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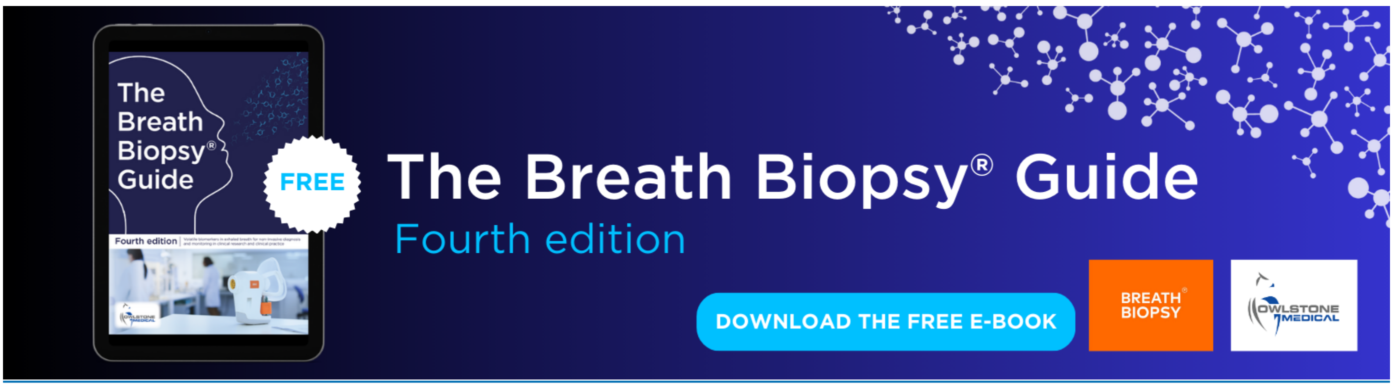

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Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming

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Abstract

Methane mitigation is essential for addressing climate change, but the value of rapidly implementing available mitigation measures is not well understood. In this paper, we analyze the climate benefits of fast action to reduce methane emissions as compared to slower and delayed mitigation timelines. We find that the scale up and deployment of greatly underutilized but available mitigation measures will have significant near-term temperature benefits beyond that from slow or delayed action. Overall, strategies exist to cut global methane emissions from human activities in half within the next ten years and half of these strategies currently incur no net cost. Pursuing all mitigation measures now could slow the global-mean rate of near-term decadal warming by around 30%, avoid a quarter of a degree centigrade of additional global-mean warming by midcentury, and set ourselves on a path to avoid more than half a degree centigrade by end of century. On the other hand, slow implementation of these measures may result in an additional tenth of a degree of global-mean warming by midcentury and 5% faster warming rate (relative to fast action), and waiting to pursue these measures until midcentury may result in an additional two tenths of a degree centigrade by midcentury and 15% faster warming rate (relative to fast action). Slow or delayed methane action is viewed by many as reasonable given that current and on-the-horizon climate policies heavily emphasize actions that benefit the climate in the long-term, such as decarbonization and reaching net-zero emissions, whereas methane emitted over the next couple of decades will play a limited role in long-term warming. However, given that fast methane action can considerably limit climate damages in the near-term, it is urgent to scale up efforts and take advantage of this achievable and affordable opportunity as we simultaneously reduce carbon dioxide emissions.

1. Introduction

Methane is a major contributor to climate change and plays a dominating role in how fast the climate warms (Myhre *et al* 2013). However, although myriad mitigation strategies have been identified over the last decade (e.g. EPA 2013), uptake remains slow and global emissions continue to rise (Saunois *et al* 2020). Given that climate policies are mostly oriented around long-term climate stability goals (IPCC 2018) and use climate metrics that undervalue methane's role in the near-term (Ocko *et al* 2017), there is less urgency to reduce methane now at the extent warranted. Here we demonstrate the value of fast action to deploy readily available methane mitigation measures as opposed to slow and delayed action, with a key focus on sectoral roles. We have a powerful opportunity to slow down the rate of warming and limit temperature rise by midcentury if we act now, which would provide considerable benefits to society and ecosystems.

The prominent and growing role of methane emissions in present and future climate change is increasingly understood—methane contributes to at least a quarter of today's gross warming (Myhre *et al* 2013, Ocko *et al* 2018), its concentration continues to rise rapidly in large part from anthropogenic sources (Schwietzke *et al* 2016, Fletcher and Schaefer 2019, Nisbet *et al* 2019, Hmiel *et al* 2020, Jackson *et al* 2020, Saunois *et al* 2020), and several studies have shown the outsized value of its mitigation in limiting warming over the next few decades due to its short atmospheric lifetime (Shindell *et al* 2012, Shoemaker *et al* 2013, Collins *et al* 2018, Smith *et al* 2020). These insights have led to the development of innovative technologies and strategies to reduce methane emissions from all major emitting sectors—such as the straightforward plugging of natural gas leaks (IEA 2017) to ruminant feed supplements (Hristov *et al* 2015)—and the resulting abatement potentials for readily available measures have been characterized (EPA 2013, 2019, IEA 2017, Harmsen *et al* 2019, 2020, Höglund-Isaksson *et al* 2020, Arndt *et al* 2021).

Given methane's short-lived presence in the atmosphere, deployment of these mitigation measures would have a near-immediate impact on slowing down the rate of warming. However, current government and company climate policies are focused on addressing long-term climate stability in particular (such as via net zero targets), which inadvertently imply that methane mitigation can wait until midcentury due to its short lifetime (IPCC 2018). Further, these policies use the traditional climate metrics Global Warming Potential and its Carbon Dioxide Equivalence counterpart, with a 100 year time horizon that undervalues the role of short-lived climate pollutants—such as methane—in driving near-term and rate of warming (Ocko *et al* 2017). While there is vast scientific consensus that severely limiting total global warming over the next century is essential to preventing profound damages to life on Earth, many risks to society and ecosystems arise from the rate of warming, and the ability to adapt to anticipated changes is greatly diminished by a quicker pace (IPCC 2018).

Therefore, while it is essential to minimize warming over the coming decades in addition to the long-term, we are currently on a path that supports either slow or delayed action on methane despite numerous readily available and affordable mitigation measures for each major-emitting sector (e.g. Höglund-Isaksson *et al* 2020). It is therefore possible that we are situated to miss an unmatched opportunity to slow down the rate of warming and its concomitant damages immediately (McKenna *et al* 2021).

Several studies to date analyze the climate benefits of methane mitigation (Shindell *et al* 2012, Hu *et al* 2013, Shoemaker *et al* 2013, Rogelj *et al* 2015, Stohl *et al* 2015, Collins *et al* 2018, Harmsen *et al* 2020, Lund *et al* 2020, Smith *et al* 2020). These studies cover a range of mitigation assumptions and timelines; employ different methodologies for determining climate impacts (from simple metrics to reduced complexity models to earth system models); contain varying scopes of temporal, spatial, and sectoral breakdowns; and assess different climate impact variables (mostly radiative forcing and temperature but also precipitation and sea level rise). Studies find that mitigation of methane can slow down the rate of warming and sea level rise (e.g. Hu *et al* 2013, Shoemaker *et al* 2013), lower midcentury warming (e.g. Shindell *et al* 2012, Smith *et al* 2020), and is essential to achieving long-term temperature targets (e.g. Collins *et al* 2018, IPCC 2018). Studies also show that direct methane mitigation measures are more effective at reducing emissions than reductions as a result of ambitious carbon dioxide mitigation (Harmsen *et al* 2020), and that stringent methane mitigation can allow for higher carbon dioxide budgets for a specific temperature target (Rogelj *et al* 2015).

Despite the range of methane mitigation timelines and magnitudes analyzed in previous studies, the benefits of rapidly deploying available mitigation measures compared to gradual or delayed actions remain unclear. Here, we synthesize the latest assessments on readily available opportunities to reduce methane emissions from agriculture, energy systems, and waste management, and evaluate the climate benefits of their deployment over different timelines by using a well-known reduced-complexity climate model. We divide methane mitigation measures into two categories: those that can be pursued now at no net cost even in the absence of carbon pricing (herein referred to as 'economically feasible' actions), and those that can be pursued now based on all existing technologies and strategies (herein referred to as 'technically feasible' actions). We evaluate the climate benefits over all timescales—both in the near- and long-term—for three implementation timelines: fast, slow, and delayed action. We present our results for aggregate methane emissions and also by individual sector, to show how sector-based mitigation contributes to the climate benefits.

By connecting existing sector-specific methane abatement measures to tangible near-term temperature benefits, we aim to mobilize the political and corporate will to accelerate and scale up deployment of these already available but greatly underutilized mitigation opportunities, and as a result, reduce climate damages well before midcentury. We emphasize that methane mitigation is not intended to replace the unequivocal need to urgently act to reduce carbon dioxide emissions, but rather is a complementary approach that can add critical near-term benefits not otherwise achievable.

2. Methods

2.1. Emissions scenarios

We develop three sets of future methane emissions: a baseline scenario representing no further climate action, and two scenarios for methane mitigation that represent a range of potential ambition from minimum to maximum action based on current cost assessments and available technologies. We consider three implementation timelines for both sets of mitigation scenarios: one with fast action beginning in 2020 with full deployment by 2030; one with slow action beginning in 2020 with full deployment by 2050; and one with delayed action beginning in 2040 with full deployment by 2050.

2.1.1. Baseline projections

Several previous assessments have developed global methane emissions projections for future baseline scenarios (e.g. Riahi *et al* 2007, 2017, JRC 2019, 2020, Harmsen *et al* 2019, 2020, EPA 2019, Höglund-Isaksson *et al* 2020). There is a widespread range of socioeconomic and technological assumptions embedded in these projections, as well as different regional, sectoral, and temporal coverage. Emissions range from 332 to 439 million metric tonnes (MMt) in 2020, 398 to 677 MMt in 2050, and 460 to 888 MMt in 2100.

For this analysis, we use the baseline methane emissions scenario developed by Höglund-Isaksson *et al* (2020). This is because of the availability of sector and subsector information, incorporation of the latest science and data (such as oil and gas estimates), and emissions that are in the middle of the range of available projections (2020: 351 MMt and 2050: 447 MMt). Höglund-Isaksson *et al* (2020) uses the integrated assessment modelling framework, GAINSv4, to estimate methane emissions through 2050 with a bottom-up sectoral approach informed by numerous resources. Baseline emissions consider effects from regulations and legislation adopted as of December 2018, with no further climate action beyond these measures. Extrapolation of baseline emissions trends through 2100 provides reasonable estimates when compared to other baseline scenarios that have projections throughout the end of the century (i.e. Riahi *et al* 2007, 2017, JRC 2019, Climate Watch 2021), and yields a total amount of 611 MMt of methane emitted in 2100. See supplemental material for data and comparisons with other assessments for total emissions and by sector (figure S1 (available online at stacks.iop.org/ERL/16/054042/mmedia)).

For baseline emissions of non-methane climate forcers, which are particularly important for analysing changes in the rate of warming, we use the most commonly employed RCP8.5 scenario. While some have argued that this is an unrealistic baseline (e.g. Hausfather and Peters 2020), others assert that RCP8.5 is particularly well-suited for emissions out to midcentury and not unreasonable for late century (Schwalm *et al* 2020). Given that this work is focused on the midcentury timeline and that the majority of our analysis is for methane impacts only (of which the magnitude of methane baseline or avoided warming is insensitive to the selection of a non-methane baseline—see supplemental material for more details), RCP8.5 is suitable for our purposes.

2.1.2. Abatement potentials

We consider two levels of methane mitigation that encompass a range of realistic methane actions. As a lower bound, we consider only actions that can be achieved at no net cost, without a price on carbon or methane; for actions that capture methane, the value of the captured methane is included in the cost assessment. The only exception is the inclusion of commitments made by oil and gas companies, which we consider as cost-effective in that companies have determined that these measures fit within their business models in the existing economic framework. We refer to this lower bound mitigation case as 'economically feasible.' As an upper bound, we consider the other end of the spectrum: the most optimistic case conceivable for methane abatement within the next ten years given existing technologies, practices, and structural changes that are either readily available for deployment or require at most minor improvements. However, we do not include consideration of more radical policy proposals (such as phase-out of methane pipelines or combustion) and changes in dietary behaviour (such as global veganism) as the achievability of these measures is much less realistic than implementation of technological strategies. We refer to this upper bound mitigation case as 'technically feasible,' and it inherently includes the economically feasible actions as well.

We surveyed the literature to identify economically and technically feasible abatement potentials for the six major emitting sectors that represent 90% of current emissions (livestock, rice production, the oil and gas supply chain, coal mining, landfills, and wastewater treatment; figure 1). Given that the relative abatement potentials of specific mitigation measures within each sector (such as an individual technology or action) will depend on a range of scientific and non-scientific characteristics that are regionally dependent (Höglund-Isaksson *et al* 2020), we restrict our analysis to assessing the relative climate benefits of total potential methane mitigation from

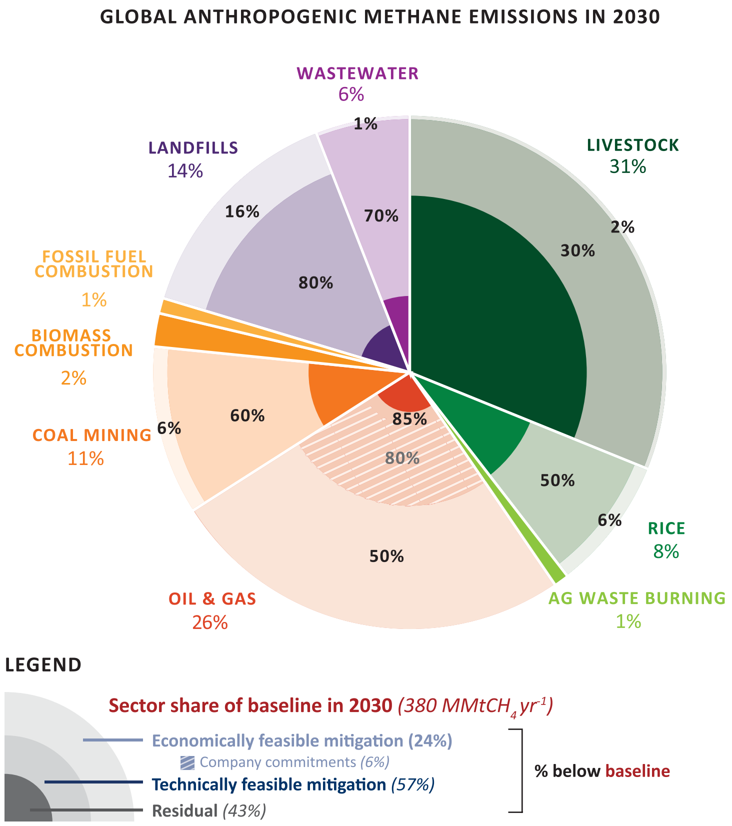

Figure 1. Global annual anthropogenic methane emissions abatement potentials in 2030 relative to baseline. Mitigation potentials are divided into two categories: economically feasible actions (no net cost based current cost assessments) and technically feasible actions (all available technologies); technically feasible includes economically feasible. Implementation of measures begin in 2020 with full deployment achieved by 2030. Sector percentages on the verge of the pie refer to share of total sector baseline emissions in 2030 assuming no further climate action. Sector percentages within the pie refer to economically and technically feasible abatement potentials as a percent below the baseline. In addition to no net cost options, we consider commitments made by oil and gas companies as 'economically feasible,' with the assumption that companies have found it fits into their business models. The contribution of company commitments to abatement potentials is shown in the line pattern. Note that more radical policy proposals or behavioural changes are not included here, which could increase mitigation levels. For example, human dietary changes could considerably reduce methane emissions from livestock at no cost. More information on data sources, assumptions, and explanations can be found in the supplemental material.

each major sector. However, we include a list of the most prominent mitigation measures within each sector that are considered in the literature (table 1) and discuss in more detail in the supplemental material.

For abatement potentials at no cost ('economically feasible'), we use marginal abatement cost curve assessments developed by four sources: IEA (2017), EPA (2019), Harmsen *et al* (2019), and Höglund-Isaksson *et al* (2020). Given that Harmsen *et al* (2019) includes advancements in technology over time, we only use their estimates of abatement potentials for 2020 emissions, whereas we use 2030 estimates for EPA (2019) and Höglund-Isaksson *et al* (2020).

Abatement potentials at no cost are averaged across EPA (2019), Harmsen *et al* (2019), and Höglund-Isaksson *et al* (2020) for rice (6%), coal mining (6%), landfills (16%), and wastewater (1%) (% represents how much can be abated below 2030 baseline). For livestock (2%), we average EPA (2019) and Höglund-Isaksson *et al* (2020) estimates given that these values are more conservative than the Harmsen *et al* (2019) outlier value of 22%. For oil and gas emissions, we supplement IEA (2017) no cost abatement potential of 45% below present-day emissions with oil and gas company commitments of limiting upstream natural gas leaks to 0.2% of total production levels. This yields an increase in the abatement potential from 50% below 2030 levels to 77%. More details regarding this calculation and its feasibility are provided in the supplemental material. Further, locked in capital makes several measures more expensive today than they may become in the future, and therefore we expect that several measures will become more cost effective over time. In addition, as the price of oil and gas fluctuates, the amount of emissions that can be reduced for no net cost from oil and gas measures will also fluctuate. We do not include changing cost effectiveness over time in our analysis.

For abatement potentials that cover all existing technological mitigation measures at any cost ('technically feasible'), we survey the scientific literature in addition to the above sources. We apply the most

Table 1. List of prominent methane mitigation measures for each sector that are specified in at least one assessment of marginal abatement cost curves and maximum technical abatement potentials.

	Example mitigation measures considered in abatement potentials (* indicates sometimes can be at no net cost)
Livestock	Methane inhibitors*, electron sinks*, oils and oilseeds*, intensive grazing*, improved feed conversion*, manure coverage and digester systems*, selective breeding; do not include changing human diet
Rice	Improved irrigation systems*, cropping techniques*, and fertilization levels* such as incorporation of rice straw compost before transplanting coupled with intermittent irrigation and use of alternative hybrids and soil amendment
Oil & Gas	Upstream leak detection and replacement*, replacing pumps*, replacing with instrument air systems*, vapour recovery units*, blowdown capture*, replace with electric motor, early replacement of devices, replace compressor seal or rod, install flares, install plunger, downstream leak detection and replacement
Coal mining	Pre-mining degasification*, coal drying*, flooding abandoned mines*, ventilation air methane oxidation with improved ventilation, open flaring,
Landfills	Electricity generation with reciprocating engine/gas turbine/CHP/microturbine and landfill gas recovery for direct use*, source separation with recycling or treatment with energy recovery for municipal, recycling or treatment with energy recovery for industrial; no landfills of organic waste
Wastewater	Open sewer to aerobic wastewater treatment plan*, domestic wastewater treatment is upgraded from primary treatment to secondary/tertiary anaerobic treatment with biogas recovery and utilization, industrial wastewater treatment is upgraded to two-stage treatment such as anaerobic with biogas recovery followed by aerobic treatment

optimistic abatement potentials by sector to global emissions, therefore representing a best-case scenario of potential reductions with all-in methane action. However, we note that there is large diversity in systems and practices across world regions and thus applying optimistic abatement potentials on a global scale has uncertainties. Further, we do not include political, social, and information barriers to implementing available technologies, that undoubtedly exist in many parts of the world. The reason for this approach is to provide information on the maximum climate benefits achievable from deployment of readily available measures.

For the livestock sector, we apply the upper end abatement potentials from a meta-analysis on methane mitigation strategies for livestock (30% below baseline; Arndt *et al* 2021). We use estimates from Höglund-Isaksson *et al* (2020) for rice (49%), coal mining (61%), landfills (80%), and wastewater (72%). While these potentials are identified for 2050, they do not reflect any major developments in technology beyond today, and for our upper end 'technically feasible' estimates, we do not consider the role of locked in capital. For oil and gas, we supplement the IEA (2017) abatement potential of 75% below current levels with voluntary company commitments of capping upstream leakage. This results in an 83% below 2030 level abatement potential rather than 77% without industry targets.

Overall, while the existing potential to reduce methane emissions varies considerably by sector and by mitigation level (figure 1), if deployed in parallel they can cut anticipated methane emissions in 2030 in half, with a quarter of total emissions reduced at no net cost.

2.1.3. Mitigation timelines

Abatement potentials are applied to baseline emissions throughout the century to develop two sets of methane mitigation scenarios: economically feasible and technically feasible paths. For each of these scenarios, we develop three implementation timelines that vary mitigation deployment between 2020 and 2050. After 2050, both sets of mitigation scenarios are identical amongst the three timelines.

To capture the climate benefits of an immediate effort to deploy available methane mitigation measures, we assume an early and rapid implementation plan with deployment beginning now and reaching maximum abatement potentials in 2030. This leads to an immediate drop in emissions from 2020 to 2030. However, because the majority of abatement potentials are defined as a reduction potential below a baseline, as populations grow and countries develop, emissions will continue to slowly rise even with sustained mitigation efforts. This is because demand for livestock, for example, will increase in the future, yet we hold the abatement potential (percent below baseline) constant throughout the end of the century (i.e. no further mitigation potential is tapped after 2030).

To compare the benefits to slower and delayed implementation plans, we also analyse implementation beginning in 2020 with linear ramp up reaching full potential by 2050 ('slow' mitigation), and implementation beginning in 2040 and reaching full potential by 2050 ('delayed' mitigation consistent with what is needed to achieve long-term temperature targets).

We compare our mitigation scenarios with existing literature in the supplemental material (figure S2). Overall, our pathways fall within the realm of previously developed scenarios. Comparing our technically feasible fast action scenario in particular shows that it is most similar to methane emissions developed by JRC GECO (2019, 2020) for paths consistent with 1.5 °C temperature targets, as well as a short-lived climate pollutant mitigation path developed using ECLIPSE (Stohl *et al* 2015). In the long-run, given that we keep mitigation levels at the same abatement potentials for each sector (and do not account for new technologies, etc), we find that our economically feasible scenarios lead to emissions that are higher in 2100 than all but one scenario (SSP4-60). Our technically feasible scenarios lead to emissions in 2100 that are in the middle of the range. Overall, most existing methane mitigation scenarios are characterized as having slow implementation of mitigation measures in the near-term.

2.2. Climate model

We employ a prominent and freely available reduced-complexity climate model, Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) version 6 (Meinshausen *et al* 2011), which has been used in several policy-oriented climate analyses involving short-lived climate pollutants (e.g. Shoemaker *et al* 2013, IEA 2017, Reisinger and Clark 2018, Smith *et al* 2020). MAGICC's ability to simulate temperature responses to methane emissions has been previously validated with a higher complexity climate model; Ocko *et al* (2018) performed a series of experiments to compare forcing and temperature responses to historical methane emissions in MAGICC to those from a more complex coupled global chemistry–climate model, GFDL-CM3. Overall forcings and temperature responses were comparable between the two models for both direct and indirect methane effects. Further confidence in MAGICC comes from decades of work improving model parameterizations (Meinshausen *et al* 2011) and comparisons of its performance within the context of other reduced complexity climate models (Nicholls *et al* 2020).

The major benefits of using a reduced-complexity climate model are ease of use with basic knowledge and limited computational infrastructure; rapid results for time-sensitive policy purposes; and the ability to analyse small forcing changes due to the absence of unforced internal variability. However, limitations exist, such as coarse spatial resolutions and parametrizations, and one common to all climate models, uncertainties based on the extent of our physical understanding of myriad systems.

MAGICC represents the coupled carbon-cycle climate system as a hemispherically averaged upwelling-diffusion ocean coupled to a four-box atmosphere and a globally averaged carbon cycle model (Meinshausen *et al* 2011). We use default model properties and inputs, but update methane-related properties based on the latest science; detailed information on model components, inputs, and parameters, as well as modifications for this analysis, can be found in the supplemental material. We run 50 distinct 335 year integrations from 1765 to 2100. For 11 integrations, we include a 190-member ensemble based on simulations run using different sets of atmospheric, oceanic, and carbon cycle parameters derived from 19 atmosphere-ocean global climate models and 10 carbon cycle models (Meinshausen *et al* 2011); equilibrium climate sensitivity (ECS) in the ensemble ranges from 1.9 °C to 5.73 °C, with a mean (median) of 2.88 °C (2.59 °C). In the default model properties, the ECS is 3 °C, and therefore single-run simulations have slightly higher temperature responses than ensemble means. A full list of experiments can be found in the supplemental material, and include baseline scenarios, mitigation pathways by sector and in parallel, as well as sensitivity tests and uncertainty assessments (such as how uncertainties in methane parameters including lifetime and oxidation effects impact our results). Unless otherwise noted, all uncertainty ranges reported herein refer to ±one standard deviation from the mean based on the 190-member ensemble.

3. Results

We analyze the anticipated temperature responses to baseline methane emissions in the absence of further climate action, and assess the benefits of implementation of available mitigation measures that could prevent a large fraction of methane from being emitted over different timelines. In the baseline case, methane emissions from human activities are expected to continue rising over the next few decades and throughout this century, yielding a potential increase in emissions by end of century of more than 70% relative to current levels, with emissions exceeding 600 MMt per year by 2100 compared to today's level around 375 MMt yr^{-1}. Three quarters of emissions are projected to come from the livestock, oil and gas, and landfill sectors—with similar emissions magnitudes projected for each.

Historical methane emissions contribute to around 0.5 °C (±0.1 °C) of present-day global-mean warming above preindustrial levels (1850–1900; figure 2), which is around half of carbon dioxide's contribution (0.9 ± 0.2 °C) and a quarter of the gross warming from all warming pollutants (1.85 ± 0.4 °C); note that cooling climate pollutants mask some of this warming in the net absolute global-mean temperature. With the expected rise in methane emissions over the next few decades, methane may contribute 0.6 °C (±0.1 °C) by 2050, which would account for more than 20% of the warming from all warming pollutants if non-methane forcers followed an RCP8.5 trajectory. By end of century, methane emissions in the absence of further climate action could contribute to around 0.9 °C (±0.2 °C)

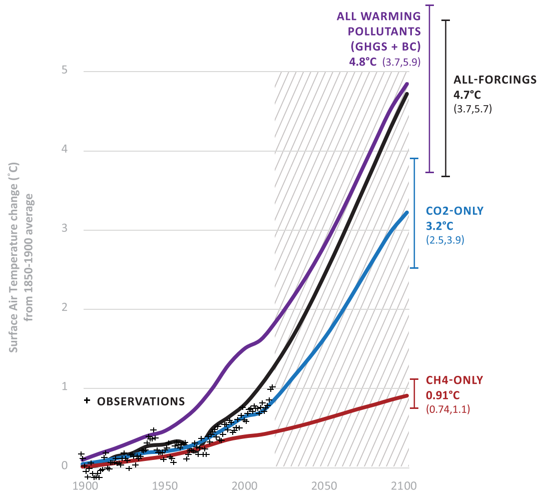

Figure 2. Global-mean surface air temperature change (°C relative to the 1850–1900 global-mean average) in response to historical and future (baseline) anthropogenic methane emissions, compared to temperature responses from all anthropogenic and natural forcings, all anthropogenic warming pollutant emissions (greenhouse gases and black carbon), and anthropogenic carbon dioxide emissions - for 'no further climate action' scenarios. Error bars show ±one standard deviation from the ensemble-mean based on a 190-member ensemble developed by combinations of climate and carbon cycle parameters based on 19 AOGCMs and 10 carbon cycle models, respectively. Future emissions of all non-methane climate pollutants are from RCP 8.5, and the methane-only temperature responses is insensitive to the non-methane climate pollutant emission scenario. Observations of temperature changes to date relative to 1880 global temperatures are shown in +markers and are taken from NOAA (2020) data.

of global-mean warming (figure 2). We note that this temperature response is insensitive to the non-methane baseline emissions assumptions (see supplemental material). Given that several methane baseline projections in the literature suggest even larger future methane emissions in the absence of further climate action, this level of warming could be even higher.

However, a survey of the literature suggests that rapid deployment of available abatement technologies and strategies by sector could cut anticipated global methane emissions in 2030 by 57% (figures 1 and 3(a)). Further, we could achieve a reduction of 24% below anticipated levels in 2030 through deployment of cost effective measures alone (figures 1 and 3(a)). Given methane's strong radiative efficiency yet short atmospheric lifetime (Myhre *et al* 2013), these actions to reduce methane emissions will have near-immediate effects in lowering global-mean temperatures.

We find that relative to global-mean average warming rates around 0.4 °C per decade from 2030 to 2050 in the absence of further climate action, fast action to pursue all economically feasible measures by 2030 could slow this rate of warming by 12% (±1%), and this benefit could double to 26% (24,30) with deployment of all technically feasible measures (figure 3(c)). This slower pace of global-mean warming means over a tenth of a degree (°C; ±0.01) may be avoided by midcentury from economically feasible actions with over a quarter of degree (°C; ±0.04) avoided from technically feasible mitigation measures (figures 3(b)–(c)).

However, many of these near-term benefits are missed if methane action is slow or delayed. For example, we could lose the opportunity to avoid an additional 0.2 °C of global-mean warming in 2050 if we delay methane mitigation until 2040 (figures 3(b)–(c)) and lose the chance to slow global-mean warming by nearly an additional 20%; this is an entirely feasible path given the current focus on net zero commitments for a 2050 timeframe. The rate of implementation also matters, because we miss some benefits even if we act early, but slowly. Beginning actions now but with full implementation only achieved by 2050, could yield 0.07 °C additional global-mean warming by 2050 and a greater than 5% increase in global-mean warming rate from 2030 to 2050 compared to early and rapid mitigation (figures 3(b)–(c)).

In the long-term, we find that sustaining economically feasible mitigation measures throughout the 21st century could avoid additional global-mean warming by nearly a quarter of a degree (°C; ±0.05) by 2100, whereas pursuing all technically feasible measures could avoid half a degree (°C; ±0.09) (figure 3(b)). This level of avoided warming is crucial for staying below the widely agreed upon global-mean temperature target of 2 °C above preindustrial levels.

While the different mitigation implementation timelines continue to play a role after 2050 in determining overall magnitudes and rates of global-mean warming from methane—even though the emissions pathways are identical post-2050 (figures 3(a) and (b))—the differences become smaller over time and generally merge by 2100. Therefore, if climate policy continues to focus on long-term time horizons, the powerful near-term climate benefits of fast methane

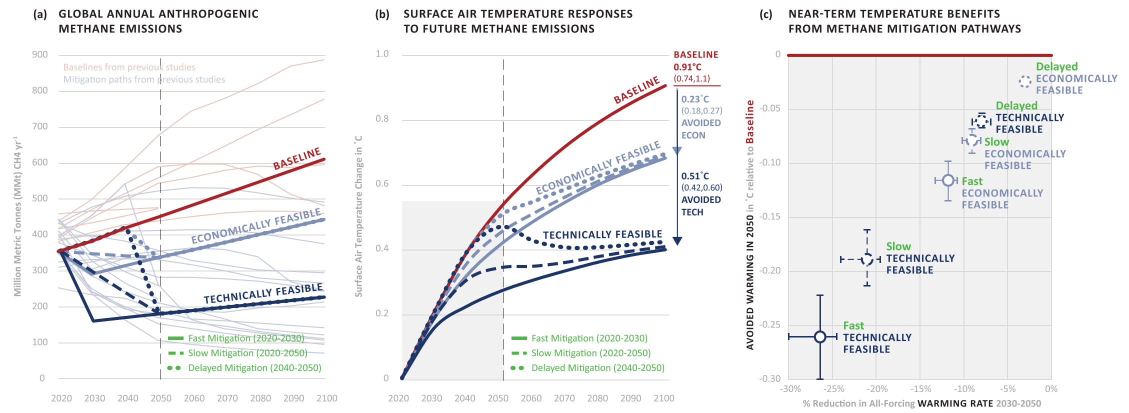

Figure 3. Global anthropogenic methane emissions and resulting temperature responses from 2020 through 2100 for baseline and mitigation scenarios. (a) Emissions for baseline (red) and mitigation (blue) scenarios for three implementation timelines: fast mitigation (solid blue lines), slow mitigation (dashed lines), and delayed mitigation (dotted lines). (b) Global-mean temperature responses (°C) attributed to future global anthropogenic methane emissions only based on a 190-member ensemble. (c) Near-term temperature benefits of mitigation actions in terms of avoided warming (°C) in 2050 and reduction in 2030–2050 decadal warming rate (%) relative to the all-forcing baseline scenario. Error bars represent ±one standard deviation from the ensemble-mean based on a 190-member ensemble.

action relative to slow or delayed action can be overlooked given that long-term impacts are similar for all timelines. This would miss a major opportunity to limit warming and its damages over the next few decades. We note that the magnitudes of avoided global-mean warming reported herein are insensitive to the non-methane baseline emissions assumptions, however, the relative reductions in the global-mean rate of warming would increase if non-methane baseline emissions decrease (see supplemental material for more information).

The relative roles of major sectors in contributing to the near- and long-term climate benefits from fast methane action vary considerably by sector (figure 4). The majority of economically feasible actions come from the oil and gas sector, accounting for around 80% of the avoided warming from economically feasible methane mitigation actions over all timescales (figure 4); 20% of this avoided warming comes from agreed upon targets by top oil and gas companies to reduce upstream leakage (OGCI 2018). We find that implementing current net zero cost oil and gas supply chain mitigation measures, such as leak detection and repair programs, along with fulfilment of company commitments of capped leakage rates, could avoid around 0.1 °C of global-mean warming by midcentury and 0.2 °C by end of century relative to a no further action baseline that suggests the oil and gas sector could contribute 0.15 °C to warming by 2050 and 0.25 °C by 2100 (figure 4).

For technically feasible mitigation, abatement measures for landfills and livestock play important roles in addition to oil and gas (figure 4). Implementation of all available landfill measures (requiring at most only minor improvements)—such as source separation—could avoid 0.16 °C of global-mean warming in 2100 relative to a no further action baseline (figure 4). Deploying all livestock abatement strategies—such as methane inhibitors and improved manure management—could avoid nearly 0.1 °C of global-mean warming in 2100 relative to a no further action baseline (figure 4). However, given the amount of livestock emissions that currently cannot be addressed with existing technologies, residual methane emissions from livestock are expected to contribute to half of the remaining future methane emissions unless there are behavioral changes and technological advancements.

Given that there are specific uncertainties associated with methane's climate impacts in addition to the various uncertainties associated with all models and emissions estimates, we perform several sensitivity tests to assess how methane-related model parameters affect our results. For example, there are uncertainties associated with the radiative effects from methane's oxidation processes and methane's atmospheric lifetime. Overall, the consideration of their individual uncertainties in our analysis suggests a global-mean temperature rise by end of century from baseline methane emissions that ranges from 0.75 °C to 1.5 °C; see supplementary material for more details. Further, we note that accounting for positive climate feedbacks such as melting tundra may lead to even more warming from methane emissions and is currently not included in our model.

4. Conclusions

The goal of this study is to assess the value of rapidly deploying available methane mitigation measures as compared to slower implementation timelines or delayed action, with an emphasis on sectoral contributions to climate benefits over all timescales. We find that while the potential to reduce methane emissions

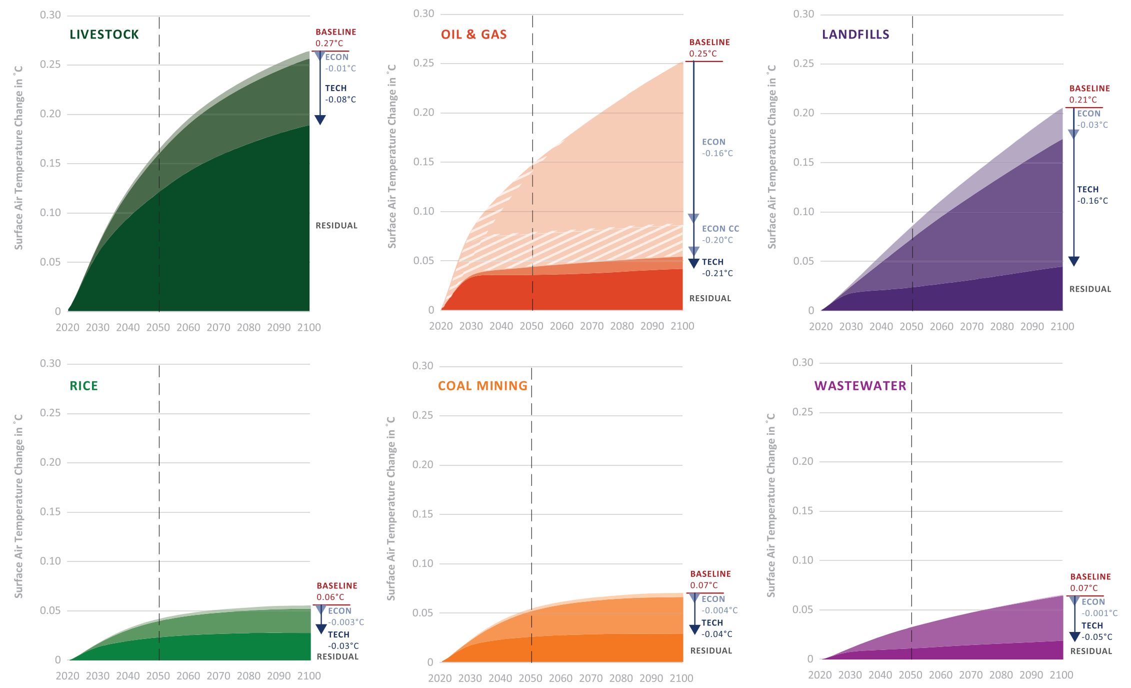

Figure 4. Baseline temperature responses and avoided warming in °C by sector for methane mitigation measures fully employed by 2030 and maintained throughout the 21st century, for both economically and technically feasible measures. Economically feasible measures ('econ') refer to current no net cost options. For oil and gas, we include commitments made by oil and gas companies, with the assumption that companies have found it fits into their business models. The contribution of company commitments to avoided warming beyond current no net cost options is shown in the line pattern ('econ cc'). Technically feasible measures include all readily available technologies in addition to no net cost options. Note that the sum of sector totals are slightly than those in figure 3(b), which is mainly due to a higher ECS used in single model runs (3 °C) compared to the 190-member ensemble means (2.88 °C).

with existing mitigation measures varies considerably by sector, if deployed in parallel can cut expected 2030 methane emissions in half, with a quarter at no net cost. We find that full deployment of these available mitigation measures by 2030 can slow the rate of global-mean warming over the next few decades by more than 25%, while preventing around a quarter degree (°C) of additional global-mean warming in 2050 and half a degree (°C) in 2100. On the other hand, slow or delayed methane action leads to a 5% or nearly 20% increase in global-mean warming rate from 2030 to 2050 relative to fast action, respectively. Oil and gas measures dominate the avoided warming from economically feasible actions, and landfill measures play a secondary role to oil and gas in the avoided warming from technically feasible actions. Livestock measures also play an important role for technically feasible methane mitigation, but a considerable fraction of emissions from livestock still remain unabated.

Our results are in agreement with previous studies that show sizable near-term and long-term climate benefits from stringent methane mitigation, with similar levels of avoided warming in midcentury and end of century given the range in assumptions and methods (Shindell *et al* 2012, Shoemaker *et al* 2013, Stohl *et al* 2015, Rogelj *et al* 2015, Reisinger and Clark 2018, Collins *et al* 2018, Harmsen *et al* 2020, Smith *et al* 2020). Our analysis adds to this growing body of literature by assessing the role of different mitigation timelines in affecting the near-term climate benefits, and by showing the sectoral contributions over time. This study illuminates the near-term value of fast methane action as opposed to slower or delayed action.

In the long-term, the large potential in avoided warming from technically feasible measures is similar in magnitude to the upper end of projections of avoided global-mean warming from phasing out another important short-lived climate pollutant, hydrofluorocarbons (HFCs; Xu *et al* 2013). The potential avoided warming from HFC phase-out sparked an international agreement to curb future emissions growth—the Kigali Amendment to the Montreal Protocol—which entered into force in January 2019. Methane mitigation has even larger potential benefits than HFC mitigation because its future impact is projected to be double that of HFCs (figure 3(b)).

The long-term climate benefits from both economically and technically feasible methane mitigation scenarios in this analysis can also be considered underestimates given that we expect more abatement actions to become cost effective with technology turnovers, and more abatement actions to become available with technological advancements; neither of which are considered in our mitigation pathways. For example, the discovery, development, and scale up of emerging techniques could lead to higher sectoral abatement potentials, such as genetic selection for low-methane emitting phenotype (de Haas *et al* 2017). Methane emissions can be further reduced by shifts in behaviors such as decreased consumption of cattle products and reduced food waste. Proposals to remove methane from the atmosphere could also come to fruition (Jackson *et al* 2019). In addition, as more economies put a price on carbon or consider other forms of payment to account for methane damages (via ozone) to public health, agriculture, forests, etc (Shindell *et al* 2012, 2017), the cost effective options will expand, and the economically feasible potential would move closer to the technically feasible potential.

While we do not expect the methane mitigation measures we consider in our analysis to significantly affect emissions of other major climate pollutants, it is possible that some mitigation strategies for rice paddies can increase nitrous oxide emissions—although techniques exist to prevent this from occurring (Kritee *et al* 2018). On the other hand, actions designed to address other climate pollutant emissions, mainly carbon dioxide, can simultaneously reduce methane emissions from the energy sector. However, studies show that direct methane mitigation measures play a larger role in reducing methane compared to indirect methane reductions (Harmsen *et al* 2020), and provide important, additional climate benefits (IEA 2017). Further, many decarbonization pathways suggest that methane emissions will not be considerably reduced before midcentury (Riahi *et al* 2017) given that many strategies include an initial phase of switching from coal to natural gas, or, deployment of carbon capture and storage technologies—both of which will not appreciably reduce methane emissions. Therefore, we do not expect decarbonization of energy systems to affect the majority of our near-term climate benefits from direct methane mitigation measures.

Overall, the ability to substantially mitigate methane emissions with existing strategies is clearly an effective lever to limit future warming and associated damage to social and natural systems. Through immediate and rapid implementation of available methane mitigation measures, many that incur no net cost, we could see significant benefits in a single generation through slowed rates of warming, while also setting ourselves on a better course for generations to come. Employing these measures is undoubtedly essential to achieving ambitious warming targets, and can reduce the likelihood of passing tipping points and triggering positive feedbacks (Collins *et al* 2018, Fu *et al* 2020). Further, methane mitigation has been shown to be of additional benefit through reductions in tropospheric ozone that is toxic to many crops (Shindell *et al* 2012). While not a substitute for the unequivocally-imperative need of reaching carbon dioxide neutrality, methane mitigation is a powerful ally that should be pursued now with increased seriousness.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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