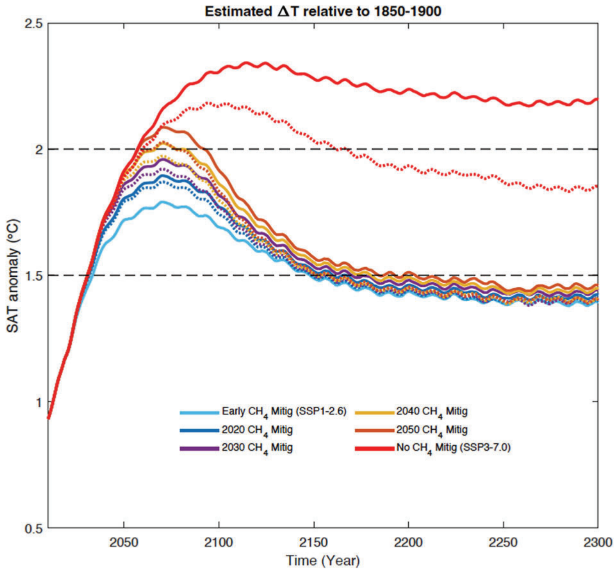

Fig. 3 Projected changes in air temperature relative to the pre-industrial era under the mitigation scenarios explored in this study. Changes are shown for global mean surface air temperature (SAT) relative to 1850–1900 for different initiation of CH_4 mitigation under the assumption that non-CH_4 forcing agents evolve according to SSP1-2.6. An estimate of 0.97 °C is considered for the global warming level in the 2006-2015 decade relative to the 1850–1900 period[29]. The variability in the SAT curves is associated with the solar cycle. Given that the observed historical warming level for the 2006-2015 decade relative to the 1850–1900 period is associated with an uncertainty of ±0.12 °C[29], we provide a version of this figure with the uncertainty range in the supplementary information (Supplementary Fig. 5). The dashed lines correspond to model simulations with prescribed CO_2 concentration from the Early CH_4 Mitig (SSP1-2.6) scenario, which imply climate projections without the carbon-climate feedback. The difference between dashed and continuous lines of the same color illustrates the magnitude of the carbon-climate feedback.

emissions between early and delayed CH_4 mitigation scenarios do not exceed 1 Tg CH_4 yr^{-1} for more than two centuries (Fig. 2a), which translates into a negligible fraction of [CH_4] and SAT differences between these mitigation scenarios. We conclude that the importance of the feedback between wetland CH_4 emissions and climate change is small under the low CO_2 emission scenarios explored in this study.

Timing of CH_4 mitigation and stringent warming limits. Determining the historical warming level is a critical aspect for assessing the implications of future climate projections on global warming limits in the Paris Agreement[27,28]. Our model simulates a global warming level of 1.1 °C for the 2006-2015 decade relative to the 1850–1900 period, whereas the recent Sixth Assessment Report (AR6) by the IPCC provides an estimate of 0.97 °C for the global warming level over the same decade relative to the same baseline period[29]. Hence, for this study, we adopt the above IPCC estimate to project future global warming levels associated with different scenarios of CH_4 mitigation (Fig. 3).

According to our model simulations, the 2 °C temperature goal can be achieved through rapid and deep cuts in anthropogenic CH_4 emissions along with stringent CO_2 mitigation. Our results suggest that global warming relative to the pre-industrial period (1850–1900) could be limited to well below 2 °C throughout the 21st century if global-scale CH_4 mitigation is initiated before 2030 while all other anthropogenic emissions evolve according to SSP1-2.6 (Fig. 3). However, if CH_4 mitigation is delayed to 2040, our results suggest that the 2 °C warming target will be overshot for at least two decades in the 21st century (Fig. 3), with longer mitigation delays implying longer overshoot periods of the 2 °C threshold. As expected with SSP1-2.6, all our considered CH_4 mitigation scenarios imply a breaching of the 1.5 °C limit relative to the 1850–1900 levels (Fig. 3).

Timing of CH_4 mitigation and its implications beyond the 21st century. The timing of CH_4 mitigation over the next three decades has implications beyond the 21st century. While anthropogenic CH_4 emissions prescribed to our model converge by the year 2100 for all considered scenarios other than SSP3-7.0 (Fig. 1), atmospheric [CH_4] levels for delayed and early CH_4 mitigation scenarios converge in the first half of the 22nd century (Fig. 2b). However, SAT differences between our mitigation scenarios persist for more than two centuries in the future (Fig. 2d), owing partly to the carbon-climate feedback (Fig. 2c and Fig. 3) as well as inertia in the climate system. These results suggest that, although CH_4 stays in the atmosphere for only about a decade, delaying CH_4 mitigation by 10–30 years will have an impact on global warming over many centuries.

The timing of CH_4 mitigation has long-term implications for achieving the temperature goals in the Paris Agreement. When implemented alongside CO_2 mitigation, rapid and deep reductions in CH_4 emissions will provide long-term benefits with regards to lowering global warming levels. According to our model simulations, initiating CH_4 mitigation before 2050 will increase the likelihood of limiting global warming to 1.5 °C in the long run—from the second half of the 22nd century onwards, after an overshoot in the first half of the 21st century (Fig. 3). However, even under the assumption of net-zero CO_2 emissions by mid-century, an eventual failure to mitigate CH_4 in the current century will raise global warming to >2 °C above pre-industrial levels throughout the 21st century and beyond (Fig. 3). We conclude that rapid CH_4 mitigation efforts will provide a long-term safeguard for the temperature goals in the Paris Agreement, whereas a failure to mitigate CH_4 within the next few decades will constitute a serious challenge for achieving the 2 °C warming limit.

Discussion

Previous studies have demonstrated that deep reductions in CH_4 emissions alongside stringent CO_2 mitigation by mid-century are needed to limit global warming to below 2 °C above pre-industrial levels, in agreement with our results[18,19,30,31]. Our study presents two additional findings: (i) the importance of biogeochemical feedbacks in the context of CH_4 mitigation to achieve stringent temperature limits, and (ii) long-term climate impacts of a delay or failure to mitigate CH_4 in the current century. Our study shows that the carbon-climate feedback amplifies the SAT response for delayed versus early CH_4 mitigation. In particular, our results suggest that the strength of the carbon-climate feedback increases for every 10-year delay in CH_4 mitigation (Fig. 3). The simulated contribution from the carbon-climate feedback to the peak warming ranges from ~0.03 °C to ~0.06 °C for CH_4 mitigation initiated in 2020 and 2050, respectively. Given that the UVic ESCM has a relatively high carbon-climate feedback parameter compared to most other ESMs[32] and a TCRE (transient climate response to cumulative emissions) value close to the CMIP6 ensemble mean[14,21], we infer that our estimated warming from the carbon-climate feedback lies in the upper 50-percentile of what the CMIP6 ESM ensemble would simulate in the context of this study. With regards to climate-CH_4 feedbacks, our model simulations suggest a negligible contribution from wetland CH_4 emissions to temperature change for every 10-year delay CH_4

mitigation in a low CO_2 emission scenario. However, we do not rule out the potential for a strong climate-CH_4 feedback involving wetlands, wildfires, and atmospheric CH_4 oxidation[15]—which would imply a potential underestimation of the contribution from the climate-CH_4 feedback to the additional peak warming under delayed CH_4 mitigation.

Despite that CH_4 stays in the atmosphere for only about 10 years, delaying CH_4 mitigation by 2-3 decades will have an impact on global warming over many centuries (Fig. 2d and Fig. 3). Such a delayed CH_4 mitigation may result in other long-term impacts such as a persistent sea-level rise over many centuries[33]. On the contrary, early CH_4 mitigation reduces the risk of losing the summer sea-ice across the Arctic Ocean[34]. A failure to mitigate CH_4 in the current century implies a high risk for global warming to exceed the 2 °C warming limit for more than two centuries even under net-zero CO_2 emissions by 2050 (Fig. 3). Such an overshoot of the 2 °C threshold has the potential to increase the risk for record-breaking climate extremes[35] and tipping elements in the Earth's climate system such as the dieback of the Amazon rainforest as well as the melting of the Greenland and West Antarctic Ice Sheets[36].

While mitigation research and efforts generally focus on achieving net-zero CO_2 emissions by 2050[12,19], it is becoming more clear that rapid reductions of both CO_2 and CH_4 emissions are crucial for holding global warming to well below 2 °C above pre-industrial levels[37]. To pave the way for CH_4 mitigation in the context of meeting the temperature goals in the Paris Agreement, there is a growing number of studies on: (i) understanding processes and reasons behind changes in [CH_4] trends in recent decades[2,5], (ii) constraining the global CH_4 budget[2,38], and (iii) developing strategies for reducing anthropogenic CH_4 emissions[39] as well as technologies for atmospheric CH_4 removal[40]. Research suggests that many anthropogenic sources of CH_4 can be reduced cost-efficiently[19,25,39,41], and that the priority for deep emission cuts should be in the energy, industry and transport sectors without neglecting the high potential from the waste and agricultural sectors[6,7,19,30,31,39]. If deployed rapidly, readily available measures for large-scale CH_4 mitigation by sector can contribute to slowdown global warming[18]. In addition to the Global Methane Pledge by >100 countries representing 70% of the global economy[13], multilateral partnerships already exist to support large-scale CH_4 mitigation (e.g. the Climate and Clean Air Coalition as well as the Global Methane Initiative[42–45]). Given that atmospheric CH_4 is a precursor to ground-level ozone (O_3)—an air pollutant with negative impacts on human health and crop yields, CH_4 mitigation offers the opportunity of simultaneously tackling climate change and improving air quality, global health, as well as food security[17,46,47].

Limitations of this study include uncertainties in the areal extent and dynamics of natural wetlands, as well as in the wide array of physical, biological, and chemical controls on CH_4 production and oxidation which determine the response of wetland CH_4 emissions to climate change[48]. Despite its simplicity, our wetland CH_4 model is capable of reproducing present-day wetland CH_4 emissions based on soil moisture, carbon, and temperature simulated by the UVic ESCM[22] (Supplementary Table 2). Additional limitations of this study are associated with: (i) static CH_4 emissions from non-wetland natural sources, and (ii) a constant lifetime for atmospheric CH_4 as part of the parameterization for atmospheric CH_4 decay. Natural CH_4 emissions from non-wetland sources (such as termites, lakes, wildfires, geologic seeps, marine hydrates) are not represented in the UVic ESCM and are held fixed in our model simulations (See Methods). Processes governing the future evolution of these natural CH_4 sources are poorly understood[2,49].

The consideration of a constant lifetime for atmospheric CH_4 is a simplified assumption made in this study as part of initial steps to represent the atmospheric CH_4 decay and the global CH_4 cycle in the UVic ESCM (See Methods and Supplementary Note 5). In reality, the atmospheric CH_4 lifetime varies by a few months to a few years mostly due to changes in atmospheric chemistry associated with CH_4 sinks[50], and this variation in the CH_4 lifetime has been invoked to explain past changes in the growth rates of atmospheric CH_4 levels[3,50]. Variations in the atmospheric CH_4 lifetime are mainly regulated by a chemical feedback involving the oxidation of CH_4 by the OH radical[3,50], a process not simulated by our model. This feedback mechanism is such that increasing [CH_4] (e.g. under delayed CH_4 mitigation) reduces the abundance of the OH radical, which further increases [CH_4] and raises the global warming level. Therefore, one consequence of our assumption of a constant lifetime for atmospheric CH_4 is a potential underestimation of the [CH_4] peak in delayed mitigation scenarios. However, our main result that delaying CH_4 mitigation increases the risk of breaching the 2 °C warming limit is not considerably affected by the use of different values for the atmospheric CH_4 lifetime in the range of published estimates (i.e. 7–11 years)[2] (Supplementary Fig. 4).

By design, this study makes a fundamental assumption with regards to future emission scenarios: effective mitigation of CO_2, other non-CH_4 greenhouse gases (GHGs), as well as aerosols, except for CH_4. This assumption is such that future emissions of non-CH_4 GHGs (including CO_2) and aerosols decline by mid-century according to a scenario consistent with limiting global warming to 2 °C by 2100 (i.e. SSP1-2.6), while anthropogenic CH_4 emissions continue to increase throughout the next three decades and beyond (i.e. SSP3-7.0). While we acknowledge the importance of aerosols and other non-CO_2 forcing agents in the context of climate mitigation to achieve the temperature goals in the Paris Agreement[16,51], our future scenarios focus on CH_4 mitigation to investigate recent concerns raised about sustained [CH_4] growth since 2007 and the associated potential challenge for achieving the 2 °C warming limit even under stringent CO_2 mitigation by mid-century[5,38].

Our study suggests that aggressive reductions of anthropogenic CO_2 emissions without CH_4 mitigation could push the Earth system beyond the 2 °C warming limit above pre-industrial levels for more than two centuries in the future. Initiating large-scale CH_4 mitigation in the current decade, along with stringent CO_2 mitigation, can allow to achieve the temperature goals in the Paris Agreement. However, delaying CH_4 mitigation to the next decade or beyond will increase the risk of breaching the 2 °C warming limit. According to our model simulations, every 10-year delay in CH_4 mitigation will result in an additional peak warming of about 0.1 °C. Consequences of such an increased peak warming over time and breaching the 2 °C warming limit are widespread, including an increased risk for an Arctic Ocean without sea ice in the summer[34], record-breaking climate extremes[35], the dieback of the Amazon rainforest[36], the disintegration of major ice sheets[36], persistent sea-level rise over multiple centuries[33], and several other global and regional impacts of increasing global warming levels on natural and socio-economic systems[52,53]. Considering that [CH_4] has been rising steadily since 2007 in line with unmitigated emission scenarios[5,6], we highlight the importance of immediate cuts in anthropogenic CH_4 emissions globally, along with stringent CO_2 mitigation, in order to increase the likelihood of keeping global warming to well below 2 °C above pre-industrial levels. Actions associated with the Global Methane Pledge[13] launched at COP26 in November 2021 should not be delayed, because every year of delayed CH_4 mitigation implies additional global warming.

Methods

Model description. We use the University of Victoria Earth System Climate (UVic ESCM) for our simulations. The UVic ESCM consists of a 2-D (vertically-integrated) energy-moisture balance model for the atmosphere coupled to a comprehensive 3-D ocean general circulation model (OGCM) with marine biogeochemistry, a thermodynamic sea ice model, and a land surface model with dynamic vegetation as well terrestrial carbon fluxes (in the form of CO_2)[54,55]. In this study, we use a version of the EMIC based on UVic ESCM 2.10[21] which features a multi-layer ground structure (i.e. 14 ground layers of unequal thicknesses extending down to a depth of 250 m) that is capable of simulating permafrost freeze-thaw processes as well as permafrost CO_2 fluxes (i.e. CO_2 release and uptake)[56]. Furthermore, the version of the UVic ESCM used in this study simulates the spatial and temporal dynamics of wetlands[57]. In particular, sub-grid scale wetlands are identified in the EMIC following a TOPMODEL approach for global models[58]. The areal extent of wetlands varies in response to changes in soil hydrology (soil moisture content, runoff, surface inundation, etc.), which is affected by changes in precipitation, evapo-transpiration, temperature, vegetation—among many other atmospheric and terrestrial processes. In this study, we use a modified version of UVic ESCM 2.10 into which we incorporated a simplified representation of the global CH_4 cycle (See next sections).

Wetland CH_4 emissions. Wetland CH_4 emissions are simulated in the UVic ESCM following a recent model development[22]. Wetland CH_4 emissions are calculated as the balance between microbial production and oxidation of CH_4 in the soil column. CH_4 production is calculated in each soil layer as a function of moisture content, carbon content, temperature, and the relative depth from the soil surface. In this approach, soil moisture (i.e. water saturation) represents potential anoxic conditions. Soil carbon represents organic matter that may be accessed by methanogens. Soil temperature allows to estimate potential changes in methanogenic activity, whereas the relative depth from the soil surface allows to represent the net effect of depth-dependent controls on CH_4 production that are unresolved by the UVic ESCM (e.g. the quality of organic matter and the distribution of methanogens in the soil). CH_4 production is assumed to not take place in dry soil layers (i.e soil layers unsaturated with water) as well as in frozen soil layers. CH_4 oxidation is calculated for the entire soil column as a fraction of the amount of CH_4 produced in the soil column. The oxidized CH_4 fraction is determined based on an estimated oxic zone depth, which represents the prevalence of methanotrophs in the soil. This fraction increases as the oxic zone deepens. By design, our model simulates wetland CH_4 emissions associated with CH_4 production across the globe (including CH_4 emissions from previously frozen soil carbon upon permafrost thaw)[22].

Atmospheric CH_4 and associated radiative forcing. A simple one-box model is used to simulate the evolution of the atmospheric CH_4 burden (B) with time as the balance between total CH_4 emissions (E) and total CH_4 sinks (S). The box model is defined as $\frac{\mathrm{dB}}{\mathrm{dt}} = (\mathrm{E} - \mathrm{S})$, where $\mathrm{E} = \mathrm{E}_a + \mathrm{E}_w + \mathrm{E}_n$ represents the sum of prescribed anthropogenic CH_4 emissions (E_a), simulated wetland CH_4 emissions (E_w), as well as natural CH_4 emissions from non-wetland sources (E_n) such as termites, wild ruminants, wildfires, lakes, rivers, geologic seeps, and marine hydrates. Given that the UVic ESCM does not incorporate these non-wetland natural sources and in the absence of dataset for CH_4 emissions from these sources, we assume that non-wetland natural CH_4 emissions remain constant in time at 45 Tg C yr^{-1} (equivalent to 60 Tg CH_4 yr^{-1}). This value is in the range of estimated total CH_4 emissions from non-wetland natural sources over the last four decades[2,3] as well as pre-industrial periods[59]. Sinks of atmospheric CH_4 are aggregated into a single term (S) calculated as $\mathrm{S} = \mathrm{B}\,(1 - \exp(-\frac{1}{\tau_{\mathrm{CH4}}}))$, where τ_{CH4} is the atmospheric CH_4 lifetime assumed to be 9.3 years[2]. Similar estimates for the atmospheric CH_4 lifetime have been reported for the pre-industrial era (9.5 ± 1.3 years) and present-day (9.1 ± 0.9 years)[60]. At each time step, [CH_4] is determined based on the atmospheric CH_4 burden (B) by using a factor equivalent to ~2.8 Tg CH_4/ppb. Radiative forcing associated with changes in [CH_4] is calculated using the formulation in ref. [61] and is accounted separately from the aggregated forcing of other non-CO_2 GHGs that is prescribed to the UVic ESCM in its standard configuration[21].

Non-CH_4 radiative forcing agents. To drive the UVic ESCM over the 1850–2300 period (1850–2014 for the historical simulation and 2015-2300 for future projections), we use CMIP6 data for non-CH_4 natural and anthropogenic radiative forcing agents[23,62–64]. For natural forcing agents (volcanic and solar), we use volcanic radiative forcing anomalies spanning the historical period (1850–2014)[64] and solar constant data prescribed to 2300[63]. For anthropogenic forcing agents, we (i) use CMIP6 data for the historical simulation, and (ii) assume that all non-CH_4 GHGs (including CO_2) as well as aerosols evolve according to a scenario consistent with limiting global warming to 2 °C throughout the future (i.e. SSP1-2.6). Specifically, we prescribe CO_2 emissions from fossil fuels as defined in the SSP1-2.6 scenario and their long-term extension[23,24]. The SSP1-2.6 scenario features strong reductions in CO_2 emissions as well as negative CO_2 emissions (i.e. artificial removal of atmospheric CO_2) in the second half of the 21st century[65]. Furthermore, we prescribe gridded land-use change (LUC) data according to SSP1-2.6[66] and the UVic ESCM internally calculates corresponding LUC CO_2 emissions. The radiative forcing of CO_2 is calculated within the UVic ESCM following the formulation from ref. [61]. Radiative forcing values of other non-CH_4 GHGs are calculated externally using concentration data and their extension[23], which are then summed up into an aggregated forcing that is prescribed to the UVic ESCM. For anthropogenic sulfate aerosols, we prescribe SSP1-2.6 gridded aerosol optical depth (AOD) data to the UVic ESCM[67,68] and the model uses this data to internally calculate the associated radiative forcing. While forcing data for CO_2 and other non-CH_4 GHGs extend to 2300[23], forcing data for LUC and sulfate aerosols are prescribed to 2100 and their radiative forcing are held fixed at their 2100 values in our climate simulations.

Reporting summary. Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The model outputs analyzed in this study are archived at https://doi.org/10.20383/102.0748[69].

Code availability

The code for the University of Victoria Earth System Climate Model (UVic ESCM) used in this study is available at https://doi.org/10.5281/zenodo.7999745[70].

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Author contributions

C.-M.N. conceived the study and designed the model experiments, with contributions from K.Z.. C.-M.N. implemented the representation of the global CH_4 cycle in the UVic ESCM, with contributions from AJM on the atmospheric CH_4 module. C.-M.N. performed the model simulations, model validation, as well as the analysis and interpretation of results. K.Z. contributed to the interpretation of results. C.-M.N. wrote the manuscript and all authors provided critical feedback that helped shape its final version.

Competing interests

The authors declare no competing interests.

Additional information

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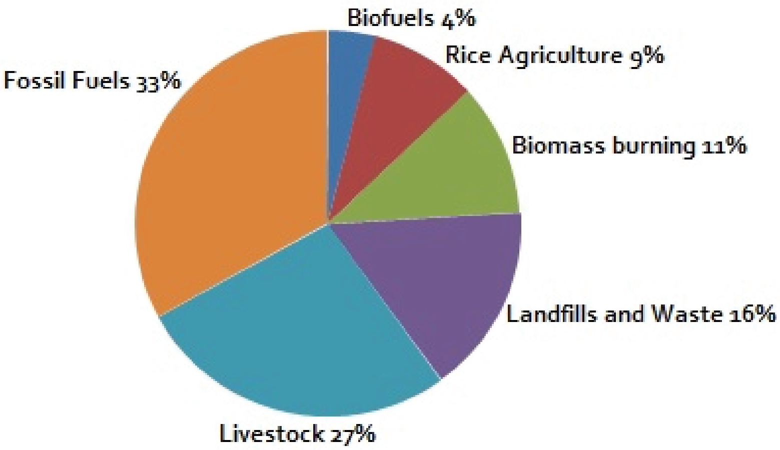
The Challenge

Methane is a powerful greenhouses gas with a 100-year global warming potential 28-34 times that of CO2. Measured over a 20-year period, that ratio grows to 84-86 times.

About 60% of global methane emissions are due to human activities. The main sources of anthropogenic methane emissions are the oil and gas industries, agriculture (including fermentation, manure management, and rice cultivation), landfills, wastewater treatment, and emissions from coal mines. Fossil fuel production, distribution and use are estimated to emit 110 million tonnes of methane annually.



Methane is the primary component of natural gas, with some emitted to the atmosphere during its production, processing, storage, transmission, distribution, and use. It is estimated that around 3% of total worldwide natural gas production is lost annually to venting, leakage, and flaring, resulting in substantial economic and environmental costs.

Coal is another important source of methane emissions (/node/33). Coal mining related activities (extraction, crushing, distribution, etc.) release some of the methane trapped around and within the rock. Methane is emitted from active underground and surface mines as well as from abandoned mines and undeveloped coal seams.

The geological formation of oil can also create large methane deposits that get released during drilling and extraction. The production, refinement, transportation and storage of oil are all sources of methane emissions, as is incomplete combustion of fossil fuels. No combustion process is perfectly efficient, so when fossil fuels are used to generate electricity, heat, or power vehicles these all contribute as sources of methane emissions.

On a global scale, methane emissions from oil and natural gas systems account for 1,680 MtCO2e. The estimates are considered to be uncertain and are thought to be low.

Based on the best currently available data, around 3.6 trillion cubic feet (Tcf) (or 102 billion cubic meters (bcm)) of natural gas escaped into the atmosphere in 2012 from global oil and gas operations. This wasted gas translates into roughly U.S. $30 billion of lost revenue at average 2012 delivered prices, and representes about 3% of global natural gas production.

Emissions are expected to grow under a central growth scenario by 23% between 2012 and 2030.

Regarding the global reduction potential by 2030, it is estimated that emissions could be reduced by 26% using existing technology (equal to 1,219 MtCO2e).

Despite methane’s short residence time, the fact that it has a much higher warming potential than CO2 and that its atmospheric volumes are continuously replenished make effective methane management a potentially important element in countries’ climate change mitigation strategies. As of today, however, there is neither a common technological approach to monitoring and recording methane emissions, nor a standard method for reporting them.
