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# The role of biomethane in reaching net carbon zero

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## Abstract

Biomethane, methane produced from organic waste residues through the actions of mixed microbial communities, can be used as a net zero replacement for natural gas and have a direct environmental impact through the reduction of carbon dioxide emissions and therefore global warming. Biomethane offers a viable alternative to liquid transport fuels and could be used as a chemical precursor for carbon-containing materials such as plastics or fixed into sequestering materials for carbon capture. Here, improvements, challenges and the potential of this technology are considered and how biomethane can take a pivotal role in reaching net zero carbon emissions is discussed.

## Introduction

Fossil fuel reserves are being depleted, and their use has a heavy impact on the planet in the form of global warming and increased pollution. Increasing numbers of countries are committing to net zero by 2050 with the goal of replacing fossil fuels with energy sources that do not add to the carbon dioxide and other greenhouse gases being emitted into the atmosphere [1]. However, the transition to renewable sources such as solar, wind, and geothermal energy faces challenges. The energy output from wind and solar power is variable due to a reliance on factors such as the weather [2]. Current infrastructure requires large-scale investment to support a transition to e.g. electricity for domestic heating and electric vehicle charging. In addition, current electric vehicles are not sufficiently powerful to replace fossil fuel-powered HGVs and ships for moving goods [3]. The World Energy Outlook report in 2021 illustrated that despite the reliance of society on carbon for energy and materials, in all scenarios examined there was a decline in fossil fuel demand for the first time [4]. In all scenarios, there is a sharp decline in the demand for coal, with a predicted decline of 50% in global use, which is still far from the 90% coal demand decrease needed to meet net zero by 2050 [4]. The demand for natural gas is predicted to increase in the next 5 years but then decline as we reach 2050 net zero goals [4]. However, unless further pledges are made, society will still be partially reliant on fossil fuels and incapable of meeting the 2050 net zero goals.

Investment in energy was proposed to increase by 8% in 2022, however, these increases are largely due to increases in costs and economic uncertainty [5]. Almost three-quarters of energy investment growth in 2022 is attributed to clean energy [5]. In 2022, the World Energy Investment report valued this investment to exceed 1.4 trillion US dollars [5].

Methane plays a considerable role in climate change, so is an excellent target for emergent biotechnology approaches that can capture and harness methane as an energy source. Methane ($CH_4$) is the second most important greenhouse gas (GHG); around 30% of the global temperature rise since the Industrial Revolution has been attributed to atmospheric $CH_4$ [5]. A molecule of methane is estimated to have 84-86 times the global warming potential (GWP) of a molecule of carbon dioxide ($CO_2$) over 20 years [6]. Gobally-averaged atmospheric methane emissions have increased from 1644.69 parts per billion (ppb) in 1984 to 1895.63 ppb in 2021, with an increase of 16.94 ppb between 2020 and 2021 alone [111].

Along with GWP, $CH_4$ impacts air quality through the production of surface ozone ($O_3$). Nitrogen oxides ($NO_x$) combined with $CH_4$ produce ozone via photochemical reactions [7]. At the tropospheric level, ozone is a pollutant associated with the premature deaths of over a million people annually [8]. To limit global warming in line with the Paris Agreement, the Intergovernmental Panel on Climate Change (IPCC) calculated that a 45% cut in global GHG emissions compared to 2010 levels needed to be achieved by 2030 [9]. A report in March 2021 by the UNFCCC showed that only 1% of this target had been met [10]. The environmental impact of methane is mitigated by the fact that atmospheric methane has a short lifetime in the troposphere of around nine years [6], compared with centuries for $CO_2$ [4]. Thus, methane is a good target for reduction that would lead to a short-term lowering of global temperatures.

Biomethane, methane produced from organic waste residues through the actions of mixed microbial communities, is a good choice as both a transitional and long-term solution which can partly circumvent the challenges posed by methane emissions by capturing methane before emission while also providing an additional revenue stream for some industries. Using currently available feedstocks, biomethane has the potential to substitute 26-37% of natural gas consumed globally [11] and could cut global GHG emissions by 10% by 2030. Biomethane used to its full potential could reduce total UK GHG emissions by 6% in the hardest-to-decarbonise sectors [10]. This reduction is through two streams: capturing methane that would otherwise be emitted from organic waste to generate biogas, and through the displacement of fossil fuel and artificial fertiliser use [10].

## Methane emissions

Annual global methane emissions are estimated at 576 million tonnes (Mt) [6]. Determining the source of these emissions is essential for methane mitigation to reach net carbon zero [12]. While this is challenging on a global scale, one method to estimate the source of emissions is based on methane carbon isotope records. Measurements of $^{13}CH_4$ [13] and more recently, $^{14}CH_4$ [14], have enabled 60% of global methane emissions (359 Mt $yr^{-1}$) to be linked to anthropogenic sources [6,15]. The agricultural and waste sectors combined are responsible for estimated emissions of 206 Mt per year, around 56% of anthropogenic emissions [6]. Most of the remainder of anthropogenic emissions are attributed to the global energy sector, equivalent to ~135 Mt $CH_4$ per year [15]. Of this, emissions from oil and gas production represent around 25% of anthropogenic emissions, equivalent to 80 Mt $CH_4$ per year [16]. These emissions, mainly attributed to leaks during the production and transmission of oil and gas [16], are known as fugitive emissions [17].

Following the recent launch of the TROPOspheric Monitoring Instrument (TROPOMI), which samples daily $CH_4$ column mole fractions (Figure 1), Lauvaux et al. (2022) were able to identify several "ultra-emitters" releasing over 25 tonnes/hour of $CH_4$. Around two-thirds of ultra-emitters were linked to oil and gas production or transmission facilities. Due to the high monetary value of methane, it would be possible to cut fugitive methane emissions from the oil and gas industry by 45% at no net cost simply by capturing the gas emitted [17]. Wastes including landfills and wastewater are further responsible for an estimated 65 Mt $CH_4$ emissions annually [18].

## The environmental process of anaerobic digestion

The warming planet is driving the release of methane from other sources. Annual methane emissions from wetlands are estimated at 181 Mt $CH_4$ and other natural sources at 37 Mt $CH_4$ [6]. Most methane produced from natural sources (i.e. biomethane) is through the activity of microorganisms breaking down organic carbon sources. Methanogenic archaea (methanogens) produce methane under anaerobic conditions which occur in water-saturated environments when the decomposition of organic matter depletes oxygen [6]. Methanogens have been found in many environments including wetlands, the digestive tract of animals including humans and even more extreme conditions such as hot springs and geothermal vents [19,20]

Permanently frozen ground, permafrost, is rapidly melting and forming wetlands [21]. Estimates suggest >1 trillion tonnes of carbon are stored in the top 3m of Northern Hemisphere permafrost region soils alone [22]. As permafrost thaws, the carbon in the organic material originally captured is released in the form of $CO_2$ and $CH_4$ through decomposition by microorganisms [21]. This process releases an estimated 0.3 - 0.6 billion tonnes of carbon per year [23]. The warming planet also stimulates increased non-permafrost microbial activity, resulting in further methane emissions [24].

The digestive tract of ruminant animals also provides an environment where methanogens thrive, resulting in methane production from agriculture [25,26].

Volatile fatty acids (VFAs) present in bovine rumen fluid act as substrates for ruminal methanogens [26]. Levels of methane production can vary across livestock farms, including differences between dairy cattle and cattle raised for meat [27]. The United Nations Food and Agriculture Organisation (FAO) developed the Global Livestock Environmental Assessment Model (GLEAM) to analyse data from the agricultural industry. GLEAM uses a life cycle assessment (LCA) approach including GHG emissions and waste production and management in livestock supply chains to understand emissions [27]. Control methods for limiting methane production include herd management, dietary supplementation, and selective breeding [27]. Aside from enteric fermentation, other sources of methane emission in agriculture include rice cultivation, manure management and biomass burning for land-use changes [6]. This naturally occurring process of anaerobic digestion can be harnessed on a larger industrial scale in order to recover and use biomethane as an energy source.

## Biomethane recovery

Through the industrialisation of anaerobic digestion, potential carbon emissions are reduced and the resulting biomethane can be recovered (Figure 2). The gas produced is subsequently refined and can then be used to produce high-value products (Figure 3) [28,29]. Landfill gas recovery captures biomethane from landfill sites, but does not usually completely prevent carbon loss to the atmosphere [30]. Anaerobic digestion is used at scale to recover resources (biogas and a nitrogen-rich digestate) from organic waste streams. Biogas can be used directly in combined heat and power engines, as cooking fuel, or upgraded to biomethane that can be injected into distribution networks as a net zero replacement for natural gas [31,32].

## Anaerobic Digestion (AD)

### Biology

Biomethane is made by upgrading biogas produced by a biological process called anaerobic digestion (AD) [33]. In AD, a mixed community of anaerobic microorganisms recover resources from complex organic materials in four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, ultimately yielding biogas (mainly $CH_4$ and $CO_2$) [34]. AD occurs in the absence of oxygen [35]. AD is used for the treatment of various anthropogenic wastes, such as sewage sludge, food, and agricultural residues, in purpose-built vessels called anaerobic bioreactors or digesters [36]. AD enables the recovery of energy and useful carbon-neutral products from waste materials [37,38]. The use of anaerobic digesters to process organic wastes also prevents the release of biogas, produced by indigenous microbial communities that come into contact with these wastes, directly into the atmosphere [33].

The communities of microorganisms that underpin AD are complex and interactive, with community health and performance being contingent on the well-being of multiple community members [39]. AD has the potential to be adopted as a terminal destination for all spent organic residues, which has advantages over purpose-grown feedstocks such as energy crops.

### Monitoring the microbial community

Process disruptions such as foaming can be a major barrier to cost-effective AD [40,41]. Potential disruption could be avoided by monitoring the "health" of AD microbial communities to identify warning signs of destabilisation and enable preventative action to be taken [42,43].

An ideal monitoring technology would combine low cost with accurate real-time prediction of community health [44]. While many techniques are currently available, these generally come with at least one major drawback [42]. Another barrier to effective monitoring is that the microbial communities that underpin AD vary from digester to digester, so there is no universal set of monitoring parameters that indicate AD community health [43,45]. For these reasons, techniques routinely used for real-time monitoring of AD in industry are primarily restricted to simple measurements, such as pH or temperature, which provide limited information about the status of the microbial community [42,45]. The development of techniques such as loop-mediated isothermal amplification (LAMP) provides a promising, low-cost method for detecting key species that could provide an indication of operational performance, as demonstrated for hydrogenotrophic methanogens [46].

## Feedstocks

One of the benefits of AD is the ability to use different feedstocks from a variety of biomass sources. The biomethane potential of organic materials varies widely, and this needs to be considered when choosing the appropriateness of a feedstock for a digester [47]. The biomethane potential can be estimated using commercially available tests, however, the results of these often vary significantly [48]. As a result, there have been calls for standardisation in testing this measure

[48,49]. The biogas potential of feedstocks used for anaerobic digestion plants is key to evaluating their economic viability. However, the operating conditions of the plant performing the testing, and other factors such as the physical properties of the inoculum, frequency of feed addition, operating temperature and location of sampling can all influence the test results [49]. Methodologies used to determine the biogas potential of materials and the practicality of using these methods are discussed in [50,51].

Table 1: The most commonly used single-source feedstocks and their approximate usage in the UK as of 2022, and the benefits and disadvantages to each feedstock when used as a single source [52]. The NNFCC stated that in 2022 the UK produced over 100 million tonnes of organic material that could be used as a feedstock for AD [109]. Usage statistics for single feedstocks in Table 1 below are reported from the NNFCC 2022 report unless stated differently.

Table 1

| Feedstock | Usage | Pros | Cons | References |
|---|---|---|---|---|
| Wastewater | 75% of the 1.1 million tonnes of sewage sludge produced in England and Wales is used on agricultural land. | - High volumes of sludge are available and require treatment.<br>- Carbon content can be recycled<br>- Total volume of sludge to be processed is greatly reduced<br>- Pathogen levels are reduced through treatment. | - Close monitoring of pathogens and pollutants such as heavy metals is required before digestate is applied to land. | [52–55, 109] |
| Agricultural waste and energy crop | 90 million tonnes of manures and slurries per annum | - Can be used for both animal waste (manure) and crop residues.<br>- There is a high abundance of low-value crop waste that is otherwise not utilised. | - Seasonal variations based on crop growing seasons.<br>- Manures may contain high concentrations of ammonia which can be inhibitory to AD.<br>- Crop wastes can contain a high percentage of lignocellulose which is hard to degrade.<br>- Land use required for energy crops | [55–58, 109] |
| Municipal solid and food waste | 16-18 million tonnes of food waste, both industrial and household | - Can provide a source of energy and revenue from an otherwise high volume low revenue waste. | - For municipal waste, the organic fraction of MSW first needs to be separated from non-organics such as plastic or glass and other hazardous materials.<br>- For food waste pH imbalances and high concentrations of lipids can cause clogging, foaming and inhibitory concentrations of ammonia, hydrogen sulphide and long-chain fatty acids.<br>- Communities may also require trace element supplementation to maintain maximum productivity. | [53,59,60,109,110] |

## Co-digestion

Combining organic wastes from different sources, known as co-digestion, is increasingly used [61]. In AD, food or animal wastes can be combined with cellulosic substrates (e.g. wheat straw) or waste-activated sludge (WAS) to produce biogas through anaerobic co-digestion (AcD). AcD results in a better nutrient balance for methanogens [62] and higher biogas yields [63]. Co-digestion is particularly effective on difficult-to-digest feedstocks such as wheat straw or WAS, and could overcome difficulties experienced by mono-digestion systems, such as digester instability [61,64]. Co-digestion can also help mitigate issues arising from seasonal fluctuations in feedstock [65]. Both WAS and agricultural wastes including wheat straw are difficult to digest anaerobically and have lower digestion efficiencies and organic loading rates (OLR) compared to food waste [66,67]. Agricultural wastes such as wheat straw contain a high concentration of lignin which is difficult for microbes to digest [68]. WAS digestion is often rate-limited by extracellular polymeric substances (EPS) and cell-wall-derived matter [66]. Co-digestion can lead to greater microbial diversity in the digester, resulting in functional redundancy. Thus, stresses to an AD system, which may result in the loss of particular taxa, are less catastrophic due to the availability of other organisms to fill that niche [67,69,70]. A greater understanding of the role that microbial communities play in digester productivity is key to determining how mixing different microbial communities can impact digester stability and productivity [61,67].

Co-digestion legislation may not permit the combination of certain wastes. In the EU, there are strict regulations on the segregation of agricultural waste and sewage sludge for AD [71]. Whereas, in the US, food waste co-digestion is increasing due to restrictions on landfill use for food waste in some states [71].

## Biomethanisation

Biogas produced in conventional AD contains predominantly $CH_4$ (50-70%) and $CO_2$ (30-50%). Biogas also contains other minor constituents like hydrogen sulphide and carbon monoxide that need to be removed before biogas can be used as biomethane [32,72]. 'Upgrading' is required to increase the concentration of methane to at least 95% before it can be injected into gas networks or used to fuel vehicles [73,74]. Abiotic upgrading technologies which exploit the different properties of the various gases are most commonly used for the conversion or separation of $CO_2$ and other gases in biogas. These technologies include chemical reduction, pressure swing absorption, membrane separation, cryogenic fractionation and chemical absorption [72,75]. Although abiotic technologies are effective, they can emit $CO_2$ and still require toxic chemicals, high energy input or significant capital expenditure [75]. An alternative biogas upgrading approach is to utilise biological processes (e.g. [74,76–78] ). Biological upgrading processes are attractive due to being renewable, operable in low-cost ambient conditions, and their ability to capture and convert $CO_2$ into additional $CH_4$ or renewable products [73].

Due to their high growth rates and the added benefit of simultaneous nutrient recovery from digestate liquors, microalgae have been identified as suitable organisms for the utilisation of biogas $CO_2$ by photosynthesis [79]. Toledo-Cervantes et al. [79] achieved a $CH_4$ concentration of 96.2% in biogas bubbled through a column of algal cultivation broth that was recirculated from a high-rate algal growth pond, Marín et al. used a similar algal $CO_2$-scrubbing pilot-scale system to upgrade $CH_4$ to a concentration of 97.9% and calculated that the treatment of biogas consumed 0.14 kWh $m^{-3}$. However, the challenges associated with sustaining high productivity of algal biomass at an industrial scale include maintaining exposure to suitable levels of photosynthetic active radiation and loss of yield due to seasonal temperature fluctuation in low-tech exposed algal ponds [80].

## Biomethane compatibility with the energy grid

It is possible to upgrade biogas to a biomethane level comparable to fossil natural gas, with a methane content of ≥ 90% and a lower heating value (LHV) of around 36 $MJ/m^3$ [81]. A major advantage of biomethane is its compatibility with existing natural gas infrastructure and natural gas vehicles [81,82]. Currently, around 3.5 million tonnes of oil equivalent (Mtoe) of biomethane are produced globally, the vast majority in Europe and North America, representing about 0.1% of the global demand for natural gas [81]. In 2020, European biogas and biomethane production resulted in 191 TWh of energy. This capacity is increasing, almost 300 new biogas and biomethane plants have been built since 2020, and Europe's sustainable biomethane production could meet 30-40% of the estimated EU gas consumption needs (~1,000-1,700 TWh) by 2050 [83].

$H_2$ supplementation of biogas is the most researched method of biological upgrading and can be used to promote the pathways of homoacetogenesis, acetoclastic methanogenesis and hydrogenotrophic methanogenesis which are frequently limited by the availability of $H_2$ gas [84]. $H_2$ can be added either *in-situ* by direct injection into AD reactors, or *ex-situ* by adding $H_2$ to biogas and using the gaseous mixture as a feedstock for microbial cultures in a second, segregated, bioreactor. *Ex-situ* systems have consistently achieved high biomethane concentrations above 96% [45]. *In-situ* systems are convenient due to the potential to use existing infrastructure, but upgrading results have been more variable. This variability can be attributed to the role of $H_2$ in multiple AD metabolic pathways, thus creating the potential for $H_2$ addition to unbalance the core biogas production process [78,85]. Using hydrogen as part of the upgrading process is preferential to the replacement of hydrogen in place of natural gas which is often proposed. Sole replacement by hydrogen is driven by a desire for lower $CO_2$ emissions, however, hydrogen has several limitations compared to biomethane. Hydrogen presents a greater safety risk due to a higher occurrence of leaks and subsequently increased explosion risks [86]. It is also less compatible with existing gas grid infrastructure and so greater modifications would be needed at both a high and end-user level [87].

## Potential of biomethane

Life cycle analysis (LCA) comparing the sustainability of upgraded biogas for transport to direct injection into the grid showed that upgrading resulted in lower environmental burdens, due to a greater reduction of global warming potential and non-renewable energy potential [88]. This may not hold for other downstream uses and depends on the method of upgrading [88]. Many of the sustainability benefits that come from upgraded biomethane within the transport sector are derived from the replacement of fossil fuels which makes the direct comparison between biogas and upgraded biomethane difficult [88]. Adoption of fully renewable sources of energy can be limited due to country-specific restrictions and the cost required for infrastructure changes [89,90]. One such example is in Spain, where the minimum percentage of $CH_4$ for injection into the grid has been lowered from 95% to 90% to enhance the uptake of biogas generation [91]. Additional restrictions in Spain mean that direct injection into the grid is often economically unfeasible without investments in equipment and technology to make it more cost-effective [91]. In cases such as these, or where energy output is not consistent, hybrid plants that combine renewable energy sources such as solar and AD could present a viable, sustainable solution [89]. However, most of this data is derived from feasibility studies rather than current operating plants [89,92,93].

## Domestic Heating, Transport and other uses

Biomethane provides an economical short-term solution to decarbonise space and water heating with the added advantage that any reduction in production can be compensated with fuels such as natural gas in the short term. The use of biomethane may also overcome the limitations of all-electric heating systems, which primarily depend on heat pumps that require costly retrofitting [86].

Vehicles which run on natural gas can also run on grid-quality biomethane with no alteration. Currently, liquified natural gas (LNG) and compressed natural gas (CNG) are used as transport fuels, however, biomethane has a very similar chemical composition to natural gas. Biomethane can potentially reduce the carbon footprint and harmful emissions from heavy-duty diesel engines, found in heavy goods vehicles, buses and off-road heavy machinery, which are more challenging to electrify than light vehicles [94].

Biomethane can be used as a fuel in spark-ignition (gasoline) engines or diesel engines converted to spark ignition. Another option for diesel engines is a methane/diesel dual fuel mode of operation. Using a small quantity of diesel fuel to initiate combustion allows a conventional diesel engine to operate on methane and greatly reduce pollutants [94,95]. A key advantage of using biomethane over a dual-fuel methane/diesel engine is the greater reduction in GHG emissions, with a reduction of ~80% for dedicated biomethane compared to <50% for dual fuel [96].

At present, the use of biomethane for transportation fuel is most practical in urban areas due to the presence of existing natural gas infrastructure and the desire of governments to reduce air pollution in these regions. The viability of biomethane as a substitute for liquid fuels is dependent on overall uptake, public policies and investment [94].

## High-value products

Biomethane derived from biogas can be used as a carbon feedstock to produce high-value products such as hydrogen, methanol and ectoine (worth ~$1000 per kg) [29] using both chemical and biological methods [28,29] (see Figure 3).

Chemical methods of methane transformation require expensive catalysts and extreme operating conditions. One of the main uses of methane as a chemical feedstock is for the production of hydrogen for the synthesis of ammonia [97]. Methane is reformed into a syngas (here, a mix of CO and $H_2$) using steam methane reforming (SMR). While this process is energy-intensive, the use of biomethane instead of fossil-derived methane provides a more sustainable route for both hydrogen and ammonia production [97].

Aerobic methane-oxidising microorganisms (methanotrophs) can be used as biocatalysts to transform methane into high-value products [98]. These high-value products, such as ectoine, biopolymers (e.g. poly-β-hydroxybutyrate (PHB)) and methanol can be produced through metabolic pathways [29]. Through genetic engineering, it is possible to turn methanotrophs into cell factories, which can improve the production of native compounds or enable the production of additional high-value compounds [98]. Single-cell protein can be produced from methane by a mixed microbial community including the methanotroph *Methylococcus capsulatus* (Bath). This is approved for use as salmon and piglet feed in the EU - one such product available on the market is FeedKind® [98].

The osmoprotective compounds ectoine and hydroxyectoine are naturally synthesised in high-salt environments by halotolerant and halophilic methanotrophs, such as *Methylobacterium alcaliphilum [29]*. Ectoine is used in the pharmaceutical industry because of its osmotic properties. Around 15,000 tonnes of ectoine are consumed a year, ectoine retails for ~$1000 per kg making it a highly lucrative compound [29,98]. Other methanotrophs, such as *Methylosinus* and *Methylocystis*, have been used to produce polymers that can be used for bioplastics, such as PHB, in situations with excessive carbon or when nutrient-limited [29,99]. PHB is biodegradable yet has similar mechanical properties to polypropylene, making it a promising environmentally friendly alternative to oil-based plastics [99].

## Prospects

As outlined by Spiers et al who did a systematic review on decarbonisation strategies and the implications for infrastructure, biomethane production has potential as a transition technology as the world moves to net zero. One of the major strengths of biomethane over other decarbonising methods such as hydrogen is that the existing natural gas infrastructure can be used to store, distribute and utilise energy with little alteration required [86]. Another advantage of using biomethane over other decarbonising methods is that a wide variety of feedstocks can be used as outlined previously, see Table 1. This means that the feedstocks of choice can be adapted to respond to resource availability such as the seasonal variation in crop waste [55,65]. Transitioning the global energy infrastructure away from fossil fuels is an enormous task that is often underestimated [4,5]. To achieve this mitigation without widespread price increases and energy insecurity, we need a reliable supply of drop-in fuels that provide meaningful GHG reductions in a cost-effective and timely manner. As biomethane can be injected into the grid to supplement or replace natural gas, this may allow for a simpler shift from natural gas without the need for a complex and costly retrofit of the grid infrastructure to handle hydrogen [100]. Biomethane could provide additional energy security and buffer against fluctuating natural gas prices whilst providing revenue and a route for the responsible disposal of organic wastes [86]. Biomethane is also a viable replacement for diesel for long-distance transportation of heavy loads [88]. In the long term, AD facilities could be used to capture carbon from organic residues either for storage or for utilisation in carbon-requiring materials such as plastics [98].

To facilitate the move to greener technologies such as anaerobic digestion appropriate financial incentives may be required at governmental scale [90,101]. The lack of financial incentives for industries is a major barrier to greater adoption of AD, which indicates the need to support the development of this infrastructure [10]. Reducing the legislative burden around administration and regulations for smaller and medium companies with fewer resources would also enable companies who wish to support sustainability but feel it is currently not viable [90,101]. As outlined in the World Biogas Association's *Pathways to 2030* report, as the biogas energy market matures, funding can move from infrastructure changes to make the technology more efficient and affordable [10,101].

$H_2$ supplementation to enhance biomethane yield is still not a mature technology, and additional research is required to realise this at an industrial scale. In particular further work is needed to optimise in-situ $H_2$ injection methods to effectively support both the microbial community and mitigate any operational safety concerns [78,84,102]. The sustainability of exogenous $H_2$ from renewable sources such as water electrolysers also needs to be considered [103]. However, the global environmental drive to develop and utilise renewable biomethane is likely to significantly reduce the associated costs and expand the use of biological biogas upgrading technologies [45,103].

Thermal gasification of waste-derived solid biomass is a promising alternative route for the capture of methane from biowastes that is currently underutilised at an industrial scale [94,104,105]. Dry biomass is transformed into a synthetic mixture of $CH_4$, $CO_2$ and other gases (syngas) in a multi-step process that requires low oxygen, high temperature (700 – 800°C), and high pressure [105,106]. The treatment capacity of a syngas plant is almost double that of a biogas plant (51 kt/y and 35 kt/y respectively) [107] and thermal gasification has the potential to rapidly decompose feedstocks that AD cannot, such as woody biomass [94].

Ensuring the scale of these changes is sufficient will require both financial and political backing. The introduction of Environmental, Social and Governance (ESG) criteria for companies suggests that there has been a shift toward investments in the green economy and companies focusing on sustainability [10]. Biomethane from AD could play an important role in both the transition and maintenance of a net zero economy and is therefore worthy of additional research and investment.

Keywords:

- Life Cycle Analysis
- Anaerobic digestion
- Biomethane
- Thermal gasification
- Co-digestion
- Green House Gases
- Net-zero
- Net-carbon zero

Figures:

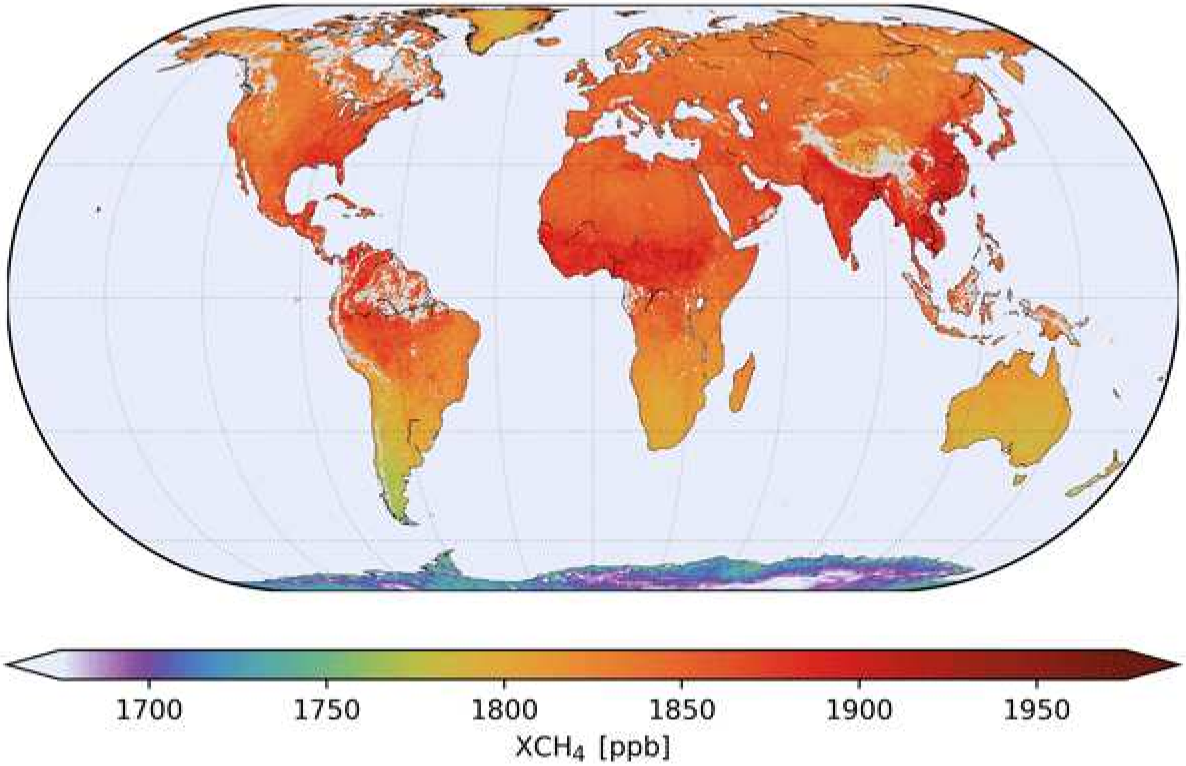


**Figure 1: Corrected global distribution of $XCH_4$ in parts per billion for 2019 from the TROPOspheric Monitoring Instrument (TROPOMI).** Taken from Figure 5 Lorente et al. 2021 [108]

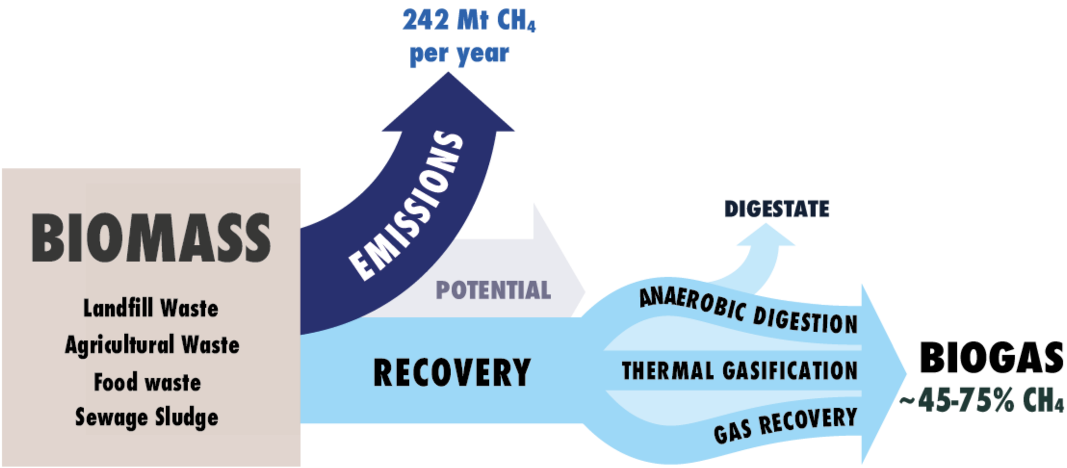


**Figure 2: Methane production from biomass.** Waste organic residues result in significant biogas emissions that could potentially be recovered via a number of routes as a net zero fossil fuel replacement that would support a reduction in fossil fuel requirements.

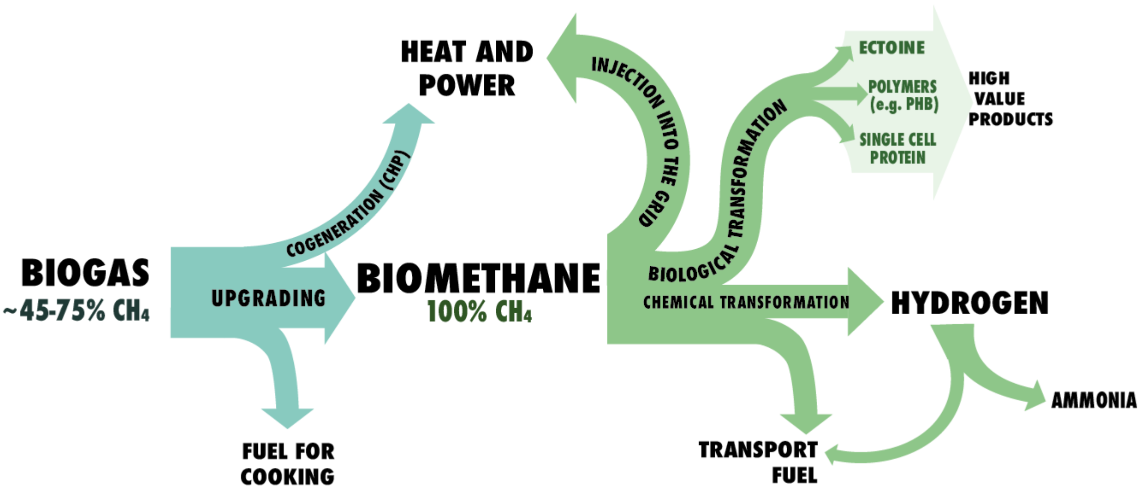


**Figure 3: Potential biogas applications.** Biogas and upgraded biomethane is currently mainly consumed as a fuel for heat, power and cooking (blue), but could be

further utilised in a range of applications supporting a transition to net zero emissions (green).

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