European Commission

JRC TECHNICAL REPORT

Methane as a greenhouse gas

From 'unconventional' methane production and recovery to biological mitigation options: A literature review relying on text-mining tools

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2020

Joint Research Centre

EUR 30392

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EU Science Hub
https://ec.europa.eu/jrc

JRC121995

EUR 30392

PDF ISBN 978-92-76-22969-8 ISSN 1831-9424 doi:10.2760/09370

Luxembourg: Publications Office of the European Union, 2020

How to cite this report: Marmier, A., Schosger, J.-P., *Methane as greenhouse gas, From 'unconventional' methane production and recovery to biological mitigation options: A literature review relying on text-mining tools*, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-22969-8, doi:10.2760/09370, JRC121995.

Contents

Foreword

Methane is making the news. And the news is not always positive:

- *Nature Climate Change*, 10 June 2020: 'Remote sensing northern lake methane ebullition', https://www.nature.com/articles/s41558-020-0762-8.pdf, referred to by the NASA Earth Observatory: 'Satellites size up bubbles of methane in lake ice', https://earthobservatory.nasa.gov/images/146940/satellites-size-up-bubbles-of-methane-in-lake-ice
- *Nature*, 14 July 2020: 'Global methane levels soar to record high', https://www.nature.com/articles/d41586-020-02116-8
- *The Guardian*, 22 July 2020: 'First active leak of sea-bed methane discovered in Antarctica', https://www.theguardian.com/environment/2020/jul/22/first-active-leak-of-sea-bed-methane-discovered-in-antarctica
- *Science*, 28 July 2020: 'Siberia's "gateway to the underworld" grows as record heat wave thaws permafrost', https://www.sciencemag.org/news/2020/07/siberia-s-gateway-underworld-grows-record-heat-wave-thaws-permafrost
- Phys.org, 29 July 2020: 'New space satellite pinpoints industrial methane emissions', https://phys.org/news/2020-07-space-satellite-industrial-methane-emissions.html
- Space.com, 29 July 2020: 'Strange gas signature on Mars may help explain methane mystery', https://www.space.com/mars-atmosphere-gas-detections-methane-mystery.html
- Helmholtz Centre for Ocean Research Kiel (GEOMAR), 30 July 2020: 'New study confirms extensive gas leaks in the North Sea', https://www.eurekalert.org/pub_releases/2020-07/hcfo-nsc073020.php

This report builds on JRC's horizon scanning capacities, led within the JRC by the JRC.I2 unit. It dives deeper into the emerging issue of global warming, focusing on methane as a recovered or biogenerated primary energy source and on biological mitigation processes of methane, a potent greenhouse gas. It follows JRC.C7 involvement in negative emissions technologies in the framework of the Future and Emerging Technologies work package of the Low Carbon Energy Observatory, which highlighted the significant efforts to remove carbon dioxide from the atmosphere. Motivations for further work on methane are summarised in the JRC Science behind the Debate fact sheet JRC121991, while an overview of JRC activities related to methane is available in Annex 2.

Acknowledgements

The authors acknowledge the reviews provided by Elisa Boelman and Laura Contor (JRC.C7) and Robert Ziegler (JRC.C3).

Authors

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Abstract

This report aims to address climate change by focusing on methane (CH_4), a greenhouse gas with high global warming potential. Methane is the second most important greenhouse gas in terms of concentration and impact on the climate. This highlights the importance of focusing on processes that are able to lower the methane concentration in the atmosphere, where it is considered a significant contributor to climate change. This can be achieved by (a combination of) emissions avoidance, recovery, mitigation, capture and combustion or use.

This review, in itself, is also significant in terms of scientific process. The narrow literature review allowed for the (manual) definition of a mapping structure. By using text-mining tools, this structure can now be applied to a broader set of scientific documents. Such scaling up will enrich the mapping and help to enhance the mapping structure. This enhanced knowledge gathering will in turn lead to better mapping of ongoing activities and thus mapping of the gaps within.

The review analysed 109 scientific communications, mapped along various dimensions:

- by type of document: 17 documents reviewed specific aspects of methane;
- by environment (e.g. atmosphere, soil, freshwater and saline water) and by source of methane held in these environments;
- by process: methane production through methanogenesis, methane absorption for separation or for storage, genetic approaches, as well as methanotrophy, methane oxidation and methane conversion;
- by by- and co-products, such as carbonates, chromate, copper, iron, manganese, nitrous compounds (N_2O, NOx), ammonia, nitrate, sulfur and sulfate, but also fuels and chemicals, such as lactic acid, methanol and acetate;
- by technologies relying on living organisms and micro-organisms, such as biochar, biotrickling filtration, digesters, microbial fuel cells and relevant genetic technologies (e.g. next-generation sequencing), or relying on ((in)organic) materials such as membranes, sorbents or pressure swing absorption;
- by stage of development: demonstration or commercial projects, patents, estimates of the potential for methane emission reduction, quantified costs, other economic aspects, programmes and partnerships.

The review provides a list of possible technologies and constitutes a step towards finding the most cost-effective approaches to methane emission mitigation. It identifies processes and technologies for the biological oxidation of methane, as well as for methane recovery and controlled biomethane production. However, it also highlights how broad the topic is and the numerous questions that remain. As such, this review calls for additional and more targeted investigations. The most salient investigations are as follows:

- the ongoing efforts to thoroughly identify the spatial/geographical distribution of greenhouse gas sources to better understand the contributions of each greenhouse gas, source and sector to global warming;

  the role of microorganisms in methane production and mitigation and the ethics of genetically modifying such natural processes;
- the added value of joint anaerobic oxidation of methane and denitrification processes, leading to both nitrous oxide (N_2O) and CH_4 consumption, which are powerful greenhouse gases;
- the feasibility of developing the air capture/consumption of greenhouse gases besides and/or coupled to carbon dioxide (CO_2).

Technology is an enabler. Should the technological bottlenecks above be removed, the economic, environmental and social benefits could be realised.

1. Introduction

Three gases (carbon dioxide or CO_2, methane or CH_4 and nitrous oxide or N_2O) account for about 98 % of the global annual emissions of greenhouse gases (GHGs). CH_4, formed when four hydrogen atoms bond to one atom of carbon, is a molecule that is lighter than air. It is the primary component of natural gas, which generates roughly 22 % of the world's electricity, making it the largest primary energy source for electricity after coal.

In order to compare the warming potential of various GHGs over a certain period of time with that of CO_2, the Intergovernmental Panel on Climate Change (IPCC) has set up a common scale for measuring the climate effects of different gases. These are calculated as the global warming potential (GWP) and correspond to the mass of CO_2 needed to produce a similar warming effect over a given period of time, typically 20 and 100 years

In its Fifth Assessment Report (AR5) ([1]), the IPCC estimates the GWP of CH_4 to be 84 over a period of 20 years and 28 over a period of 100 years. Therefore, 1 tonne of emitted CH_4 can be considered to be equivalent to 28 tonnes of emitted CO_2 when looking at its warming impact over 100 years.

The current atmospheric concentrations of CO_2 and CH_4 are about 400 ppm and 2 ppm, respectively; therefore, the concentration of CH_4 is 200 times lower than that of CO_2. Nevertheless, this tiny fraction of CH_4 has a warming potential equivalent to $2 \times 28 = 56$ ppm of CO_2 over 100 years and $2 \times 84 = 168$ ppm of CO_2 over 20 years. Therefore, even though CH_4 is 200 times less concentrated than CO_2, its warming potential is only about seven times lower than that of CO_2 over a period of 100 years and about 40 % of the CO_2 warming potential over a period of 20 years.

Therefore, rising CH_4 concentrations in the atmosphere deserve special attention because of CH_4's significant potency as a GHG. Efforts to identify the various sources of CH_4 and mitigate its warming effects should be strengthened.

The objective of this study is to map CH_4 recovery and emission mitigation processes and technologies (including their current level of development), as well as CH_4 sources. While this mapping is not exhaustive, it nonetheless remains instrumental for issuing recommendations on emission reductions and atmospheric concentration reductions and in the effort to limit the impact of climate change and global warming.

([1]) IPCC, *Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*, IPCC, Geneva, Switzerland, 2014, available online at: https://www.ipcc.ch/assessment-report/ar5/, accessed 4.9.2020.

2. Methane recovery technologies and controlled biomethane production, starting from an economic perspective

Methane is considered to be a primary energy source and an energy carrier: an economic asset subject to its own market and geopolitics. Outside the traditional natural gas industry, which is generally not considered in this review, numerous technologies, including separation and concentration, target the economic production of CH_4. Patents (Air Liquide targets landfill gas-to-energy, 2007), demonstration or commercial projects (Bhattarai et al., 2017; Fei et al., 2020; He et al., 2018; Hur et al., 2017; Liu et al., 2020b; Kosmack et al., 2008; Rice, 1980; Utaki, 2010; Yang et al., 2016), programmes (Bracmort et al., 2014; Chianese et al., 2015) or partnerships (Industry news, 2004) refer primarily to the **fossil fuel industry** (e.g. from CH_4 recovery from coal mines to purification for injection into the natural gas grid). **Coal bed methane** can be used as a high-energy fuel. The concentration of CH_4 is, however, critical for its use (Liu et al., 2020a). Technologies for separating the gas mixtures from coal mines with low concentrations of CH_4 have been developed (Moiseev et al., 2016b). Besides fossil fuels, CH_4 is emitted from a number of sources (Bracmort et al., 2014), linked directly or indirectly to human activities. Some of these sources can be used for the controlled production of biomethane:

1. **animal residues** are a source of biogas (Wentworth et al., 1979), especially when coupled to digesters, a proven technology for the capture and use of the biomethane produced (Chianese et al., 2015);

2. the recovery and treatment of CH_4 generated by sanitary **landfills** is also a commercial reality (Rice, 1980), including the production of pipeline-grade biomethane from landfill gas (Cavenati et al., 2005) ([2]).

Hydrate-based gas separation technologies for CH_4 recovery from biogas have also gained prominence (Zang and Liang, 2018).

2.1. Current processes and technologies for methane concentration and upgrading

Various **physico-chemical (adsorption, absorption, cryogenic and membrane separations) and biological (*in situ* and *ex situ*) processes** exist for biogas upgrading (Kapoor et al., 2019). Important considerations for biogas cleaning and upgrading technologies include product purity and impurities; CH_4 recovery and loss; upgrading efficiency; and the investment and operating costs. In addition, the potential utilisation of the biogas and the corresponding requirements for gas quality are also important. Recommendations on the appropriate technology rely on comparisons between the technical features of the **upgrading technologies**, the specific requirements for different gas utilisations and the relevant investment and operating costs (Sun et al., 2015). Suitable technologies for CH_4 upgrading include **membrane separation, chemical adsorption** (Vignali and Vitale, 2017) and water scrubbing ([3]).

Adsorbents are already used for adsorption and enrichment of CH_4 from low-concentration gas mixtures (Liu et al., 2020a). Solid adsorbents have also been developed and tested to capture CH_4 emissions, ideally under atmospheric conditions, with the objective of developing new yet artificial remediation technologies (Delgado et al., 2018). Indeed, novel nanomaterials are being used as adsorbents for CO_2 and CH_4 with the objective of mitigating their emissions (Alonso et al., 2017). Nanomaterials used for CH_4 adsorption are divided into non-carbonaceous materials (e.g. zeolites, metal-organic frameworks and porous polymers) and carbonaceous materials (e.g. activated carbons, ordered porous carbons and activated carbon fibres) (Choi et al., 2016). Carbon-based materials, such as activated carbons, are promising as **storage** adsorbents for natural gas because of their high surface area, high porosity and high volumetric storage capacity (Poomisitiporn et al., 2016). **Technologies based on adsorbents** include the vacuum pressure swing adsorption unit (Cavenati et al., 2005; Utaki, 2010; Yang et al., 2018) and adsorption with displacement chromatography (Yang et al., 2016) for the recovery of ventilation air methane from coal mines. **Membranes for gas separation** have also been studied and are already used for the separation of CH_4 from air. Economics are dictated by the CH_4 concentration, making the technology less suited for mine ventilation exhaust (2 vol. per cent or less) than for

([2]) 'Horizon 2020 Store&Go project demonstrates new methanation technologies at three pilot sites', available online at: https://www.storeandgo.info/demonstration-sites/, accessed 4.9.2020.

([3]) Ofori-Boateng, C., Kwofie, E.M., 'Water scrubbing: a better option for biogas purification for effective storage', *World Applied Sciences Journal*, 5, pp. 122–125, available online at: https://www.researchgate.net/publication/265180428_Water_Scrubbing_A_Better_Option_for_Biogas_Purification_for_Effective_Storage, accessed 16.10.2020; Chandra, R., Vijay, V.K., Subbarao, P.M.V., 'Vehicular quality biomethane production from biogas by using an automated water scrubbing system', *International Scholarly Research Notices*, 2012, 904167, available online at: https://www.hindawi.com/journals/isrn/2012/904167/, accessed 4.9.2020.

gob hole [4] (mining cavities that have collapsed) methane-air mixtures with higher CH_4 concentrations (from 30 to 100 vol. per cent) (Garcia and Cervik, 1988). Each process is site and case specific (Kapoor et al., 2019).

2.2. Technologies behind biomethane production

Whether produced from manure or landfill or as fossil fuel, CH_4 is the product of biological processes and is derived from biological material. Digesters are a proven emission reduction technology and allow the capture and use of CH_4 produced by the anaerobic digestion of manures (Chianese et al., 2015). Further, anaerobic digestion technology and its economics make biogas production from selected animal residues worthy of development (Wentworth et al., 1979) and a reality [5]. Conventional anaerobic digestion, together with landfill gas recovery, have also been investigated for reducing emissions from municipal solid waste. Improved technology for enhancing CH_4 recovery from landfills appears to have greater potential than using conventional sludge digestion technology (Wise et al., 1981). It remains that these technologies rely on microorganisms and could therefore benefit from a biotrickling filter (BTF), which allows for the enrichment of microorganisms (Cassarini et al., 2019a) (see Chapter 3).

(4) Saki, S.A., *Gob ventilation borehole design and performance optimisation for longwall coal mining using computational fluid dynamics*, PhD thesis, January 2016, doi:10.13140/RG.2.1.5119.9129.

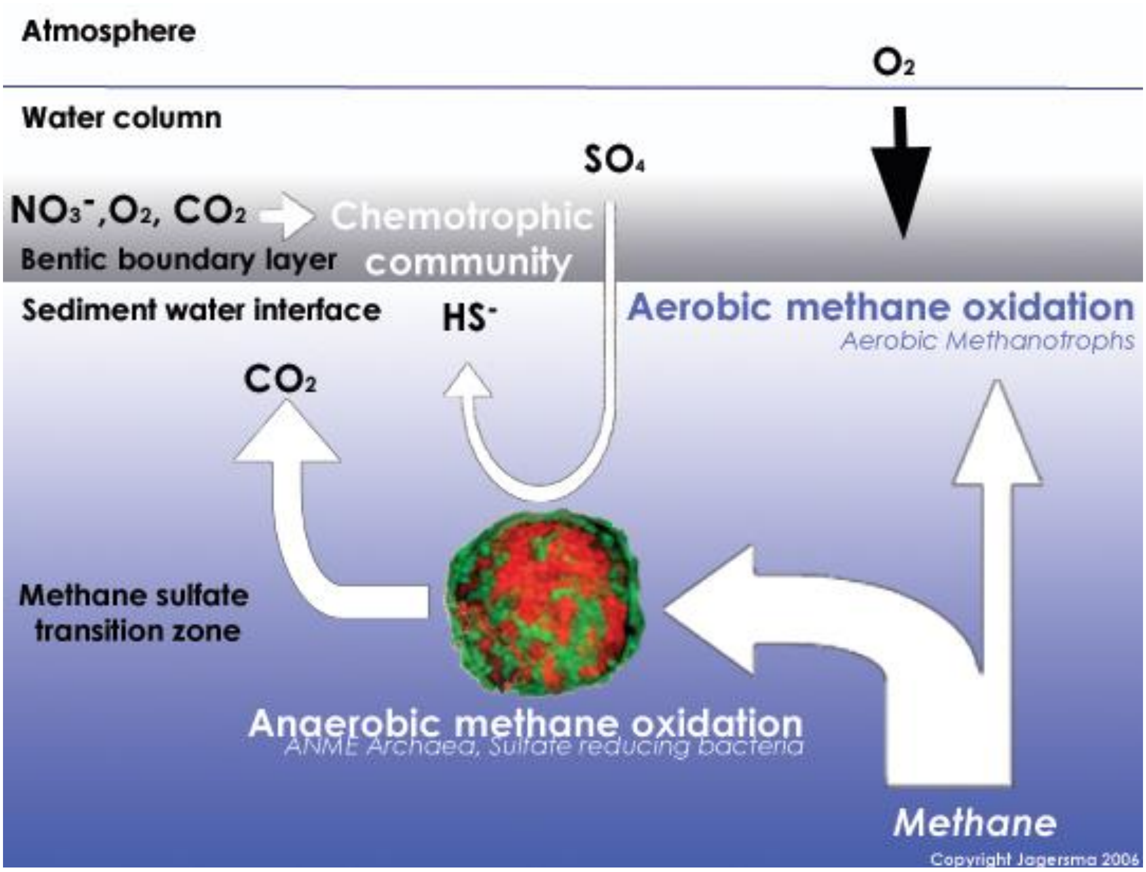
(5) Strauch, S., Krassowski, J., Singhal, A., *Biomethane Guide for Decision Makers – Policy guide on biogas injection into the natural gas grid*, WP2/D2.3, April 2013, available online at: https://www.dena.de/fileadmin/dena/Dokumente/Themen_und_Projekte/Erneuerbare_Energien/GreenGasGrids/Policy_Guide_for_Decision_Makers.pdf, accessed 4.9.2020.

3. Towards biological remediation strategies

Digestion stems from methanogenesis, a process in which microorganisms synthesise methane. This process takes place in most environments (soil (Gutknecht et al., 2006), including permafrost (Li et al., 2020), and water (Martinez-Cruz et al., 2017)). Together with other processes (such as nitrification and denitrification), methanogenesis influences atmospheric chemistry (Gutknecht et al., 2006).

Methanotrophs are bacteria capable of using CH_4 as their sole carbon source (Strong et al., 2015). Three major functional types of methanotrophs are known to consume CH_4: (1) anaerobic methane-oxidising archaea, also called anaerobic methanotrophs (ANME); (2) anaerobic methane-oxidising bacteria (NC10 phylum); and (3) aerobic methane-oxidising bacteria (Proteobacteria and Verrucomicrobia). These conduct different types of methanotrophy (Kalyuzhnaya et al., 2018), as shown in Figure 1.

Figure 1. Illustration of CH_4 oxidation (vertical air-water cross-section. The blue line represents the air-water interface). Anaerobic CH_4 oxidation is visualised by the red and green consortium, representing ANME and sulfate-reducing bacteria, respectively.



Source: WUR ([6]).

Considering CH_4 as a GHG, some of the above processes could be artificially enhanced and become instrumental in the reduction of emissions and atmospheric concentrations. These could be complemented by natural and industrial processes and technologies.

It should be noted that all biological oxidation processes oxidise CH_4 into CO_2, which is also a GHG, but with a significantly lower warming potential than CH_4.

Some of the newly discovered physiological types of anaerobic CH_4 oxidisers challenge the view of obligate syntrophy for the anaerobic oxidation of methane (AOM) (Bhattarai et al., 2019). It appears, for instance, that

([6]) Wageningen University and Research, 'Anaerobic oxidation of methane', available online at: https://www.wur.nl/en/show/Anaerobic-oxidation-of-methane.htm, accessed 4.9.2020.

ANME can also produce CH_4, but only during net CH_4 oxidation (i.e. enzymatic back-flux) (Timmers et al., 2017).

AOM is catalysed by ANME via a **reverse and modified methanogenesis pathway**. The reversibility of the methanogenesis pathway and essential differences between ANME and methanogens have been subject to **genetic investigations** (Timmers et al., 2017). Other potential technologies for CH_4 consumption linked to genetic investigations include the following:

- Next-generation sequencing (NGS) opens up possibilities for improving our knowledge of microorganisms (Cruaud et al., 2014).
- The *pmoA* gene sequence diversity highlights the diversity of cultivated and uncultivated aerobic methanotrophic bacteria (Knief, 2015).

This knowledge will enable progress to be made towards **engineering** native methanotrophs for aerobic and anaerobic CH_4 utilisation and synthetic methylotrophs for methanol utilisation (Bennett et al., 2018) or the production of other chemicals (Lieven et al., 2018).

The study of hydrate environments has allowed the recovery of 124 379 bacterial and 130 351 archaeal reads. This has provided insights into the **distributions and capacities of microbial communities** (Lin et al., 2014).

Regarding microbial capacities, the reduction of sulfate, nitrite/nitrate and iron/manganese can be coupled with AOM (Luo et al., 2019). Net AOM is actually exergonic when coupled to an external electron acceptor (Timmers et al., 2017). This redox process leads to the formation of two main biomineral by-products: calcium carbonates and iron sulfides (Wrede et al., 2013a). However, methanotrophic bacteria have numerous potential **biotechnological applications**, thereby generating value while using CH_4 as a carbon source (Strong et al., 2015). These include **microbial fuel cells** (McAnulty et al., 2017) for electricity production; metal-AOM (He et al., 2018) for the production of iron and manganese, carbonates (Chen et al., 2014; Wrede et al., 2013a,b), chromate (Lv et al., 2019), copper (Kampman et al., 2014; Ro and Rosenzweig, 2018; Semrau et al., 2010; Ve et al., 2012), nitrous compounds (He et al., 2018; Kampman et al., 2014; Kolb and Horn, 2012; Li et al., 2020; Lin et al., 2014; Luo et al., 2019; McAnulty et al., 2017; Mei et al., 2019; Menyailo et al., 2008; Modin et al., 2008; Ren et al., 2018; Rissanen et al., 2018; Shi et al., 2019; Strong et al., 2015; Sun et al., 2013; Timmers et al., 2017; Urbanová et al., 2011; Vaksmaa et al., 2016; van Grinsven et al., 2020; Winkel et al., 2018; Xie et al., 2018), sulfur (Aromokeye et al., 2020; Bar-Or et al., 2017; Bhattarai et al., 2017; Bhattarai et al., 2018, 2019; Bomberg et al., 2015; Cassarini et al., 2019a,b,c; Chen et al., 2014; Cruaud et al., 2015; Gutknecht et al., 2006; Hatzenpichler et al., 2016; He et al., 2018; Lin et al., 2014; Luo et al., 2019; McAnulty et al., 2017; Mei et al., 2019; Ren et al., 2018; Scheller et al., 2016; Skennerton et al., 2017; Timmers et al., 2017; Valenzuela et al., 2017; van Grinsven et al., 2020; Vigneron et al., 2019; Winkel et al., 2018; Wrede et al., 2013a,b) or the transformation of CH_4 in fuels and chemicals (Bennett et al., 2018), lactic acid (Fei et al., 2020), methanol (Hur et al., 2017; Ito et al., 2018; Wrede et al., 2013b) and acetate (McAnulty et al., 2017); and other numerous applications (Strong et al., 2015).

Regarding their distribution, ANME groups occur widely in association with gas hydrates, cold seeps and organic-rich thermal sediments, as well as in anoxic water bodies such as the Black Sea and Cariaco Basin (Jiao et al., 2012). Methanotrophy (at large) takes place in various environments, such as wetlands (Gutknecht et al., 2006) and the deep oceans and marine sediments (Jiao et al., 2012). However, climate change and global warming stem from the accumulation of GHGs in the **atmosphere**. There is thus an interest in focusing on the capture of CH_4 under conditions related to the atmospheric environment.

- The microbiota of acidic wetlands seem to consume both atmospheric CH_4 (likely through *Methylocystis*-related species) and atmospheric N_2O (through denitrifier communities) (Kolb and Horn, 2012).
- Although afforestation is beneficial for atmospheric CO_2 assimilation, it shows negative effects on CH_4 uptake from well-aerated grassland in Siberia (Menyailo et al., 2008).
- Airborne methanotrophs are also found in air and rainwater. Once enriched, they have been successfully used for the degradation of atmospheric CH_4 (Šantl-Temkiv et al., 2013).

A BTF enables the enrichment of microorganisms, such as those mediating AOM (Cassarini et al., 2019a; Ito et al., 2018). This technology may potentially support natural processes in the consumption of CH_4. A biotrickling filtration system composed of methane-consuming bacteria has been modelled to assess the utility of these systems in removing CH_4 from the atmosphere. While the current atmospheric CH_4 concentration does not allow use of this technology, this approach could be applied to other environments with higher CH_4 concentrations, such as landfills or factory farms (Yoon et al., 2009). Although there are indeed limitations of ANME laboratory-based cultivation systems, as well as advantages and potential improvements to be made (Bhattarai et al., 2019), such systems enable the study of the characteristics of CH_4 bio-oxidation and methane-oxidising microorganisms (Mei et al., 2019), facilitating progress in their development for the consumption of CH_4.

The biotrickling filtration system (Yoon et al., 2009) is one of the few technologies to have been assessed from the perspectives of its **CH_4 emission reduction potential** (Annachhatre and Khanna, 1987; Aromokeye et al., 2020; Hur et al., 2017; Industry news, 2004; Kosmack et al., 2008; Li et al., 2020; Lima et al., 2008; Liu et al., 2020b; Mei et al., 2019; Sanchis-Perucho et al., 2020; Serrano-Silva et al., 2014; Shi et al., 2020; Utaki, 2010; Vaksmaa et al., 2016; Valenzuela et al., 2017; Winkel et al., 2018; Yang et al., 2016; Yoon et al., 2009; Zhang et al., 2019) and its **economics/costs** (Fei et al., 2020; Yoon et al., 2009). This demonstrates that such CH_4 emission mitigation technologies are at an early stage of development. However, innovation is ongoing, for instance work on CH_4 cracking/pyrolysis for the production of clean hydrogen and solid carbon for storage ([7]).

([7]) TNO, 'EMBER methane pyrolysis technology produces hydrogen without CO_2 emissions', available online at: https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/towards-co2-neutral-fuels-and-feedstock/hydrogen-for-a-sustainable-energy-supply/optimising-production-hydrogen/ember-methane-pyrolysis/, accessed 4.9.2020.

4. Recommendations and open questions

This review, together with its accompanying fact sheet (8), identified the following areas for further investigation.

4.1. Knowledge gathering and sharing

- Develop a list of definitions, abbreviations and acronyms linked to the topic.
- (Further support ongoing efforts (9) to) Identify spatial/geographical distributions of GHG sources to better understand the contributions of each GHG/source/sector to global warming, possibly through satellite imaging.
- Identify GHG consumption processes and technologies, also possibly linked to GHG sources.
- (Linked to the discussion on afforestation) Assess the environment and sources of emissions at GWP level, instead of focusing on individual GHGs separately.
- This review is significant in terms of scientific process. The narrow literature review allowed for the (manual) definition of a mapping structure (see the structure presented above). By using text-mining tools, this structure can now be applied to a broader set of scientific documents. Such scaling up will enrich the mapping and help to enhance the mapping structure. This enhanced knowledge gathering will in turn lead to better mapping of ongoing activities and thus mapping of the gaps within.

4.2. Specific emissions and atmospheric concentration mitigation options

- Develop more accurate CH_4 emission measurement methodologies to enable convergence of the current bottom-up and top-down approaches in order to significantly reduce uncertainties (8).
- Identify procedures to identify CH_4 leakages in industrial installations and upgrade installations to prevent these leakages and promote the recovery of the leaked CH_4 (8).
- Set up monitoring procedures for former fossil fuel exploitation sites (decommissioned coal mines, decommissioned oil and gas wells) to ensure long-term control of potential CH_4 emissions (8).
- Increase knowledge of CH_4 production as a by-product of agricultural processes (ruminant animals, flooded rice fields, animal waste and biomass) in order to control and mitigate such emissions.
- Investigate biological processes for joint AOM and denitrification, leading to both N_2O and CH_4 consumption.
- Investigate the feasibility of developing the air capture/consumption of GHGs besides and/or coupled to CO_2.
- Identify possible/more targeted topics for future fact sheets, such as CH_4 cracking. This process was not identified through this literature review, although it has potential for the decarbonisation of the hydrogen production process.

4.3. Ethical aspects

- Reflect on (ongoing) progress, objectives and, above all, risks linked to gene editing for modifying microorganisms. Considering the limited knowledge of methanogenesis and natural processes for CH_4 consumption (reverse methanogenesis and methanotrophy), such techniques may have significant potential for addressing (natural) CH_4 emissions. Gene editing, however, remains a sensitive topic.
- Carry out a benefit–risk analysis of the use of genetically modified organisms in controlled and uncontrolled conditions to mitigate CH_4 emissions compared with the consequences of CH_4 emissions for climate change.

(8) JRC, 'The special case of methane emissions, a potent greenhouse gas', JRC121991, 2020.

(9) European Space Agency, 'Mapping methane emissions on a global scale', 2020, available at: https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P/Mapping_methane_emissions_on_a_global_scale, accessed 20.10.2020; IEA, 'Global methane emissions from oil and gas', 2020, available at: https://www.iea.org/articles/global-methane-emissions-from-oil-and-gas, accessed 20.10.2020; NASA, 'New 3D view of methane tracks sources and movement around the globe', 2020, available at: https://www.nasa.gov/feature/goddard/2020/new-3d-view-of-methane-tracks-sources-and-movement-around-the-globe, accessed 16.10.2020.

5. Conclusions

Methane is a primary energy source that fuels one-quarter of the modern economy. It is mostly burned to produce heat and power. This process leads to massive CO_2 emissions that trigger climate change. As well as producing CO_2 emissions, CH_4 itself is also a powerful GHG and therefore is worthy of focused attention.

Methane emissions should be prevented because of CH_4's high GWP. The CH_4 concentration in the atmosphere has doubled since the start of the industrial age in 1750, probably because of leakages and its production as a by-product of the fossil fuel industries, as well as its production as a result of biological processes in agriculture. Efforts should be made to control and mitigate these emissions.

This review identifies processes and technologies for the biological oxidation of CH_4, as well as for CH_4 recovery and controlled biomethane production. It provides a list of possible options for CH_4 emission mitigation, to slow down the increase in CH_4 atmospheric concentrations or even reduce them. In order to foster the deployment of such technologies, further (techno-economic) analysis is recommended. This, however, requires a change of mindset: while CH_4 can be useful, it is also harmful to the environment.

Further, this review, in itself, is significant in terms of scientific process: The narrow literature review allowed the manual definition of a mapping structure. By using text-mining tools, this structure can now be applied to a broader set of scientific documents. Such scaling up will enrich the mapping and help to enhance the mapping structure. This enhanced knowledge gathering will in turn lead to better mapping of ongoing activities and thus a mapping of the gaps within.

References

The following references were retrieved from Scopus using searches for CH_4 capture-related articles.

With the objective of assessing the field, the (generic) query TITLE-ABS-KEY ((methan OR methane OR ch4) AND (greenhouse AND gases OR greenhouse AND gas OR ghg)) retrieved 14 338 results, continuously increasing from four in 1980 to 1 400 in 2019.

For the purpose of this study, the literature search was narrowed along two axes:

- With the objective of identifying technologies for 'CH4 removal', the query TITLE-ABS-KEY ((methan OR methane OR ch4) W/5 (capture OR recovery OR adsorption) AND technology) retrieved 896 results.
- With the objective of investigating (human enhancement of) the natural process of 'methanothrophy', the query ALL (artific* W/5 methano*) retrieved 521 results.

The large number of articles retrieved in the initial searches was reduced by focusing on those listed below:

- those from the 'CH4 removal' list that referred to technology in their abstract;
- those from the 'methanothrophy' list that referred to methanotrophs in their abstract; the relevance of the remaining articles was then assessed.

In addition to the 109 references listed below, eight additional references are provided as footnotes in the report. These eight references were not identified through the above searches; however, they do provide information of relevance for this report.

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List of abbreviations and definitions

ANME	anaerobic methanotroph (anaerobic methane-oxidizing archaea)
AOM	anaerobic oxidation of methane
BTF	biotrickling filter
CH_4	methane
CO_2	carbon dioxide
GHG	greenhouse gas
GWP	global warming potential
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
MOF	metal–organic framework
N_2O	nitrous oxide
NGS	next-generation sequencing

List of figures

Annexes

Annex 1: Literature mapping – Clustering of publications

This review analysed 109 scientific communications, mapped along various dimensions:

- by type of document: 17 documents reviewed specific aspects of CH_4;
- by environment (e.g. atmosphere, soil, freshwater and saline water) and by source of methane held in these environments;
- by process: methane production through methanogenesis, methane absorption for separation or for storage, genetic approaches, as well as methanotrophy, methane oxidation and methane conversion;
-
- by by- and co-products, such as carbonates, chromate, copper, iron, manganese, nitrous compounds (N_2O, NOx), ammonia, nitrate, sulfur and sulfate, but also fuels and chemicals, such as lactic acid, methanol and acetate;
- by technologies relying on living organisms and microorganisms, such as biochar, biotrickling filtration, digesters, microbial fuel cells and relevant genetic technologies (e.g. NGS), or relying on ((in)organic) materials such as membranes, sorbents or pressure swing absorption;
- by stage of developments: demonstration or commercial projects, patents, estimates of the potential for CH_4 emission reduction, quantified costs, other economic aspects, programmes and partnerships.

Types of documents

Few references review specific aspects of CH_4 production, concentration and consumption (Alonso et al., 2017 ; Bennett et al., 2018; Bhattarai et al., 2019; Choi et al., 2016; Garcia and Cervik, 1988; Gutknecht et al., 2006; He et al., 2018; Jiao et al., 2012; Kapoor et al., 2019; Knief, 2015; Lieven et al., 2018; Liu et al., 2020a; Strong et al., 2015; Sun et al., 2015; Timmers et al., 2017; Wentworth et al., 1979; Wise et al., 1981). These references are highlighted in bold in the rest of this chapter.

Environments and sources of methane

Atmosphere (Delgado et al., 2018; Kolb and Horn, 2012; Menyailo et al., 2008; Šantl-Temkiv et al., 2013; Yoon et al., 2009).

Soil:

- coal (Bracmort et al., 2014; Cramer et al., 2009; **Garcia and Cervik, 1988;** Industry news, 2004; Kosmack et al., 2008; Leisle and Kovalski, 2018; **Liu et al., 2020a;** Moiseev et al., 2016a,b; Poomisitiporn et al., 2016; Shi et al., 2020; Ternet'ev et al., 1996; Utaki, 2010; Yang et al., 2016, 2018);
- farms (animals, digestion, manure) (Bracmort et al., 2014; Chianese et al., 2015; Petersen and Ambus, 2006; **Wentworth et al., 1979;** Yoon et al., 2009);
- forest and grassland (Menyailo et al., 2008);
- hydrates (**Jiao et al., 2012;** Lin et al., 2014; Moiseev et al., 2016b; Zang and Liang, 2018);
- landfills (Air Liquide targets landfill gas-to-energy, 2007; Bracmort et al., 2014; Cavenati et al., 2005; Industry news, 2004; Mei et al., 2019; Reddy et al., 2020; Rice, 1980; **Wise et al., 1981;** Yoon et al., 2009);
- mud volcanoes (Bhattarai et al., 2018; Ren et al., 2018);
- other fossil fuels (oil and gas production, natural and shale gas, gob gas) (Ajayi et al., 2015; **Bennett et al., 2018;** Bracmort et al., 2014; Fei et al., 2020; **Garcia and Cervik, 1988;** Hur et al., 2017; Industry news, 2004; Moiseev et al., 2016b; Poomisitiporn et al., 2016; Shi et al., 2020);
- paddy fields (Li et al., 2020; Vaksmaa et al., 2016);
- peatlands (Urbanová et al., 2011);
- solid waste (Vignali and Vitale, 2017; Reddy et al., 2020; **Wise et al., 1981);**

— Undefined soil (**Gutknecht et al., 2006;** Jiang et al., 2016; Kolb and Horn, 2012; Kwon et al., 2017; Li et al., 2020; Menyailo et al., 2008; Nazaries et al., 2018; Reddy et al., 2020; Šantl-Temkiv et al., 2013; Serrano-Silva et al., 2014; Urbanová et al., 2011; Vaksmaa et al., 2016; Zhang et al., 2019);

— wetlands (**Gutknecht et al., 2006**; Kolb and Horn, 2012; Kwon et al., 2017; Liu et al., 2020b; Valenzuela et al., 2017; Zhu et al., 2007).

Freshwaters:

— dams (Lima et al., 2008);

— lakes (Bar-Or et al., 2017; Bhattarai et al., 2017; Cassarini et al., 2019c; Martinez-Cruz et al., 2017; Rissanen et al., 2018; van Grinsven et al., 2020);

— wastewater (Cashman et al., 2018; Cassarini et al., 2019a; Henares et al., 2016; Kampman et al., 2014; Li et al., 2020; Liu et al., 2020b; Modin et al., 2008; Sanchis-Perucho et al., 2020; **Strong et al., 2015);**

— water hyacinths (Annachhatre and Khanna, 1987).

Saline waters:

— oceans (Chen et al., 2014; Hatzenpichler et al., 2016; **Jiao et al., 2012**; Semrau et al., 2010; Skennerton et al., 2017; Zhai et al., 2019);

— marine environments (Aromokeye et al., 2020; Bhattarai et al., 2017; **Bhattarai et al., 2019;** Bomberg et al., 2015; Cassarini et al., 2019c; Chen et al., 2014; Cruaud et al., 2014, 2015; **Jiao et al., 2012;** Lin et al., 2014; Orphan et al., 2002; Rubin-Blum et al., 2019; Scheller et al., 2016; Vigneron et al., 2019; Winkel et al., 2018);

— saline lakes (Serrano-Silva et al., 2014);

— seas (Aromokeye et al., 2020; Bhattarai et al., 2018; **Bhattarai et al., 2019;** Cassarini et al., 2019a,b; Chen et al., 2014; Cruaud et al., 2014, 2015; **Jiao et al., 2012;** Rubin-Blum et al., 2019; Scheller et al., 2016; Vigneron et al., 2019; Wrede et al., 2013a,b).

Processes

CH_4 production (methanogenesis) (Bhattarai et al., 2017; Cruaud et al., 2014; **Gutknecht et al., 2006;** Kwon et al., 2017; Li et al., 2020; Liu et al., 2020b; Martinez-Cruz et al., 2017; Urbanová et al., 2011; Zhu et al., 2007).

Genetic approaches (Bhattarai et al., 2017; Bomberg et al., 2015; Cassarini et al., 2019b; Cruaud et al., 2014, 2015; Hatzenpichler et al., 2016; **Knief, 2015;** Kolb and Horn, 2012; Li et al., 2020; Lin et al., 2014; Luo et al., 2019; Lv et al., 2019; Mei et al., 2019; Nazaries et al., 2018; Orphan et al., 2002; Reddy et al., 2020; Ren et al., 2018; Rissanen et al., 2018; Ro and Rosenzweig, 2018; Rubin-Blum et al., 2019; Šantl-Temkiv et al., 2013; Semrau et al., 2010; Serrano-Silva et al., 2014; Shi et al., 2019; Skennerton et al., 2017; Vaksmaa et al., 2016; van Grinsven et al., 2020; Vigneron et al., 2019; Winkel et al., 2018; Xie et al., 2018; Zhang et al., 2019).

Absorption (Abbott et al., 2011; **Alonso et al., 2017;** Cavenati et al., 2005; **Choi et al., 2016;** Delgado et al., 2018; **Kapoor et al., 2019;** Kostoglou et al., 2017; **Liu et al., 2020a;** Mahmoudian et al., 2016; Moiseev et al., 2016b; Poomisitiporn et al., 2016; Rashidi et al., 2011; Shi et al., 2020; Ternet'ev et al., 1996; Ursueguía et al., 2020; Utaki, 2010; Vignali and Vitale, 2017; Yang et al., 2018; Yang et al., 2016):

— for separation (Abbott et al., 2011; **Alonso et al., 2017;** Cavenati et al., 2005; **Kapoor et al., 2019;** Kostoglou et al., 2017; Moiseev et al., 2016b; Shi et al., 2020; Ternet'ev et al., 1996; Vignali and Vitale, 2017; Yang et al., 2016, 2018);

— for storage (Abbott et al., 2011; **Alonso et al., 2017; Choi et al., 2016;** Kosmack et al., 2008; Kostoglou et al., 2017; Mahmoudian et al., 2016; Poomisitiporn et al., 2016; Rashidi et al., 2011).

Separation processes not explicitly based on adsorption (Air Liquide targets landfill gas-to-energy, 2007; Ajayi et al., 2015; Annachhatre and Khanna, 1987; Cramer et al., 2009; Fei et al., 2020; **Garcia and Cervik, 1988;** Leisle and Kovalski, 2018; Moiseev et al., 2016a; Rice, 1980; **Sun et al., 2015;** Zang and Liang, 2018).

CH_4 consumption is mainly carried out by oxidation, but also by conversion:

— conversion (**Bennett et al., 2018;** Fei et al., 2020; Hur et al., 2017; Ito et al., 2018; McAnulty et al., 2017; **Strong et al., 2015**; Wrede et al., 2013b);

— methanotrophy (Aromokeye et al., 2020; Bar-Or et al., 2017; **Bennett et al., 2018;** Bhattarai et al., 2017, 2018; **Bhattarai et al., 2019;** Bomberg et al., 2015; Casey et al., 2004; Cassarini et al., 2019a,b,c; Chen et al., 2014; Cruaud et al., 2014, 2015; Fei et al., 2020; **Gutknecht et al., 2006;** Hatzenpichler et al., 2016; **He et al., 2018;** Hur et al., 2017; Ito et al., 2018; Jiang et al., 2016; **Jiao et al., 2012;** Kalyuzhnaya et al., 2018; Kampman et al., 2014; **Knief, 2015;** Kolb and Horn, 2012; Kwon et al., 2017; Li et al., 2020; **Lieven et al., 2018;** Lin et al., 2014; Liu et al., 2020b; Luo et al., 2019; Lv et al., 2019; Martinez-Cruz et al., 2017; McAnulty et al., 2017; Mei et al., 2019; Menyailo et al., 2008; Modin et al., 2008; Myung et al., 2017; Nazaries et al., 2018; Orphan et al., 2002; Petersen and Ambus, 2006; Reddy et al., 2020; Ren et al., 2018; Rissanen et al., 2018; Ro and Rosenzweig, 2018; Rubin-Blum et al., 2019; Šantl-Temkiv et al., 2013; Scheller et al., 2016; Semrau et al., 2010; Serrano-Silva et al., 2014; Shi et al., 2019; Skennerton et al., 2017; **Strong et al., 2015;** Sun et al., 2013; **Timmers et al., 2017;** Urbanová et al., 2011; Vaksmaa et al., 2016; Valenzuela et al., 2017; van Grinsven et al., 2020; Ve et al., 2012; Vigneron et al., 2019; Winkel et al., 2018; Wrede et al., 2013a,b; Xie et al., 2018; Yoon et al., 2009; Zhai et al., 2019; Zhang et al., 2019; Zhu et al., 2007);

— methylotrophy (**Bennett et al., 2018;** Jiang et al., 2016; **Lieven et al., 2018;** Martinez-Cruz et al., 2017; Reddy et al., 2020; Rubin-Blum et al., 2019; Wrede et al., 2013b; Xie et al., 2018);

— other oxidation, not explicitly linked to reduction (**Bhattarai et al., 2019;** Casey et al., 2004; Jiang et al., 2016; Kalyuzhnaya et al., 2018; Kosmack et al., 2008; **Knief, 2015;** Kwon et al., 2017; Mei et al., 2019; Menyailo et al., 2008; Orphan et al., 2002; Petersen and Ambus, 2006; Reddy et al., 2020; Šantl-Temkiv et al., 2013; Semrau et al., 2010; Sun et al., 2013; Ve et al., 2012) and including:

  - hydroxylation (Ito et al., 2018);
  - photooxidation (Šantl-Temkiv et al., 2013);

— redox (oxidation and reduction) (Aromokeye et al., 2020; Bar-Or et al., 2017; Bhattarai et al., 2017, 2018; Cassarini et al., 2019a,b,c; Chen et al., 2014; Hatzenpichler et al., 2016; **He et al., 2018;** Liu et al., 2020b; Luo et al., 2019; Lv et al., 2019; Martinez-Cruz et al., 2017; Modin et al., 2008; Ren et al., 2018; Rissanen et al., 2018; Scheller et al., 2016; Serrano-Silva et al., 2014; Shi et al., 2019; Skennerton et al., 2017; **Timmers et al., 2017;** Vaksmaa et al., 2016; Valenzuela et al., 2017; van Grinsven et al., 2020; Vigneron et al., 2019; Winkel et al., 2018; Wrede et al., 2013a,b; Xie et al., 2018; Zhai et al., 2019; Zhang et al., 2019);

— reduction, not explicitly linked to oxidation (Cruaud et al., 2015; **Gutknecht et al., 2006;** Kolb and Horn, 2012; McAnulty et al., 2017);

— reverse methanogenesis (**Lieven et al., 2018;** Lv et al., 2019; **Timmers et al., 2017;** Wrede et al., 2013b).

Both conversion and reduction are linked to by- and co-products.

By- and co-products:

— carbonates (Chen et al., 2014; Wrede et al., 2013a,b);

— chromate (Lv et al., 2019);

— copper (Kampman et al., 2014; Ro and Rosenzweig, 2018; Semrau et al., 2010; Ve et al., 2012);

— iron (Aromokeye et al., 2020; Bar-Or et al., 2017; **Gutknecht et al., 2006;** Martinez-Cruz et al., 2017; Ren et al., 2018; Wrede et al., 2013a);

— manganese (**He et al., 2018;** Liu et al., 2020b; Luo et al., 2019; Rissanen et al., 2018; Winkel et al., 2018);

— nitrous compounds (N_2O, NOx, nitrous, ammonia, nitrate, nitrous, (de)nitrifi(cation/er)) (**He et al., 2018;** Kampman et al., 2014; Kolb and Horn, 2012; Li et al., 2020; Lin et al., 2014; Luo et al., 2019; McAnulty et al., 2017; Mei et al., 2019; Menyailo et al., 2008; Modin et al., 2008; Ren et al., 2018; Rissanen et al., 2018; Shi et al., 2019; **Strong et al., 2015;** Sun et al., 2013; **Timmers et al., 2017;** Urbanová et al., 2011; Vaksmaa et al., 2016; van Grinsven et al., 2020; Winkel et al., 2018; Xie et al., 2018);

— sulfur/sulphur/sulfate (Aromokeye et al., 2020; Bar-Or et al., 2017; Bhattarai et al., 2017, 2018; **Bhattarai et al., 2019;** Bomberg et al., 2015; Cassarini et al., 2019a,b,c; Chen et al., 2014; Cruaud et al., 2015; **Gutknecht et al., 2006;** Hatzenpichler et al., 2016; **He et al., 2018;** Lin et al., 2014; Luo et al., 2019; McAnulty et al., 2017; Mei et al., 2019; Ren et al., 2018; Scheller et al., 2016; Skennerton et al., 2017; **Timmers et al., 2017;** Valenzuela et al., 2017; van Grinsven et al., 2020; Vigneron et al., 2019; Winkel et al., 2018; Wrede et al., 2013a,b).

Further, the conversion process indicated above leads to the transformation of CH_4 in fuels and chemicals (**Bennett et al., 2018),** lactic acid (Fei et al., 2020), methanol (Hur et al., 2017; Ito et al., 2018; Wrede et al., 2013b) and acetate (McAnulty et al., 2017), and has other numerous applications (**Strong et al., 2015).**

Technologies

CH_4 technologies can be divided into two categories: those based on living organisms and those of a mineral nature.

Numerous living organisms support the processes of methanotrophy, methylotrophy and (reverse) methanogenesis, including Euryarchaeota (phylum), *Candidatus* Methanoperedens (genus), *Candidatus* Methanoperedens nitroreducens (species), *Methanosarcina mazei* (species), Candidatus Bathyarchaeota (phylum), Thaumarchaeota (phylum), *Moheibacter* (genus), Proteobacteria (phylum), *Hyphomicrobium* (genus), *Methylocystis* (genus), *Methylosinus* (genus), *Methylosinus trichosporium* OB3b (species), *Cupriavidus* (genus), *Variovorax* (genus), *Methylophilus* (genus), *Methylobacter* (genus), *Methylocaldum* (genus), *Methylococcus capsulatus* (species), *Methylomicrobium alcaliphilum* (species), *Methylomonas* (genus), *Candidatus* Methyloumidiphilus alinensis (species), Verrucomicrobia (class), *Candidatus* Methylomirabilis oxyfera (species) ([10]) (Aromokeye et al., 2020; Bar-Or et al., 2017; Bhattarai et al., 2017; Bomberg et al., 2015; Cassarini et al., 2019a,b; Hatzenpichler et al., 2016; Jiang et al., 2016; **Jiao et al., 2012;** Kalyuzhnaya et al., 2018; Kampman et al., 2014; Knief, 2015; Kolb and Horn, 2012; Liu et al., 2020b; Luo et al., 2019; Lv et al., 2019; Martinez-Cruz et al., 2017; McAnulty et al., 2017; Mei et al., 2019; Orphan et al., 2002; Reddy et al., 2020; Rissanen et al., 2018; Ro and Rosenzweig, 2018; Rubin-Blum et al., 2019; Šantl-Temkiv et al., 2013; Serrano-Silva et al., 2014; Shi et al., 2019; **Timmers et al., 2017;** Vaksmaa et al., 2016; van Grinsven et al., 2020; Ve et al., 2012; Vigneron et al., 2019; Winkel et al., 2018; Zhai et al., 2019; Zhang et al., 2019; Zhu et al., 2007).

Technologies relying on these **micro-organisms** are mainly related to biomethane production and CH_4 consumption:

— **biochar** (Reddy et al., 2020; Zhang et al., 2019);

— **biotrickling filtration** (Cassarini et al., 2019a,b; Yoon et al., 2009);

— **digesters** (Bracmort et al., 2014; Chianese et al., 2015; Vignali and Vitale, 2017; **Wentworth et al., 1979; Wise et al., 1981;** Xie et al., 2018);

— **microbial fuel cells** (McAnulty et al., 2017).

For separation/adsorption processes, **mineral-based technologies** predominate:

Membranes (Air Liquide targets landfill gas-to-energy, 2007; Ajayi et al., 2015; Bhattarai et al., 2018; Casey et al., 2004; Cashman et al., 2018; Cramer et al., 2009; **Garcia and Cervik, 1988;** Henares et al., 2016; Ito et al., 2018; Kampman et al., 2014; **Kapoor et al., 2019;** Luo et al., 2019; Lv et al., 2019; Modin et al., 2008; Moiseev et al., 2016b; Sanchis-Perucho et al., 2020; Shi et al., 2019; Sun et al., 2013; Vignali and Vitale, 2017; Xie et al., 2018):

— degasing membranes (Cramer et al., 2009; Henares et al., 2016; Moiseev et al., 2016b; Sanchis-Perucho et al., 2020);

— membrane-based reactors (Bhattarai et al., 2018; Casey et al., 2004; Cashman et al., 2018; Kampman et al., 2014; Luo et al., 2019; Lv et al., 2019; Modin et al., 2008; Shi et al., 2019; Sun et al., 2013; Xie et al., 2018);

— zeolite membranes (Ajayi et al., 2015).

Zeolites are nanomaterials that can be used as membranes for gas separation. Such **nanomaterials** are also being used for CH_4 adsorption. More generally **nanomaterials** also being used for CH_4 adsorption are divided into non-carbonaceous materials (e.g. zeolites, metal-organic frameworks and porous polymers) and carbonaceous materials (e.g. activated carbons, ordered porous carbons and activated carbon fibres) (Choi et al., 2016):

— biochar (Delgado et al., 2018);

— graphene (Alonso et al., 2017; Mahmoudian et al., 2016);

([10]) See NCBI, 'Taxonomy', n.d., available at: https://www.ncbi.nlm.nih.gov/taxonomy, accessed 20.10.2020.

- other carbonaceous materials (including activated carbon beads, ultra-microporous activated carbon cloth, coconut shell activated carbon, palm shell activated carbon and coal-based activated carbon) (Bar-Or et al., 2017; **Bennett et al., 2018;** Bhattarai et al., 2018; **Choi et al., 2016;** Kostoglou et al., 2017; Poomisitiporn et al., 2016; Rashidi et al., 2011; Ternet'ev et al., 1996; Yang et al., 2016, 2018);
- metal-organic frameworks (MOF) (Alonso et al., 2017; **Choi et al., 2016;** Delgado et al., 2018; Shi et al., 2020; Ursueguía et al., 2020);
- polymers (Abbott et al., 2011; **Choi et al., 2016;** Kostoglou et al., 2017; Cruaud et al., 2015; **Strong et al., 2015);**
- zeolites (Ajayi et al., 2015; **Choi et al., 2016;** Delgado et al., 2018).

Sorbents also form the basis of the separation process in **pressure swing adsorption** technologies (Cavenati et al., 2005; Utaki, 2010; Yang et al., 2018).

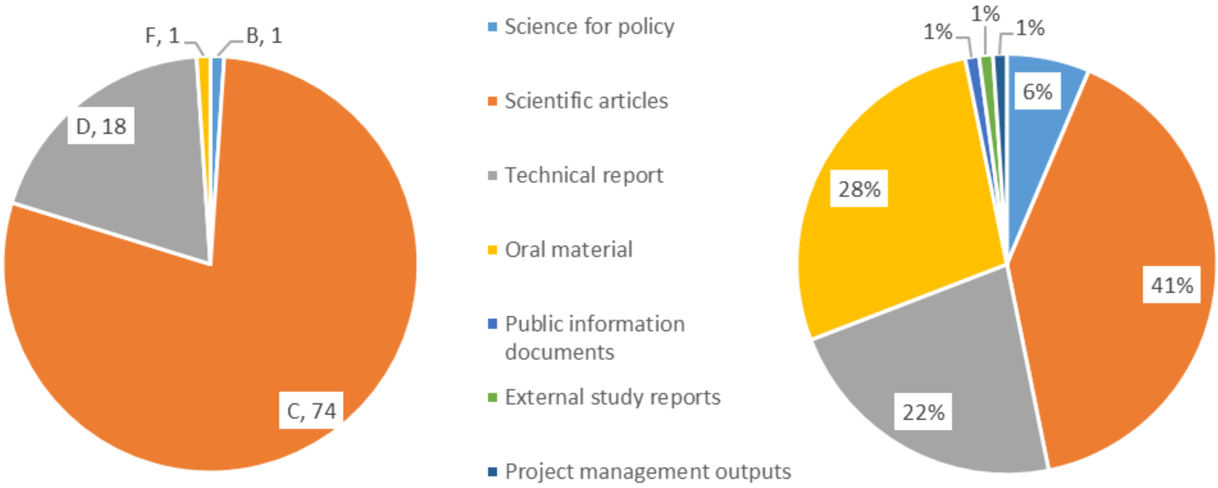
Stages of development

- Demonstration or commercial projects (Bhattarai et al., 2017; Fei et al., 2020; **He et al., 2018;** Hur et al., 2017; Kosmack et al., 2008; Liu et al., 2020b; Rice, 1980; Utaki, 2010; Yang et al., 2016).
- Patents (Air Liquide targets landfill gas-to-energy, 2007).
- Estimates of the potential for CH_4 emission reduction (Annachhatre and Khanna, 1987; Aromokeye et al., 2020; Hur et al., 2017; Industry news, 2004; Kosmack et al., 2008; Li et al., 2020; Lima et al., 2008; Liu et al., 2020b; Mei et al., 2019; Sanchis-Perucho et al., 2020; Serrano-Silva et al., 2014; Shi et al., 2020; Utaki, 2010; Vaksmaa et al., 2016; Valenzuela et al., 2017; Winkel et al., 2018; Yang et al., 2016; Yoon et al., 2009; Zhang et al., 2019).
- Quantified costs (Fei et al., 2020; Yoon et al., 2009).
- Other economic aspects (Bracmort et al., 2014; Chianese et al., 2015; **Choi et al., 2016;** Fei et al., 2020; **Garcia and Cervik, 1988; Kapoor et al., 2019;** Kosmack et al., 2008; **Lieven et al., 2018;** Mahmoudian et al., 2016; Rice, 1980; Sanchis-Perucho et al., 2020; **Wentworth et al., 1979;** Yoon et al., 2009).
- Programmes (Bracmort et al., 2014; Chianese et al., 2015).
- Partnerships (Industry news, 2004).

Annex 2: JRC activities on methane

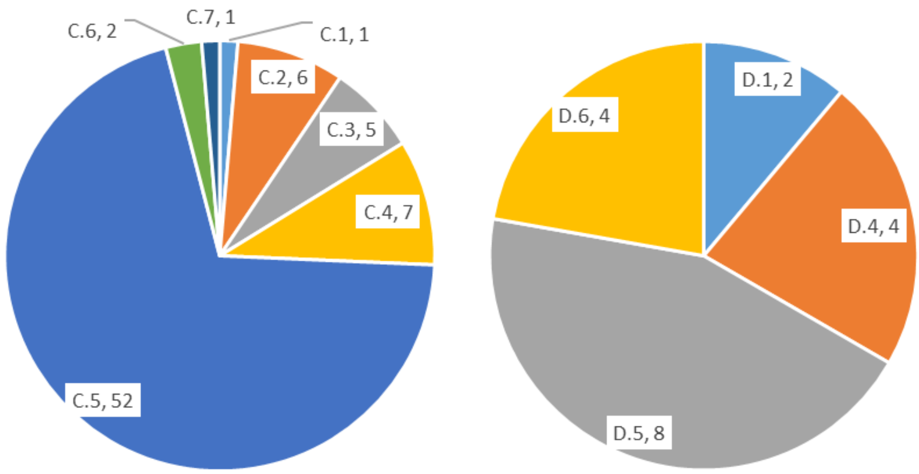
The JRC has registered 94 outputs related to CH_4 since its reorganisation in mid-2016. Figure 2 shows the JRC directorates leading these deliverables and the count of outputs produced per type of deliverable, while Figure 3 shows the JRC units leading these deliverables within Directorates C (Energy, transport and climate) and D (Sustainable resources), which lead 74 and 18 deliverables, respectively.

Figure 2. JRC outputs related to CH_4 per JRC directorate and output type



Source: JRC, 2020.

Figure 3. JRC outputs related to CH_4 per unit in JRC Directorates C and D



Source: JRC, 2020.

The analysis of these reports shows a dichotomy within the JRC, with CH_4 considered as either a primary energy source and carrier or a GHG, linked to the missions of the respective units/directorates. These different views are expected to converge with decarbonisation of the energy sector, policy integration aimed at breaking silos and upcoming JRC projects.

KJ-NA-30392-EN-N

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doi:10.2760/09370

ISBN 978-92-76-22969-8