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RECEIVED
31 August 2022

REVISED
12 December 2022

ACCEPTED FOR PUBLICATION
19 January 2023

PUBLISHED
6 February 2023

LETTER

A roadmap to achieve the global methane pledge

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Keywords: methane: Nationally Determined Contributions, climate change, mitigation

Abstract

The Global Methane Pledge (GMP), launched in 2021 and signed by 149 countries and the European Union, aims to reduce global anthropogenic methane emissions by 30% in 2030 compared to 2020 levels. However, the GMP does not specify the contribution of countries or methane-emitting sectors (fossil fuel production, agriculture and waste) to achieve this global goal. Nationally determined contributions (NDCs) describe countries' climate change commitments, and 86% of countries include methane within the scope of these targets. This paper aims to assess whether a roadmap (i.e. a set of mitigation actions) to achieve the GMP can be developed from those methane-targeted mitigation actions included within NDCs. The 476 methane-focussed mitigation actions within the 168 NDCs analysed are targeted in countries and sectors emitting approximately 40% of global methane. These mitigation actions are not specified in NDCs with implementation targets and timelines that are currently collectively sufficient to achieve the GMP goal. However, if all 476 mitigation actions are implemented to their maximum technical mitigation potential, their implementation could reduce global emissions by ∼31%. Therefore, mitigation actions in NDCs could achieve the GMP goal, but only if implemented to their fullest possible extent. There are also multiple opportunities to increase methane mitigation ambition further. Additional commitments to implement technical methane mitigation measures could lead to mitigation in excess of the GMP goal. Behavioural measures, such as dietary shifts and reduction in waste generation could further reduce methane, and are included in few NDCs currently.

1. Introduction

Global anthropogenic methane emission increases since pre-industrial have contributed 0.5 °C of global warming (IPCC 2021), and increased by ∼1% per year between 2010 and 2018 (Crippa *et al*, 2021). The primary anthropogenic methane emitting sectors are fossil fuel production, agriculture, and waste. Reducing methane emissions is necessary to limit global temperature increases to 1.5 °C (IPCC 2018), with the most cost-effective 1.5 °C-compatible pathway requiring an ∼40% methane emission reduction by 2030 compared to 2020 levels (UNEP CCAC 2021).

In 2021, the United States and European Union announced the Global Methane Pledge (GMP). Participating countries commit to collaborate to reduce global anthropogenic methane emissions by '*at least*' 30% compared to 2020 levels by 2030 (European Commission and United States of America 2021). Approximately 384 million tonnes of methane was emitted in 2020 (Crippa *et al* 2021). Therefore, achievement of the GMP requires that global anthropogenic methane emissions in 2030 do not exceed 269 million tonnes, requiring a >3% (13 million tonnes) per year reduction in global methane emissions between 2022 and 2030. The 150 GMP participants emit approximately 55% of global methane emissions (Crippa *et al* 2021). However, the GMP is explicitly framed as a global goal, rather than one that applies only to GMP-participating countries. Therefore, while the GMP states that the reduction target will be achieved '*across all sectors*', it does not elaborate on key implementation issues, including (a) the magnitude of

reductions in key sectors, (b) the geographic distribution of reductions, and (c) the reduction schedule to the 2030 goal.

Previous studies have demonstrated that achieving a 30% reduction in global methane emissions by 2030 is technically, and economically feasible, with the largest technical mitigation potential in fossil fuel production and waste sectors, and lower technical mitigation potential from agricultural methane emission sources (Lucas *et al* 2007, Höglund-Isaksson 2012, Harmsen *et al* 2020, Höglund-Isaksson *et al* 2020, Smith *et al* 2020, UNEP CCAC 2021). However, assessing whether countries have collectively committed to implement sufficient national methane mitigation measures to achieve the GMP goal is challenging, and not taken into account within these previous studies. Few countries currently have methane-specific actions plans, such as the United States (White House Office of Domestic Climate Policy 2021). However, in 2015, Paris Agreement signatories committed to submit, regularly, greenhouse gas (GHG) mitigation commitments within nationally determined contributions (NDCs). A majority (86%) of countries include methane within the scope of their GHG reduction targets, but do not state how much methane reductions will contribute to the achievement of that target (Malley *et al* 2022). However, NDCs, and documents to which they refer, commonly outline the specific mitigation measures that will be implemented to achieve the target, i.e. those measures that Governments have endorsed to contribute to contribute to its climate change targets.

In this work, analysis of the mitigation measures included within NDCs are used to develop a first roadmap to achieve the GMP taking into account those methane mitigation measures that countries have already identified to achieve their climate change mitigation commitments. A roadmap in this work is defined as a set of measures in countries and sectors whose implementation could reduce methane emissions in line with GMP target. NDCs are the documents used as the basis for developing this roadmap as their contents have already been endorsed by the national governments where they will be implemented. This study therefore aims to assess whether a roadmap to achieve the GMP can be developed from the implementation of the mitigation measures national Governments have already identified and endorsed in NDCs. The majority of NDCs include mitigation commitments to be achieved by 2030, which makes them useful to assess the scope and scale of national methane mitigation commitments relative to the GMP. However, many NDCs do not state quantitative implementation targets and timelines for specific mitigation measures. Therefore, in the absence of detailed information on implementation targets and timelines globally for methane-focussed mitigation measures in NDCs, this study evaluates the potential impact on methane emissions from implementation of mitigation measures included in NDCs to their maximum technical potential to define a roadmap from mitigation measures included within NDCs (see section 4 for further details). The analysis includes NDCs submitted by all countries, as opposed to only GMP Participants, because the GMP is an explicitly global target across all countries.

Assessing the extent to which mitigation measures included within NDCs, and their maximum technical implementation, provide a roadmap to achieve the GMP also ensures that the roadmap is consistent with national commitments on broader greenhouse gas mitigation made to achieve the goals of the Paris Agreement. This is in line with the framing of the GMP, which states that '*to keep 1.5 degrees C within reach, methane emission reductions must complement and supplement, not replace global action to reduce carbon dioxide emissions*' (European Commission, United States of America 2021). From each NDC, methane-specific mitigation measures are extracted, and the fraction of national and global methane emissions that could be reduced from their maximum technical implementation estimated. Approaches to increase the methane emission reductions beyond those estimated for the roadmap developed are also identified. Specifically, the study identifies which additional mitigation measures could be included in future NDC updates to increase methane mitigation ambition. The potential for inclusion of additional mitigation measures within future NDCs to increase methane mitigation ambition is selected as the mechanism to achieve a more ambition global methane reduction roadmap because there is an existing NDC update process outlined in the Paris Agreement, which can therefore ensure that increased methane mitigation ambition can both achieve, or exceed the GMP, and contribute to achieve the long-term temperature targets in the Paris Agreement.

2. Methods

To develop a roadmap for global methane mitigation, this study (a) identifies those mitigation measures included in NDCs to achieve national climate change targets, (b) quantifies the fraction of methane emissions emitted in these countries and sectors where mitigation measures have been identified, and (c) estimates the possible methane emission reductions that could be reduced from the full technical implementation of the global suite of methane mitigation measures identified in NDCs.

Firstly, the NDCs submitted to the United Nations Framework Convention on Climate Change (UNFCCC) up to 8th December 2022 were taken from the official NDC Registry (https://unfccc.int/ndcreg).

To identify those mitigation measures which are included within NDCs, each NDC submitted was analysed as described in Malley *et al* (2022), based on a framework outlined in CCAC SNAP (2019). A country's most recent NDC was analysed and, consistent with the purpose of NDCs outlined in the Paris Agreement (United Nations 2015), assumed to represent the most up-to-date communication on their level of climate change mitigation ambition, and how this ambition would be achieved. In addition to the NDC document itself, where an NDC identifies additional documents as being the source of information on the specific mitigation measures that would achieve a climate change mitigation target, this document(s) was also analysed. In total, NDCs from 168 Parties to the Paris Agreement were analysed in this work, including 167 countries, and the European Union, whose 27 Member States submit a single NDC. The countries covered by the 168 NDCs analysed emit ∼98% of global anthropogenic methane emissions (Crippa *et al* 2021).

The NDCs were analysed to identify those mitigation measures that a country will implement to achieve their climate change mitigation commitments. In this work, mitigation measures included within NDCs were identified for those major anthropogenic methane-emitting sectors, fossil fuel (oil, gas and coal) production, agriculture and waste. There is no standard format or convention for the description or inclusion of mitigation measures to achieve GHG emission reductions in NDCs, and therefore the detail on mitigation measures varied substantially between submissions. A consistent set of categories of mitigation measures was defined for each of the major methane-emitting sectors, shown in table 1, and based on the categorisation of mitigation measures in these sectors developed previously in international assessments (UNEP/WMO 2011, CCAC SNAP 2019, UNEP 2019).

For fossil fuel production, the categories of measures include measures to reduce flaring, venting and other fugitive methane emissions from oil and gas production, processing and distribution, and coal mining, as well as reducing expansion and production of fossil fuels. For agriculture, the categories of measures included 'on-farm' measures designed to reduce methane emissions from (a) enteric fermentation, (b) manure management and (c) rice production, and 'off farm' behavioural measures including reducing food waste and shifting diets to lower climate change impact food products. For the waste sector, the categories of measures include capturing methane at landfill sites, diverting organic waste from landfills for composting/recycling, reducing solid organic waste generation, and reducing methane emissions from wastewater treatment plants.

In each NDC analysed, the number of measures across each of these categories was then extracted. Due to the lack of standard format or consistency in the reporting of mitigation measures to achieve climate change mitigation commitments within NDCs, and because details of these mitigation measures were often included in separate, referenced documents, each NDC analysed was read in its entirety to extract the mitigation measures identified as those that would be implemented to achieve national climate change mitigation targets. For an NDC to be considered to have identified a measure within one of the categories included in table 1, it is necessary, at a minimum, that methane emissions reductions within the specific methane-emitting sector was identified within the NDC, i.e. methane emission reductions from livestock enteric fermentation was considered sufficient for inclusion within the enteric fermentation category in table 1, but general statements of GHG emission reductions from agriculture was not. More specific identification of measures were also sufficient for inclusion (e.g. feed substitution, genetic improvements to reduce enteric fermentation methane emissions). Malley *et al* (2022) describe in further detail the process of analysing each NDC, and present the results from each individual NDC analysis, including the mitigation measures identified within each NDC, and the specific text extracted from each NDC that justifies the identification of each mitigation measure.

Secondly, to assess the extent to which the implementation of mitigation measures explicitly included in NDCs could contribute to achieving the GMP, national and sectoral methane emission estimates from the Emissions Data for Global Atmospheric Research v7.0 (EDGAR) emission inventory database were used (Crippa *et al* 2021). EDGAR estimates national total emissions disaggregated into Intergovernmental Panel on Climate Change (IPCC) sector categories (IPCC 2006). In this study, the national total methane emissions disaggregated by sector for 2020 were used, for consistency with the year used to define the GMP emission reduction target. The sectors within which methane emissions could be reduced by the mitigation measures considered in this work are shown in table 1 and cover 95% of global methane emissions. The magnitude of methane emissions emitted in these sectors that could be reduced from the implementation of each type of mitigation measure where it was included within an NDC was then calculated, and aggregated across all methane emitting source sectors in countries and globally. This was used to assess the percentage of national and global methane emissions in each sector that are covered by mitigation measures included within NDCs.

Finally, further analysis was conducted to assess how much of the methane emissions covered by mitigation measures in NDCs could theoretically be reduced from their full implementation based on the technical reduction potential of these measures. The majority of countries do not specify quantitative implementation targets and timelines for the methane-focused mitigation measures in their NDC, to

Table 1. Overview of methane-focused mitigation measures whose inclusion in Nationally Determined Contributions was assessed, the maximum emission reduction factor for each mitigation measures (the percentage reduction in sectoral methane emissions that could be achieved from implementation of each mitigation measure), and the number of countries including each mitigation measures in their most recent NDCs.

No.	Sector	Mitigation measures	IPCC source sector where emissions are reduced	Maximum emission reduction factor (maximum % reduction in sectoral methane emissions from implementation of mitigation measure)	Source	No. of countries including measure in NDCs	Percent countries including measure in NDCs
1	Energy—Coal, Oil and Gas	Reduce gas flaring in oil and gas sector	1.B.2 Oil and Natural Gas	99%	Höglund-Isaksson *et al* (2020)	19	11.4
2		Minimise venting, flaring and fugitive emissions from oil and gas sector	1.B.2 Oil and Natural Gas	85%–96% 99%—extended recovery and utilization of vented associated gas	IPCC (2019) Höglund-Isaksson *et al* (2020)	30	18.0
3		Minimise methane emissions from coal mining	1.B.1 Solid Fuels	90% pre-mine degasification on both surface and underground coal mines	Höglund-Isaksson *et al* (2020)	4	2.4
4		Avoid future expansion of coal, oil and gas infrastructure	1.B.2 Oil and Natural Gas	100%		1	0.6
5	Agriculture	Reduce emissions from livestock enteric fermentation (e.g. through feed optimization, breeding and genetic improvements)	3.A.1 Enteric Fermentation	30%	Höglund-Isaksson *et al* (2020)	49	29.3
6		Reduce emissions from livestock manure management	3.A.2 Manure Management	50–75%—anaerobic digestion 94–99%—Conversion from solid storage or liquid slurry to daily spread manure management system	Höglund-Isaksson *et al* (2020) IPCC (2019)	57	34.1
7		Implement intermittent aeration of continuously flooded rice paddy fields	3.C.7 Rice Production	45%—Reduction from conversion from continuously flooded to multiple drainage period water management system	IPCC (2019)	33	19.8

(Continued.)

Table 1. (Continued.)

No.	Sector	Mitigation measures	IPCC source sector where emissions are reduced	Maximum emission reduction factor (maximum % reduction in sectoral methane emissions from implementation of mitigation measure)	Source	No. of countries including measure in NDCs	Percent countries including measure in NDCs
8		Increase proportion of people with diets that have lower climate impact (e.g. reducing red meat consumption)	3.A.1 Enteric Fermentation 3.A.2 Manure Management	25%—shifting to healthy diets that reduces red meat consumption	UNEP CCAC (2021)	3	1.8
9		Reduce proportion of food wasted	3.A.1 Enteric Fermentation 3.A.2 Manure Management 3.C.7 Rice Production	Average proportion of meat (and dairy) wasted by region (agricultural production to consumption) Europe—24.8% North America and Oceania—25.5% Industrialised Asia—22.5% Sub-Saharan Africa—29.7% North Africa, West and Central Asia—24.8% South and Southeast Asia—21.4% Latin America—22.4%	FAO (2011)	7	4.2
10	Waste	Reduce methane emissions from solid waste at landfill sites (including methane capture and use for waste to energy)	4.A Solid Waste Disposal	80%—high-end of recovery efficiencies from available studies	IPCC (2019)	99	59.3
11		Increase percentage of solid waste separated and recycled or composted	4.A Solid Waste Disposal	90% 100%	IPCC (2019), Höglund-Isaksson *et al* (2020)	94	56.3
12		Reduce solid waste generation	4.A Solid Waste Disposal	100%	IPCC (2019)	33	19.8

(Continued.)

understand how much methane could be reduced from their implementation, and therefore the analysis focused on the potential reduction from full technical implementation of the measures (Malley *et al* 2022). For the few countries that do include methane emission reduction targets in their NDCs, these are not reflected in this analysis, to provide a consistent assessment for all countries (see Discussion for further

Table 1. (Continued.)

No.	Sector	Mitigation measures	IPCC source sector where emissions are reduced	Maximum emission reduction factor (maximum % reduction in sectoral methane emissions from implementation of mitigation measure)	Source	No. of countries including measure in NDCs	Percent countries including measure in NDCs
13		Upgrade wastewater treatment plants with methane gas recovery (or use biodigesters)	4.D Wastewater Treatment and Discharge	93%—biogas recovery and utilisation 96% (difference in CH_4 emission factor between anaerobic reactor and aerobic wastewater treatment plant) 75% high end efficiency for methane recovery from anaerobic treatment plant	IPCC (2019), Höglund-Isaksson *et al* (2020)	59	35.3

information on this assumption). Each category of mitigation measures was assigned a 'maximum emission reduction factor', which is the maximum percentage reduction in methane emissions in the sector targeted that could be technically achieved from the implementation of the mitigation measures within that category (table 1). This does not account for the economic, social, political or other barriers, which, if significant, may reduce the methane emission reduction potential in particular countries or contexts below the technically-feasible reduction potential. For many of the methane-focused mitigation measures, particularly in the oil and gas, and solid waste sectors, the economic cost of implementation is relatively low. IPCC (2022) estimated that, as a global average, approximately half of the mitigation potential from reducing methane emissions from solid waste can be achieved at a negative cost, with the majority of the remaining technical mitigation potential achieved for less than 100 USD tCO_2eq^{-1}. Approximately 25% of the maximum technical mitigation potential of reducing methane from oil and gas could be achieved at negative cost, and half could be achieved for less than 20 USD tCO_2eq^{-1}. The fraction of the technical methane mitigation potential that can be achieved for different economic costs provides a guide as to those mitigation measures and sectors where economic barriers may be most likely to impede achievement the maximum technical mitigation potential, with relatively lower economic costs in oil and gas, and solid waste compared to coal mines, agriculture and wastewater. For example, over 80%, and 50%, respectively, of the technical mitigation potential from reducing coal mine methane, and on-farm methane reduction measures in agriculture could be achieved for less than 20 USD tCO_2eq^{-1}.

The maximum technical methane emission reduction potential of measures also exceeds targets that have been set for methane mitigation in many countries, regions and sectors. For the majority of NDCs, implementation targets and timelines are not specified for the mitigation measures identified to achieve an overall GHG reduction commitment, and this information is not required under the Paris Agreement (United Nations 2015, 2021). Some regions and countries have methane-specific policies. The United States Methane Emissions Reduction Action Plan outlines measures to reduce methane emissions from oil and gas by 75% and agriculture by 10%, both below the maximum technical emission reduction potential of mitigation measures in these sectors used in this study (White House Office of Domestic Climate Policy 2021) (table 1). Similarly, as part of the overall goal of Canada's Methane Strategy to reduce national total methane emissions by 35% in 2030 compared to 2020 levels, Canada committed to reducing fugitive oil and gas methane emissions by 75% compared to 2012 levels, below the maximum technical reduction potential (Environment and Climate Change Canada 2022). Therefore, the evaluation of the extent to which

mitigation measures included within NDCs could collectively reduce global methane emissions using the maximum technical potential of each measure does not reflect the extent to which countries have committed to implement these measures. However, it shows what is technically possible from full maximum implementation of measures, that countries have identified as priorities to contribute to achieve their climate change targets. The achievement of the methane emission reductions shown in section 3 would require that countries either establish implementation targets for the mitigation measures in their NDCs at the level of the maximum technical methane mitigation potential where implementation targets have not been set, or to revise existing implementation targets upwards, to reflect the maximum technical mitigation potential of the measures.

The maximum emission reduction factors were taken from previous studies (IPCC 2019, Höglund-Isaksson *et al* 2020, UNEP CCAC 2021), and ranged from a 30% reduction from the implementation of mitigation measures designed to reduce emissions from livestock enteric fermentation (e.g. breeding and feed optimisation), to near complete reduction in methane emissions for measures including reducing fugitive emissions from oil and gas through recovery and utilisation. For some measures, multiple maximum emission reduction factors were identified in different studies, and are shown in table 1 to show the range in of values for these sectors. In these instances, the higher emission reduction factor was generally used in the assessment to represent the maximum technical methane emission reduction identified from the studies assessed. This includes manure management, where the maximum emission reduction factor for anaerobic digestion (75%) was used from the range included in Höglund-Isaksson *et al* (2020). For reducing fugitive methane emissions from oil and gas, the higher maximum emission reduction factor (99%) from Höglund-Isaksson *et al* (2020) was used compared to those from IPCC (2019). For landfill gas capture, the maximum emission reduction factor was taken from the maximum efficiency of landfill gas capture technologies outlined in IPCC (2019) (80%), while for wastewater treatment the maximum emission reduction factor from Höglund-Isaksson *et al* (2020) was used (table 1).

The national total methane emissions in each sector where methane-targeted mitigation measures were identified in NDCs were then multiplied by the maximum emission reduction factor to determine the absolute reduction in methane emissions that could be achieved from the complete technically-possible implementation of the mitigation measures included within NDCs. These values were aggregated across methane-emitting sectors, at national and global levels to assess the magnitude of methane emissions that could be reduced from implementation of the global set of NDCs, as a percentage of national and global total anthropogenic methane emissions. This shows the extent to which a roadmap to reduce methane emissions constructed from those mitigation measures included within NDCs is sufficient to achieve the GMP.

3. Results

In total, across all 168 NDCs, 476 mitigation actions (i.e. number mitigation measures multiplied by the number of NDCs including them) were identified in the major methane-emitting sectors (table 1, figure 1). For the majority of sectors, a minority of countries included mitigation measures to reduce methane. In fossil fuel production, 18% and 2% of countries included measures to reduce fugitive methane emissions from oil, gas and coal production, respectively. Only one country committed to no expansion of fossil fuel infrastructure. For agriculture, on-farm measures to reduce manure management and enteric fermentation emissions were most commonly included (∼30% of NDCs each), followed by intermittent aeration of rice paddy fields (∼20%). For waste, capturing landfill gas was the most common measure included (59%), followed by organic waste diversion to composting/recycling (56%). More NDCs included measures to reduce methane from solid rather than liquid waste (table 1). Fewer NDCs included behavioural methane mitigation measures, such as dietary shifts (e.g. reducing red meat consumption, 1.8% of all NDCs evaluated), or reductions in organic waste generation (20%).

Approximately 40% of global methane emissions were emitted in countries and sectors with mitigation measures included in NDCs. After accounting for the maximum emission reductions possible from their full technical implementation potential, approximately 31% of global anthropogenic methane emissions could be reduced by the mitigation actions in NDCs (table 2, figure 2). Therefore, this study indicates that the 476 mitigation measures included within NDCs provide a global methane reduction roadmap that could achieve the GMP only if every measure is implemented to its maximum technical potential.

This roadmap to achieve the GMP methane reduction target is composed of mitigation measures across the fossil fuel production, agriculture and waste sectors. The majority of the 31% reduction in global methane emissions estimated to be achieved from the full implementation of all 476 measures is achieved from measures to reduce fugitive emissions from fossil fuel production (55% of the total methane emission reduction potential from implementation of all measures), followed by waste (27%), and agriculture (16%). These contributions from measures in each sector are determined by (a) the frequency of their inclusion in

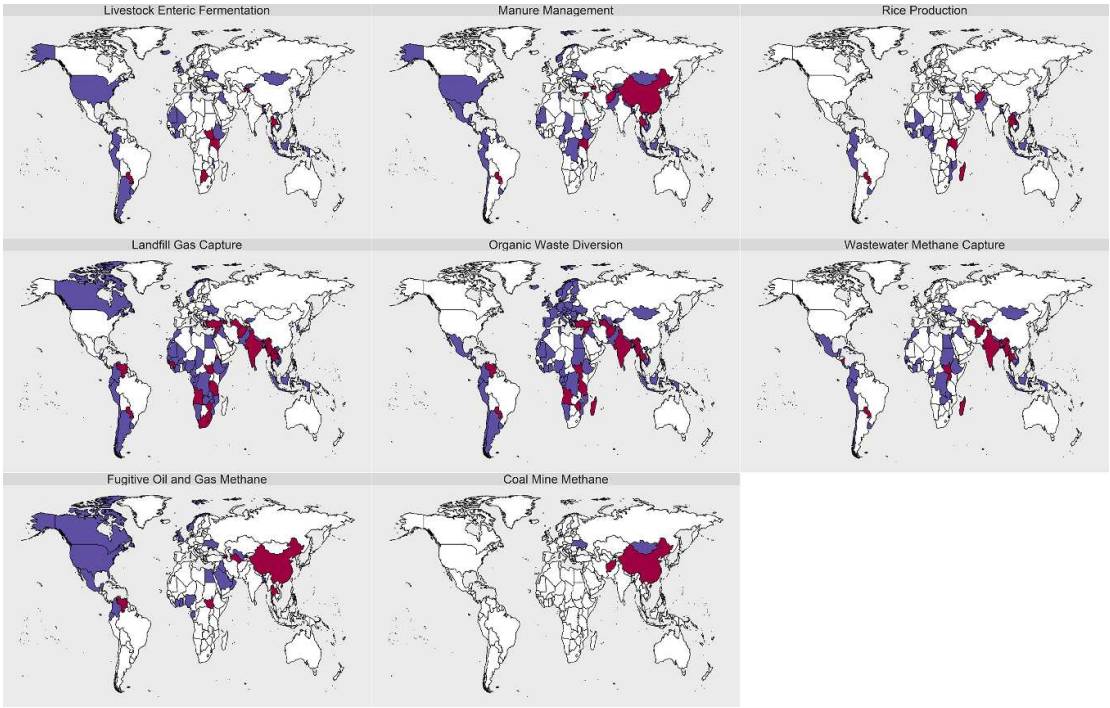

Figure 1. Countries that have identified specific methane-focused mitigation measures whose implementation will contribute to achieve climate change mitigation targets in Nationally Determined Contributions (NDCs). Full implementation of all measures highlighted in the figure is estimated to be able to reduce ∼30% of global methane emissions. Countries including mitigation measures in their NDCs are disaggregated between those participating in the Global Methane Pledge (blue) and those that are not currrently (red).

Table 2. Contribution of major source sectors to GHG, SLCP and air pollutant emissions, and the percentage of these emissions covered by mitigation measures included in NDCs.

	Global methane emissions in 2020 in key source sectors, million tonnes (% global total)	Global sectoral methane emissions emitted in countries with measures in sector identified in NDC (% global total sectoral emissions)	Estimated reduction in global total sectoral emissions from implementation of measures in NDCs (% global total sectoral emissions)
Oil and Gas	74.5 (19.4%)	58.8%	58.3%
Solid Fuels			
Coal Mining	44.8 (11.7%)	55.4%	49.9%
Charcoal Production	4.64 (1.2%)	64.2%	64.2%
Agriculture			
Enteric Fermentation	111.0 (28.9%)	27.1%	8.1%
Manure Management	12.5 (3.3%)	45.8%	34.3%
Rice Production	36.9 (9.6%)	33.2%	15.0%
Waste			
Solid Waste	35.7 (9.3%)	46.3%	41.7%
Liquid Waste	46.1 (12.0%)	38.6%	37.0%
Global Total	Global total: 384.1 Total emitted in sectors above: 366.2 (95.3%)	40.1%	31.1%

NDCs, (b) the magnitude of methane emissions in those sectors in the countries that have identified these measures to achieve their climate change mitigation targets, and (c) the maximum technical emission reduction potential assumed for measures in each sector. For example, approximately 59% of global fugitive methane emissions from oil, gas and coal production were emitted in countries including measures in this sector, and over half of fugitive methane emissions could be reduced from their full implementation (table 3). For agriculture, the maximum technical emission reduction factors of the measures (on-farm, technical measures, table 1) most frequently included in NDCs are substantially lower than for other sectors, and therefore potential methane reductions are substantially lower. Livestock enteric fermentation is the

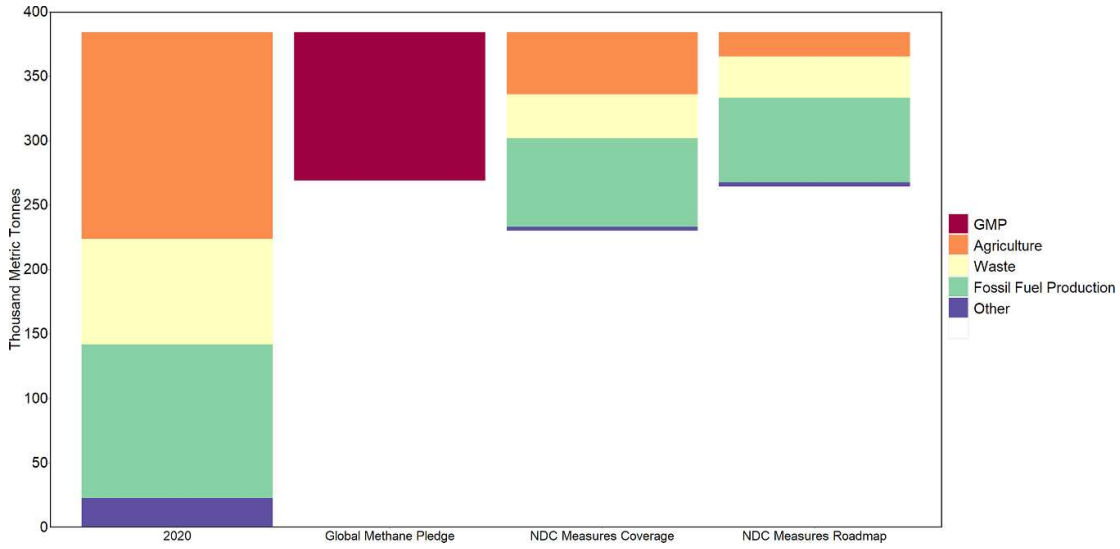

Figure 2. Summary of global methane emissions in 2020 (Crippa *et al* 2021), the Global Methane Pledge methane emission reduction target, the methane emissions emitted in sectors and countries with mitigation measures included in Nationally Determined Contributions (NDC Measures Coverage), and the reduction in global methane emissions estimated to be achievable from the implementation of all 476 methane-targeted mitigation measures included within NDCs when implemented to their fullest possible technical extent (NDC Measures Roadmap).

Table 3. Top 10 'missed opportunities' sectors for GHG and SLCP emissions for which mitigation measures were not specified in post-2020 NDCs.

Country	Sector	Percentage global 2020 methane emissions
Brazil	Enteric Fermentation	3.99%
India	Enteric Fermentation	3.73%
China	Rice Cultivation	3.67%
China	Wastewater Treatment and Discharge	2.59%
Indonesia	Solid Fuels	2.32%
Russia	Oil and Natural Gas	2.02%
China	Enteric Fermentation	1.83%
European Union	Enteric Fermentation	1.69%
China	Solid Waste	1.50%
Pakistan	Enteric Fermentation	1.38%
Total Top 10		24.7%

largest methane emission source (table 3), but the full implementation mitigation actions in NDCs was estimated to reduce only ∼8% of enteric fermentation emissions, globally. Few countries have identified measures in agriculture which could lead to larger methane emission reductions, such as dietary shift, which was only included in NDCs of a few relatively low-methane-emitting countries (e.g. Costa Rica, Ethiopia). Maximum emission reduction factors of waste measures are higher than on-farm agricultural measures, and a larger fraction of solid and liquid waste methane emissions could be reduced from full implementation of the measures included in NDCs compared to agriculture.

The implementation of mitigation measures with high maximum methane emission reduction potential in major methane emitting countries make a disproportionate contribution within the roadmap to achieving a 31% global methane emission reduction. If fully implemented, over half of this reduction could be achieved from the full implementation of only 13 NDC mitigation actions (figure 3). The achievement of the GMP through this roadmap of 476 mitigation measures also necessitates implementation of actions in non-GMP countries. Non-GMP participating countries account for over 23% of 476 methane-focused mitigation actions included in NDCs. This includes some of the actions with the largest potential methane emission reductions, such as reducing fugitive fossil fuel production emissions in China, and wastewater methane emissions in India (figure 3).

The approach chosen for the development of the roadmap in this work was to identify those measures that national Governments had already endorsed and identified to achieve their climate change mitigation targets. This approach builds a roadmap that (a) has acceptance among national Governments, as they are the source of the mitigation measures included within it, and (b) is consistent with the national

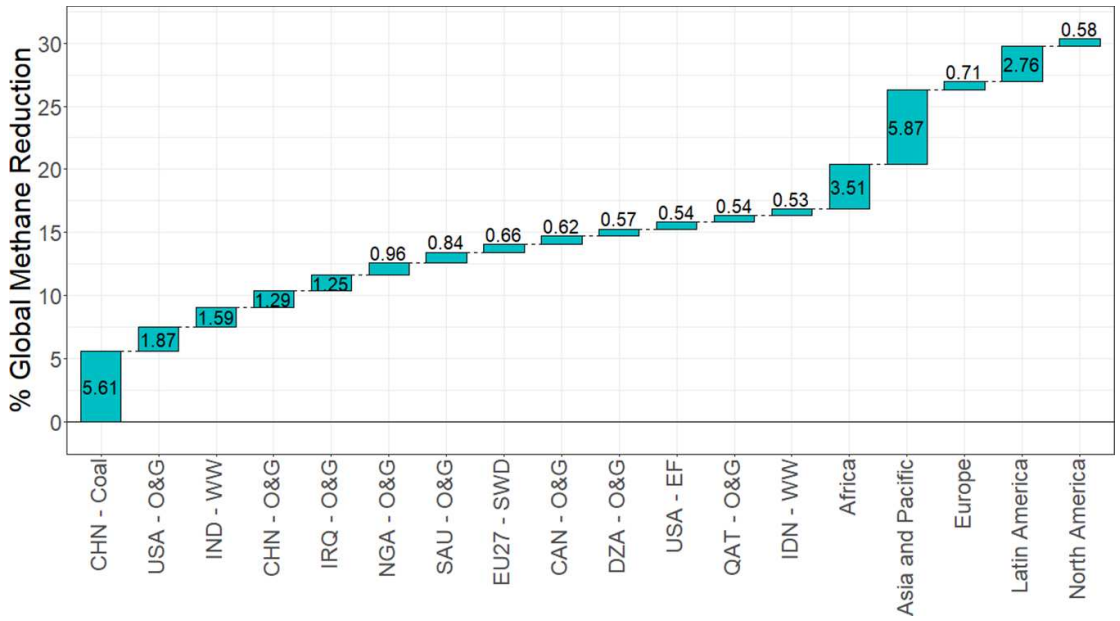

Figure 3. Percentage reduction in global methane emissions achieved from maximum implementation of all mitigation measures included in Nationally Determined Contributions. Individual mitigation measures in countries and sectors that could reduce global methane emissions by 0.5% of greater are shown individually. All other measures are aggregated by region. Abbreviations: CHN: China, IND: India, IRQ: Iraq, NGA: Nigeria, SAU: Saudi Arabia, QAT: Qatar, EU27: European Union, CAN: Canada, DZA: Algeria, IDN: Indonesia, O&G: Oil and Gas, WW: Wastewater, SWD: Solid Waste Disposal, EF: Enteric Fermentation.

commitments on greenhouse gas mitigation made to achieve the broader goals of the Paris Agreement, as the mitigation measures identified come from NDCs. However, The majority of countries have not specified implementation targets for specific mitigation measures within their NDCs, and those that have not specified the full technical implementation potentials used here (shown in table 1) (White House Office of Domestic Climate Policy 2021). Therefore, the achievement of the GMP through this roadmap, i.e. full implementation of the mitigation measures included within NDCs to their full technical potential, requires that countries increase the implementation ambition of the measures that they have already identified in their NDC.

The results from this analysis also indicate that there is substantial potential to increase methane emission reductions through the implementation of mitigation measures not currently included within NDCs. Currently, most countries, including major methane emitters, specify mitigation measures in NDCs in sectors that collectively emit less than half of their national total methane emissions. Specifically, Russia (5th largest methane emitting country) and Brazil (4th) include measures in sectors that emit less than 10% of national total methane emissions in their NDCs, and the European Union, United Kingdom, and Japan cover less than 20%. The world's 1st and 2nd largest methane emitters, China and India, include mitigation measures in sectors that emit less than 40%, and 30% of their total methane emissions, respectively (figure 3(a)).

Global methane emission reductions could be enhanced through a focus on mitigation measures in specific sectors. Reducing fugitive oil and gas emissions has been identified as having the highest potential to reduce methane by 2030 (Harmsen *et al* 2020, European Commission, United States of America 2021). If all countries committed to implementing fugitive methane mitigation measures, an additional 7.9% of global emissions could be reduced compared to implementation of current NDC mitigation measures in this sector. There are several large fossil fuel-producing countries where oil and gas production were the largest methane-emitting sector with no mitigation measure included (figure 3). Therefore, increasing methane mitigation in NDCs through additional oil and gas sector mitigation requires additional action in relatively few countries. Russia, Iran, Algeria, Indonesia, Malaysia, and Bahrain have the largest methane emissions from oil and gas without mitigation measures in NDCs. An additional 5.5% of global methane emissions would be covered by mitigation measures if these seven countries committed to mitigation in the oil and gas sector (figure 3). For coal production, the inclusion of methane recovery from coal mines within the NDCs of a small number of countries could also have a disproportionate impact on global methane emissions emitted in countries and sectors where mitigation measures are identified. An additional 4.7% of global methane emissions could be reduced if all coal-producing countries included methane recovery from coal mines in their NDCs, compared to the implementation only of mitigation measures in current NDCs. If only Indonesia, Russia and India included coal mine methane recovery in their NDCs, then global methane

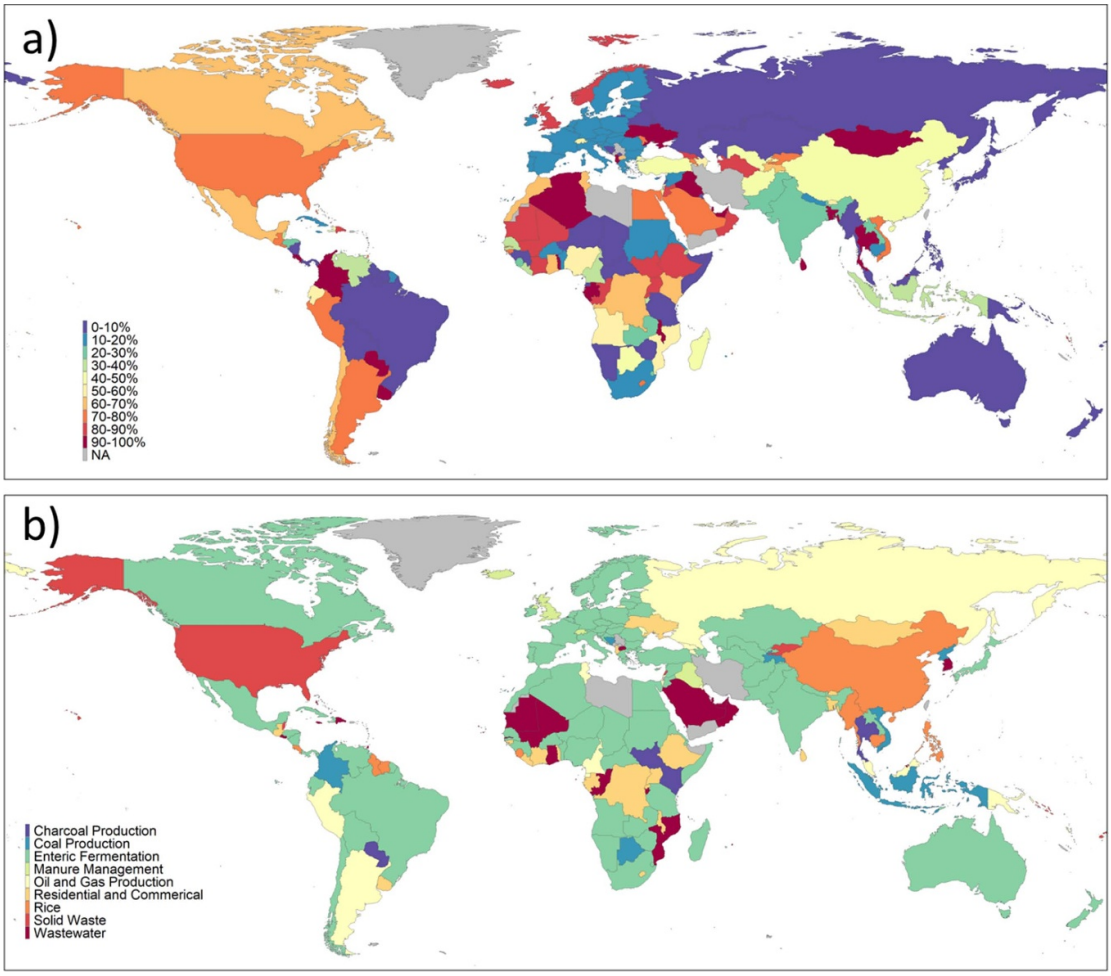

Figure 4. (a) Percentage of national total methane emissions emitted in sectors within which measures to reduce emissions are specified in Nationally Determined Contributions (NDCs) and (b) Emission source sector which makes largest contribution to national total methane emissions for which a mitigation measure was not specified in each Parties' Nationally Determined Contribution (NDC). Note that the 27 Member States of the European Union submit a single NDC.

emissions could be reduced 3.1% from full technical implementation of these measures in those three countries.

Agriculture is the largest anthropogenic methane sector, but makes the smallest contribution to the 30% reduction in global methane emissions from the roadmap outlined here from mitigation measures in NDCs (table 2). Inclusion of on-farm, technical measures to reduce methane from enteric fermentation, manure management, and rice in all NDCs could reduce an estimated additional 10.5% of global methane emissions compared to the current roadmap. This would require a substantially larger number of countries to commit to and implement these measures compared to oil and gas (figure 3). Off-farm, behaviour change measures such as dietary shifts and waste reductions reduce agricultural methane emissions further, but would require almost all countries to update NDCs including these measures (table 1).

In waste, measures to capture methane or divert waste from landfill could reduce an additional 4.9% of global methane emissions if implemented in all countries that have not currently included them in NDCs. For liquid waste, the lower inclusion of mitigation measures, and larger methane emissions compared to solid waste, means that an estimated additional reduction of 7.2% of global methane emissions could be achieved from implementation of wastewater methane mitigation measures in countries where these measures have not been identified in NDCs (table 1).

In addition, the methane emission reductions could be enhanced by considering 'missed opportunity' methane-emitting sectors in specific countries, i.e. national emission sources for which no mitigation is included in NDCs. Methane emissions from the agriculture sectors were the largest 'missed opportunities' for most countries (figure 4). If all countries commit to mitigation measures for their largest 'missed opportunity' sector, these committed mitigation measures would cover an additional 31.3% of global methane emissions compared to measures in current NDCs, and could reduce ~15.2% of global methane emissions if implemented to their full technical potential (figure 4). Furthermore, a substantial fraction of

the methane mitigation potential from 'missed opportunity' sectors is achieved from only a handful of the largest methane emitting countries. For example, the ten largest missed opportunity sources globally emit 24.7% of global methane emissions, and mitigation measures fully implemented in these sectors could reduce ~13.2% of global emissions (table 3). These large missed opportunities include emissions from solid and liquid waste, rice production and enteric fermentation in China, and also the emissions from the largest 'missed opportunity' sectors in India, Brazil, Russia, Pakistan, and Indonesia (table 3).

4. Discussion

The lack of specification of methane reduction targets for countries and sectors in the GMPe meant that, upon its announcement, there was no roadmap (set of specific mitigation measures) identified that could lead to its achievement. NDCs are a useful starting point for defining a GMP roadmap because they often summarise the mitigation measures countries will implement to achieve overall climate change targets that already have national acceptance and endorsement, promoting consistency between achieving the GMP and reducing other GHGs. There is also an existing process for updating NDCs, which requires the submission of revised NDCs every five years, and which requires that updated NDCs are not less ambitious than the previous submission (United Nations 2015, 2021). This represents a process which could be used to progressively increase methane mitigation ambition, through the progressive inclusion of additional methane mitigation measures to achieve more ambitious climate change mitigation targets. This work shows that currently, a roadmap constructed from the 476 mitigation measures identified in major methane-emitted included in 168 NDCs can achieve a 31% reduction in global methane emissions, and hence achieve the GMP, only if all mitigation measures are implemented to their maximum technical reduction potential.

To achieve the GMP through a roadmap based on the mitigation measures included within NDCs currently, there are several important implications. Firstly, the necessity to implement all measures to their full technical potential does not reflect the level of ambition included in NDCs currently. Mostly, NDCs do not state quantitative targets and timelines for mitigation measures, and report only an overall GHG reduction target, and measures to achieve this (Malley *et al* 2022). Therefore, it is not possible from current NDCs, and associated documentation, to extract the specific implementation targets for methane-focussed mitigation measures.

However, GHG reduction targets in NDCs likely do not include maximum feasible technical implementation of methane mitigation measures. For example, the United States Methane Emission Reduction Roadmap includes implementation targets for methane-focussed mitigation measures included in its 2021 NDC (White House Office of Domestic Climate Policy 2021). Measures will reduce fugitive oil and gas emissions by 75%, and agricultural methane emissions by only 10%, both of which are below the maximum emission reduction factors used in this work (table 1). Hence accounting for implementation ambition of the methane-focused mitigation measures in NDCs, where specified, would likely reduce the global reduction in methane emissions from implementation of current NDCs below 30%.

Therefore, as countries update their NDCs, they should consider first explicitly stating the implementation target for methane-focussed mitigation measures (as well as those targeting other GHGs). This would allow assessment of the gap between the theoretical global methane emission reduction achievable from full technical implementation of the NDC mitigation measures, and the global methane emission reductions that could result from implementation of the NDC mitigation measures to the extent countries commit to implement them. There are a few countries which do outline the methane reductions expected from implementation of their NDCs (e.g. Japan, Nigeria), which could be used as examples for other countries (Federal Ministry of Environment Nigeria 2021, Government of Japan 2021, Malley *et al* 2022). Countries should also be encouraged to set the implementation target for their methane-focussed measures as close to the maximum technical emission reduction potential, to ensure the implementation of the measures achieves emission reductions consistent with achieving the GMP goal. For many low- and middle-income countries, this may require increases in international financing where a large portion of their NDCs are conditional on international support. However, overall climate financing is insufficient to achieve conditional climate change mitigation commitments, and only 2% of international climate change finance is targeted at methane mitigation (Rosane *et al* 2022).

Secondly, the GMP is a commitment among 149 countries and the European Union (EU) to work together to achieve a global methane reduction goal. The roadmap developed here based on mitigation measures included within NDCs to achieve the GMP highlights that the achievement of the GMP goal does not need to be achieved only through mitigation within GMP-participating countries. A substantial number of non-GMP countries have identified methane-targeted mitigation measures within their NDCs, and over 23% of the NDC mitigation measures in major methane sectors are in the NDCs of non-GMP-participating countries. It is important that countries outside the GMP are supported to implement their existing methane

mitigation measures, and are encouraged to increase their methane mitigation ambition within their NDCs. Available baseline methane emission projections, i.e. future methane emission estimates assuming no new policies or measures are enacted and implemented to reduce methane emissions, indicate a likely future increase in global anthropogenic methane emissions without implementation of additional mitigation policies and measures, and shifts in spatial and sectoral distributions (Höglund-Isaksson *et al* 2020, Ocko *et al* 2021, UNEP CCAC 2021). Therefore, without methane emission reductions in non-GMP countries, including major methane emitters, methane emission reductions within GMP-participating countries may be (a) insufficient to achieve a 30% reduction in emissions compared to 2020 levels, or (b) offset emission reductions achieved in GMP-participating countries due to increases in other countries where mitigation measures are not implemented.

Thirdly, there are several reasons why a roadmap for global methane mitigation may need to identify additional mitigation measures across countries and sectors that could mitigate more than 30% of global methane emissions in 2020. Increasing baseline methane emissions further emphasise the necessity to ensure that mitigation measures are implemented to their fullest extent possible to reduce emissions from existing sources, and to ensure that the measures are also applied to new sources over the next decade, and thereafter (e.g. new landfill sites). In addition, the GMP's methane reduction target is the minimum methane emission reduction estimated to be consistent with limiting global temperature increases to 1.5 °C. The most cost-effective pathway to achieving the 1.5 °C limit involves a 40% reduction in global methane emissions by 2030 (UNEP CCAC 2021). Hence to limit global temperature increases to 1.5 °C requires that the GMP is a floor for methane mitigation ambition, rather than a ceiling. The updating of NDCs with additional methane mitigation actions could serve to update the global roadmap presented here to achieve the GMP to ensure that it is consistent with science-based emission reductions to limit global temperature increases to 1.5 °C. By updating NDCs as the mechanism for clarifying the roadmap for achieving or exceeding the GMP, it can be ensured that the additional methane mitigation necessary is being achieved as a complement to, not replacement for, mitigation of carbon dioxide and other GHGs necessary to achieve the Paris Agreement targets (Myles *et al* 2018).

Those countries including methane mitigation measures in their NDCs should also consider enhancing their methane mitigation ambition through the substitution/addition of measures in major methane-emitting source sectors with greater methane emission reduction potential. In fossil fuel production, the necessity to reduce oil, gas and coal production to avoid exhausting the remaining carbon budget to limit warming to 1.5 °C has been highlighted (SEI *et al* 2021). Despite this, only one country has committed to avoiding fossil fuel expansion or exploration within their NDCs (Costa Rica). The broader consideration of managed reductions in fossil fuel production could not only further reduce methane emissions from this sector, but simultaneously reduce carbon dioxide emissions. Furthermore, in the agriculture and waste sectors, few countries currently include behavioural measures to shift to low-methane emitting diets, or reduce organic waste generation. These measures have higher potential to reduce methane emissions than technical measures, and contribute to multiple Sustainable Development Goals related to human health, and sustainable consumption and production, expanding the societal benefits from methane mitigation (Haines *et al* 2017).

Finally, the relatively low inclusion of methane-focussed mitigation measures in NDCs is in contrast to other GHGs. Approximately 89% of NDCs include mitigation measures on energy generation, and 81% on the transport sector, which together account for over 60% of global carbon dioxide emissions (UNFCCC Secretariat 2021). At COP26, the Glasgow Climate Pact *resolved* countries to undertake efforts to limit global temperature increases to 'well below 2 °C', and outlined the necessity for large-scale reductions in CO_2, and non-CO_2 GHGs, like, methane, consistent with scientific assessments (IPCC 2021, United Nations 2021). However, NDC GHG targets are currently consistent with approximately 2.4 °C or 'just under 2 °C' of global temperature increases (Climate Action Tracker 2021, Meinshausen *et al* 2022), necessitating additional emission reductions to avoid the worst climate change impacts. To increase climate change mitigation ambition, this study emphasises that a different strategy is required for carbon dioxide and methane. Most countries currently identify mitigation measures in major carbon dioxide emitting sectors (UNFCCC 2021, Malley *et al* 2022). Therefore, the implementation ambition of already committed measures needs to be increased to achieve a 1.5 °C-compatible carbon dioxide emission pathway. However, for methane, a large fraction of global emissions is emitted in countries and sectors without explicit commitments to implement mitigation measures in NDCs (figure 4). Hence there is a large climate change mitigation potential from reducing methane in fossil fuel production, agriculture and waste not currently reflected or included in official climate change mitigation commitments. As countries consider the request to update their NDCs before COP27, there is a large opportunity to increase global climate change mitigation ambition by including additional methane mitigation measures.

5. Conclusions

Global anthropogenic methane mitigation requires a boost in ambition, clarity and implementation if political goals and scientific necessities to limit global temperature increases to 1.5 °C are to be achieved. This baseline assessment of the mitigation measures outlined to achieve national climate change mitigation commitments indicates that these measures could reduce global methane emissions by ∼31%, only if all are implemented to their fullest extent, i.e. maximum technical reduction potential. This reduction would be consistent with the GMP goal (30% reduction from 2020 levels by 2030), but is below emission reductions in 1.5 °C-compatible emission reduction pathways (∼40% reduction). Practical recommendations to ensure that methane mitigation ambition is enhanced through NDC updates include: (a) identify and commit to mitigation measures in major methane emitting sectors omitted from current mitigation commitments, (b) report methane mitigation measures with sufficient clarity and transparency to understand the quantity of methane reduced from their implementation, i.e. clear implementation targets and timelines, and (c) ensure that these targets are as close to their technical maximum methane mitigation potential as possible. The implementation of these recommendations in future NDC updates provides the basis to progressively update this assessment to track progress on implementation of methane mitigation actions and the Global Methane Pledge.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://unfccc.int/NDCREG.

Acknowledgments

We are grateful to Martina Otto for insightful comments on the paper. C S M and J C I K acknowledge the Climate and Clean Air Coalition and the Stockholm Environment Institute Initiative on Integrated Climate and Development Planning for funding. The authors declare no competing interests.

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