Midstream and downstream technological developments for bioCH4 and bioH2 production and offtake

Deliverable n. 1.2

GREENMEUP

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Summary

This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement No. 101075676.

Executive Summary

GreenMeUp – Green Biomethane Market Uptake is a Horizon Europe project that aims at providing a basis for policy-makers and stakeholders to develop more informed renewable energy policies and country-tailored market uptake measures, in order to improve and complement existing biomethane policy in Europe.The core activity of GreenMeUp is to reduce the gap between countries with higher rates of biomethane production and countries with lower development rates, by analyzing and comparing their framework conditions and market dynamics and promote enabling policies and measures at country level.
The project aims at providing societal acceptance of the biomethane value chain through science-based evidence and tools. The present report titled "Midstream and downstream technological developments for bioCH4 and bioH2 production and offtake" is divided into 5 main chapters and is the first of two issues of deliverable D1.2

Chapter *Developments in AD technologies* discusses the developments in anaerobic digestion technologies. It starts by highlighting the increasing global recognition of biogas as a renewable energy source and the supportive policies being implemented to promote its development. The future of the biogas industry is outlined, including integration with other renewable energy systems, hydrogen production, and decentralised, localised energy production. It also mentions the factors that contribute to more efficient biogas production and the potential improvements to biogas systems. The section touches on companies dedicated to increasing biogas production and the importance of feedstock diversification. It also discusses changes in technology framework, types of anaerobic digesters, and advancements in monitoring, concluding with other advancements in AD technologies and biogas upgrading and utilization.

The second Chapter delves into *Developments in CO2 management*, starting with the mention of the biogas and biomethane sector's potential to reduce greenhouse gas emissions and contribute to climate neutrality. The chapter outlines different ways in which biogenic CO2 can be captured, either during the process of upgrading biogas to biomethane, during combustion in combined heat and power plants, or during biohydrogen production. The chapter also provides data on the theoretical potential of biogenic CO2 production with projections for 2020, 2030, and 2050. The potential advantages of using CO2 from biogas are explored, including marketing, technical, economic, and political benefits. Various technologies for co-producing biomethane and bio-CO2, such as sorption methods, membrane separation, and cryogenic methodology, are discussed. The chapter concludes with a simplified classification of pathways for CO2 use, differentiating between pathways with and without conversion. Examples of end products from these pathways include beverage carbonation, urea production, methanol, and construction materials.

The chapter emphasizes the importance of sustainable bioenergy production methods in addressing environmental concerns, reducing carbon emissions, and meeting energy demands. Ongoing projects and advancements in these areas further highlight the potential for future implementation and scaling of these technologies. At first, it is discussed biochar production, which involves the slow pyrolysis of organic biomass materials. Biochar has multiple beneficial properties, such as improving soil quality, sequestering carbon, and providing renewable energy. It has the potential to play a significant role in sustainable agriculture and climate change mitigation efforts. Next, in the chapter explores the production of sustainable aviation fuel (SAF) through Fischer-Tropsch synthesis. This process converts biomass into liquid hydrocarbons, which can be used as aviation fuel. SAF has been certified and is already being used in commercial applications. The chapter then delves into the production of e-methane, which involves combining biogas with renewable

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hydrogen or electricity to increase biomethane yield. This technology is particularly useful in areas with a high penetration of non-dispatchable renewables, where excess renewable electricity can be converted into biomethane. Furthermore, biological and catalytic methanation are covered. These processes convert carbon dioxide and hydrogen into methane, offering cost-effectiveness and operational efficiency. They have the potential to utilize CO2 from various sources, contributing to carbon dioxide reduction efforts. The chapter then discusses biomethanol production, which is derived from renewable sources like agricultural feedstocks and industrial waste products. Biomethanol serves as a sustainable alternative to traditional methanol, with significantly lower greenhouse gas emissions throughout its life cycle. Lastly, the chapter explores biohydrogen production through biological, thermochemical, and bioelectrochemical processes. These methods utilize biogenic sources to generate hydrogen and have the potential to contribute to a sustainable and carbon-neutral energy transition.

Chapter "*Challenges for large scale injection of biomethane into gas grid*" explores the complexities of the European natural gas network, highlighting its importance in meeting Europe's energy demands. The chapter explores the gas network's intrinsic relationship with numerous international partners, with Russia, northern Africa, and the North Sea being primary sources. This chapter further differentiates between the transmission and distribution networks, explaining their unique roles in ensuring stable and efficient gas supply across the continent. The potential of biomethane as a product of biogas upgrading is also highlighted. It suggests that biomethane, provided it meets quality criteria, can leverage the extensive natural gas grid to meet ambitious production capacity targets set by RePowerEU. However, the chapter acknowledges the challenges associated with large-scale biomethane introduction into the gas grid. These include necessary infrastructure modifications, maintaining biomethane quality, and dealing with regulatory and legal barriers. Drawing from an interview with officers from a major Italian DSO, two potential solutions emerge – the introduction of reverse flow stations and grid interconnection. However, these complex solutions also bear their own constraints, including high costs and lengthy permitting procedures. The Chapter, therefore, offers a comprehensive overview of the current state of biomethane's role in the European natural gas grid and the prospective challenges and solutions associated with its large-scale integration.

Chapter "*Status and perspective on fugitive methane emissions*" provides an in-depth examination of the importance of monitoring fugitive methane emissions, especially within the rapidly expanding biomethane industry in the European Union (EU), and underscores the criticality of active measures to curb methane emissions in the face of the burgeoning biomethane industry and the pressing need for environmental sustainability. With the EU's ambitious biomethane production target set for 2030, it is anticipated a notable increase in the number of biomethane production plants, further underscoring the urgency of curbing biomethane fugitive emissions. Drawing on a broad spectrum of research, it is outlined the prevalence of fugitive methane emissions in various processes and contexts, such as wastewater treatment plants and solid waste landfills. The chapter investigates the sources and causes of these emissions, focusing specifically on phenomena within biogas/biomethane plants. A meta-analysis by JRC, offering an estimate of methane losses from these plants, is extensively discussed. It is then underlined the importance of addressing these emissions for two primary reasons - achieving the EU's biomethane production goal and preventing harmful environmental impacts. The chapter puts forth a robust case for the adoption of technical and operational emission reduction measures, emphasizing their cost-efficiency, safety implications, and odour prevention benefits. The chapter further highlights successful projects and government-endorsed initiatives that have significantly contributed to creating a body of knowledge surrounding best practices to mitigate methane emissions. Finally, the author presents a summary of measures recommended by the European Biogas Association (EBA) which, if implemented at the operational level, can significantly reduce and control biomethane fugitive emissions.

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1 Introduction

The present document is the first issue of a “technology watch” on the technological advancements in the domain of applied anaerobic digestion along the two last segments of the value chain, notably the conversion of feedstock (midstream) and the management of the products (downstream).

The first issue of the deliverable, covered by the present report, is meant to highlight the pathways the technologies are going through and the directions they’re pointing toward ; the second issue of the deliverable, foreseen in twelve months, will focus more on those innovations that during the course of the project, and in light of the evolution of the technical and legislative framework since the start of the project, gained more traction and exhibited the largest impact potential.

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2 Developments in AD technologies

Governments around the world are recognising the importance of biogas as a renewable energy source and are implementing supportive policies and market incentives to promote its development. These include feed-in tariffs, renewable energy certificates, tax incentives, and grants. Such measures stimulate investment in biogas infrastructure, encourage research and development, and create a favourable market environment for the industry to thrive.

2.1 The Future of the Biogas Industry

The future of the biogas industry looks promising, with several developments on the horizon. These include:

- Integration with Renewable Energy Systems: Biogas plants can play a vital role in integrating with other renewable energy systems like wind and solar to create hybrid energy systems. This integration enhances energy stability, optimises resource utilisation, and strengthens the overall renewable energy infrastructure.
- Hydrogen Integration: The integration of hydrogen production within the biogas production process offers new opportunities for renewable hydrogen production. Either through direct biological hydrogen production, via Dark Fermentation as mentioned above or as a raw material plant where excess electricity from renewable sources, such as wind and solar, can produce hydrogen through stream/methane reforming.
- Decentralisation and Localised Energy Production: The biogas industry has the potential to promote decentralised and localised energy production. Smaller-scale biogas plants can be established closer to the source of feedstocks, reducing transportation costs, and promoting energy autonomy in local communities. This creates the potential for co-operative models for farmers, sharing capex costs for pre-treatment equipment and nutrient recovery as well as vertical integration of processing and food manufacturing facilities.

The biogas industry continues to evolve and innovate, paving the way for a sustainable and low-carbon energy future. With advancements in anaerobic digestion technologies, feedstock diversification, biogas upgrading, and supportive policy frameworks, the industry is poised for substantial growth. The integration of biogas with renewable energy systems, hydrogen production, and decentralised energy production further expands its potential. As we strive to reduce greenhouse gas emissions, achieve energy security, and foster

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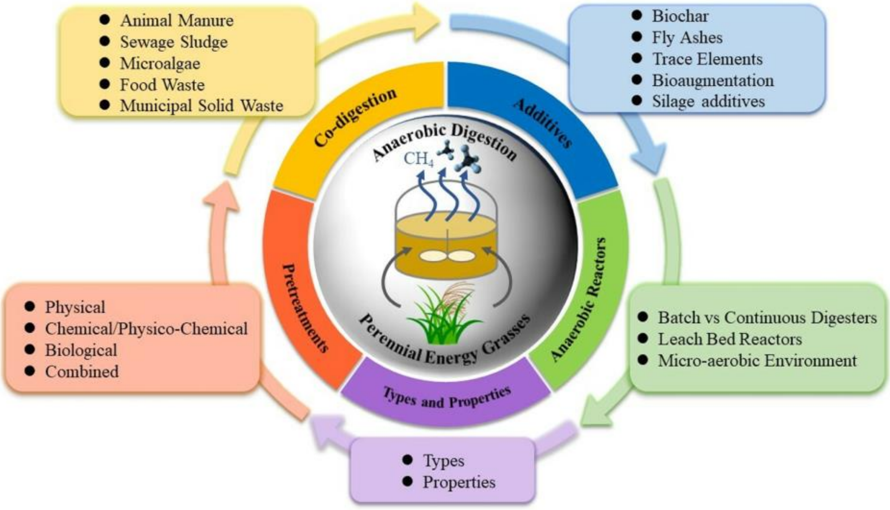
a circular economy, the biogas industry holds great promise as a renewable energy solution with vast untapped potential.[1]

When operating a biogas plant, it is very important to know what the different variables are that allow increasing biogas production[2]. For this reason, many times the main question is how to increase biogas production.

The factors that help to have a more efficient biogas production are:

- Substrate type (available nutrients);
- Digester temperature;
- The volumetric load;
- Hydraulic retention time;
- Acidity level (pH);
- Carbon Nitrogen Relation;
- Substrate concentration;
- The addition of inoculants;
- Degree of mixing;

The principal possibilities to improve biogas systems are shown in the following graph:



Currently, there are many companies on the market dedicated to increasing the production of biogas and biomethane. In the fields of feedstock there are projects for promoting perennial energy grasses, use of lignocellulose, sewage sludge, microalgae, etc.beside the traditional feedstocks like animal manure, food waste, municipal solid waste. Many different pretreatment techniques are necessary to use these resources in a co-digestion. Therefore also the fermenters have to be adapted in combination with specific additives.

2.2 Feedstock Diversification

Traditionally, biogas production relied heavily on agricultural waste and animal manure, still 65% of EU resource. However, advancements in pre-treatment techniques and inhibition mitigation technology have

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[1] Alps Ecoscience: anaerobic digestion to development sustainable green fuels

[2] https://smallops.eu/en/

enabled the utilisation of a broader range of feedstocks, including food waste, faecal slurry, energy crops, and industrial organic waste. Diversifying feedstock sources not only expands the availability of biomass for biogas production but also addresses waste management challenges and enhances the circular economy. R&D continues into secondary wastes, with particular focus on lignocellulosic biomass (straws, pulps, stalks, husks etc) which has significant energy potential but more complex cellular structures to separate.

The problem with these companies is that they usually advise buying additional equipment to increase biogas production. These purchases represent a large investment, and if not, they recommend that you modify the substrate so that you are not solely dependent on your own substrates.

2.3 Changes in technology framework

There have been some major changes in mixing regime, supporting unit, measurement, and monitoring systems, since the technology has developed. The sections mainly included are types of digesters, strategies such as upstream, mainstream, and downstream.

In upstream strategies, the hydrothermal pretreatment of anaerobic digestion showed a higher improvement of biogas by an increase of 222 % of methane content. The mainstream strategies showed that co-digestion was the best method to increase the methane yield to 305–445 mL g^{-1} VS. In downstream system, methane content can be upgraded from 60 to 90 % by applying water scrubber.

2.4 Types of Anaerobic Digesters

- Passive Systems: Biogas recovery is added to an existing treatment component.
- Low Rate Systems: Manure flowing through the digester is the main source of methane-forming microorganisms.
- High Rate Systems: Methane-forming microorganisms are trapped in the digester to increase efficiency.

Advancement in anaerobic digesters such as **continuous stirred-tank reactor (CSTR), upflow anaerobic sludge blanket (UASB) reactor, and plug flow reactor (PFR)** is needed for higher biogas production at different commercial scales of operation based on the diversity and complexity of organic residue.

2.5 Monitoring

In-line monitoring of biogas methane and carbon dioxide helps to reduce the requirement for costly laboratory analysis. By monitoring, it is possible to measure the successful operation of the plant, and by monitoring the methane/carbon dioxide ratio, the plant operator is provided with a continuous real-time indicator of digester behaviour, and with the status of the digester's micro-organisms.

As the world's first 3-in-1 in-situ biogas analyser, the MGP261 relies on CARBOCAP® technology that has been in operation in a wide variety of other industries for many years. However, uniquely, this instrument combines second generation CARBOCAP-technology for measuring methane, carbon dioxide and humidity into a single compact probe that is EX-certified for operation directly in corrosive, potentially explosive biogas streams.

From a user's perspective, the key advantages of this technology are:

- In situ measurement – direct measurement of process conditions without the cost, problems and delays associated with alternative methods
- Long term stability – maintenance is minimal; just a change of probe filter if it becomes dirty (usually undertaken during engine maintenance)
- Self-calibration – the measurement technology effectively self-calibrates, but an annual calibration

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check is recommended
- Minimal operational costs – no requirement for frequent service or calibration by technical staff
- Lower CHP engine maintenance and downtime - through reliable humidity control

Applications for this technology include anaerobic digestion and landfill gas monitoring, activated carbon filter monitoring in biogas treatment processes, and CHP engine feed gas monitoring. The typical monitoring points for methane, carbon dioxide and humidity at biogas plants would therefore be:

- within or after the digester - to optimise the digestion process by monitoring the CH4/CO2 ratio and adjusting waste loading rate accordingly
- after the heat exchanger – measuring humidity to optimise drying
- prior to the activated carbon filter - measuring humidity to optimise filtration
- prior to a CHP engine – measuring humidity to protect the engine and methane concentration to optimise engine performance
- prior to a methane upgrading plant – to optimise the process.

Effective biogas process optimisation requires in-situ monitoring of the key parameters, methane, carbon dioxide and humidity. In the past, this has not been possible with the monitoring technology available, but with the launch of Vaisala's MGP261, a new world of opportunity has been created to derive more value from waste; improve the profitability of biogas plants; help reduce waste; lower GHG emissions and recycle agricultural nutrients.

2.6 Other Advancements in AD Technologies

Temperature is the important factor which affects the biogas production. At higher temperature, maximum biogas is produced. There are other factors like the C/N ratio, pH value, compression ratio, and the total solid concentration which are affecting the biogas production.

One method of enhancing biogas potential is the **supplementation of anaerobic digesters with small amounts of trace inorganic nutrients**, e.g. nickel; cobalt; manganese; iron, which stimulate bacterial activity. At Smallops, they developed an additive. This additive is used to increase the production of biogas and is carbon-encapsulated iron nanoparticles, called OPS. The OPS help increase biogas production, acting directly on the biogas digester itself, without altering the current process for obtaining this renewable energy, and without using other substrates. The main advantages are:

- Improve the production of methane (CH4) by 20%.
- Reduce production costs while increasing biogas production.
- Elimination of hydrogen sulfide gas by up to 99%, extending the useful life of cogeneration engines.
- Increase the degradation of phytotoxic compounds such as polyphenols by 24%.
- The resulting digestate would be of greater interest and viability when applied to soils due to the higher content of iron and sulfur (essential nutrients for plants) and its lower contaminant load, which is an added value that would otherwise increase the profitability of the process.
- They provide greater stability to the biogas production process, which favors this sector towards the establishment of biogas as a reliable energy source and increasing its production. Because the biogas produced would be more constant , homogeneous, and of higher quality.

2.7 Biogas Upgrading and Utilisation

Biogas upgrading technologies play a crucial role in the efficient utilisation of biogas and its integration into existing energy systems. Upgrading processes remove impurities such as carbon dioxide, moisture, and trace contaminants from raw biogas, resulting in high-purity methane known as biomethane. Biomethane can be

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injected into the natural gas grid or used as a transportation fuel, thereby expanding its applications and market potential.

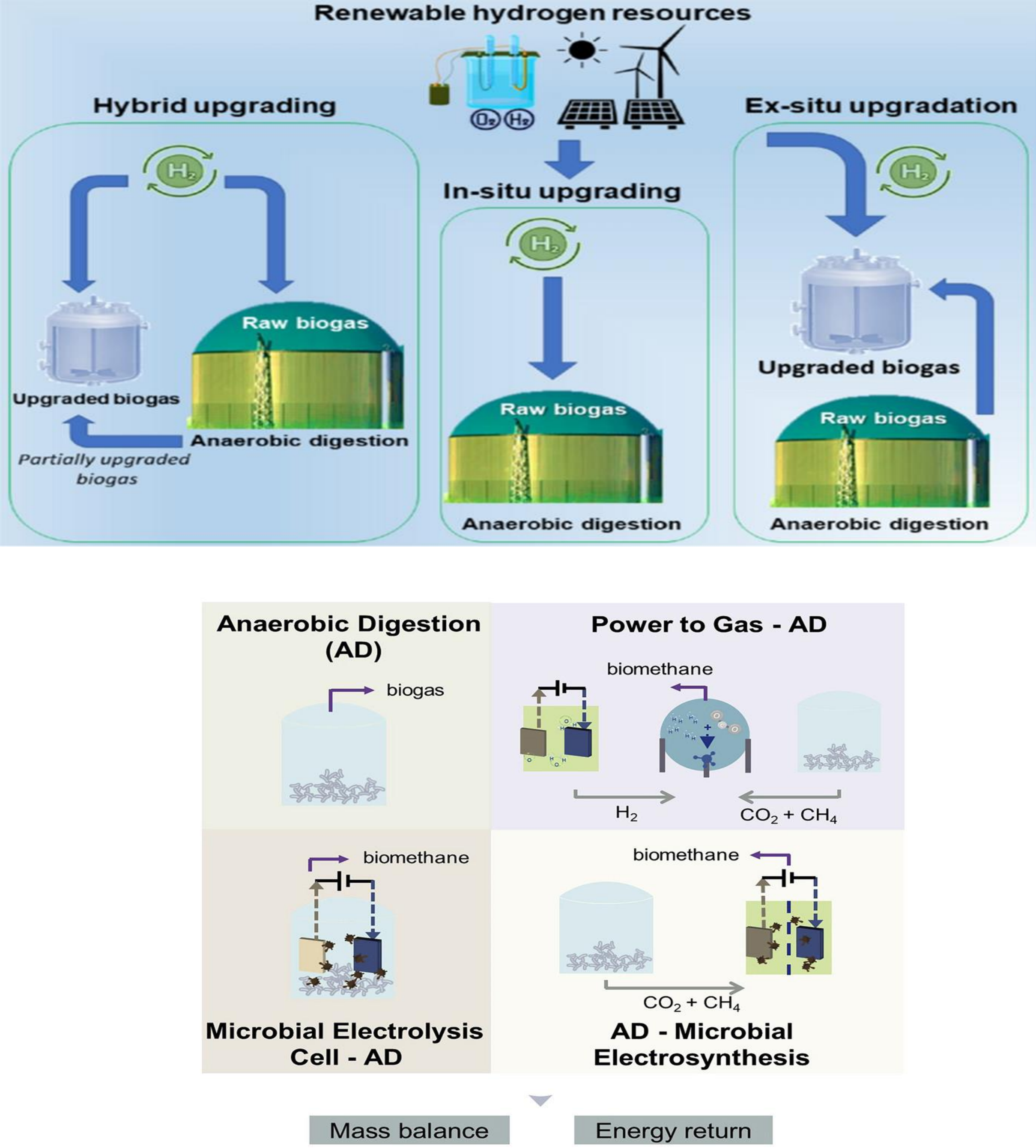

Figure 1. Three bioelectrochemical circular cascading systems with anaerobic digestion (AD) as a key platform integrated in turn with power to gas (P2G), microbial electrolysis cell (MEC) and microbial electrosynthesis (MES).

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3 Developments in CO2 management

This chapter is an excerpt EBA's work on Biogenic CO_2[3] and a summary of its findings.

Considering the need for urgent action to mitigate climate change, a reduction of carbon emissions must be complemented with options for greenhouse gas removal. While displacing fossil fuel utilisation, the biogas and biomethane sector can provide biogenic CO2 streams that may be used` in other sectors or to permanently capture and deliver negative emissions.

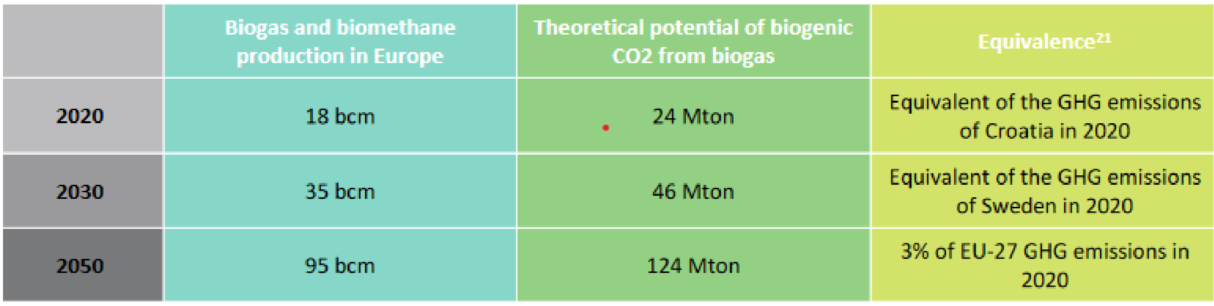
Managing the CO2 from biogas (through CCU, CCUS or CCS) helps reduce the greenhouse gas intensity of CO2 consumers and achieve an absolute removal of CO2 from the atmosphere. It makes any biogas recovery solution much more climate positive, while creating local synergies with CO2-consuming industries.

Biogenic CO2 from anaerobic digestion can be captured in various ways:

- During the process of upgrading biogas into biomethane, biogas is split into CH4 and CO2 to get biomethane, which can be used in the same applications as natural gas. The CO2 is captured at relatively low cost due to its high purity.
- In biogas plants fitted with combined heat and power (CHP), biogenic CO2 can be captured from the flue gas during biogas combustion.
- The production of biohydrogen from raw biogas, representing a possible third pathway to capture biogenic CO2. The biogas upgrading process is currently the most accessible source of concentrated biogenic CO2. This biogenic CO2 is "ready-to-use".
- Gasification of sustainable biomass can also be an additional source of biogenic CO2. This process converts dry, organic solid substances like ligno-cellulosic biomass (woody residues and waste) into biochar and "syngas". Syngas is a gaseous mixture containing mainly hydrogen, methane, carbon monoxide and carbon dioxide. While syngas can be further transformed into gaseous or liquid fuels, biogenic CO2 can also be extracted from it. Gasification combined with direct combustion of syngas to produce energy is a mature technology with more than 2,000 plants worldwide.

Assuming that all biogas is upgraded to biomethane and that all resulting biogenic CO2 is stored permanently, the theoretical potential of biogenic CO2 production in 2020, 2030 and 2050 are the following:

3.1 Theoretical potential of biogenic co2 from biogas



	Biogas and biomethane production in Europe	Theoretical potential of biogenic CO2 from biogas	Equivalence[21]
2020	18 bcm	24 Mton	Equivalent of the GHG emissions of Croatia in 2020
2030	35 bcm	46 Mton	Equivalent of the GHG emissions of Sweden in 2020
2050	95 bcm	124 Mton	3% of EU-27 GHG emissions in 2020

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[3] Europea Biogas Association (2022). Biogenic CO2 form the biogas industry: a mature opportunity to enhance carbon cycles and untap the circularity and climate benefits of biogas production.

The biogas and biomethane sector is an increasingly significant contributor to the achievement of the mid-century climate neutrality target. As calculated by the World Biogas Association, the sector has the potential to reduce global greenhouse gas (GHG) emissions by 10-13%. The biogas and biomethane industries reduce emissions in several ways, including avoiding emissions by replacing fossil fuels; avoiding methane emissions from manure; producing green fertilizer, which replaces carbon-intensive chemical fertilizers

3.2 Advantages of using CO2 from biogas

MARKETING

- Image impact (premium effect that can be marketed by the customer in its value chain)
- Biogenic status vs. fossil

TECHNICAL

- High CO2 concentration (typically >98%)
- No presence of carbon monoxide because biogas cannot have CO inside
- Typically very low concentration of NH3 the source gas before CO2 treatment plant <10ppm (typically removed in upgrading)
- Typically very low concentration of H2S and sulphur compound in the source gas before CO2 treatment plant <10ppm (typically removed in upgrading)
- The main contaminants in concentration (CH4 and air) are not toxic

ECONOMIC

- Locally produced (decentralised and de-risked model versus ultra-concentrated sourcing on few units … ref ammonia plant shut-down disorders)
- Price stability (no carbon tax nor carbon allowance within a mandatory carbon market)
- Programmable production
- Secured supply &/or exclusivity conditions

POLITICAL

- Synergies in a local bioeconomy ecosystem

3.3 Technologies to co-produce biomethane and bio-CO2

The best known and most mature technologies are sorption methods, including adsorption and absorption techniques, and separation, which refers to membrane use and cryogenic methodology.

More than 75% of the biomethane plants currently active use either membrane separation (39%), water scrubbing (22%) or chemical scrubbing (18%) as upgrading technologies

Since 2013, there has been a shift from chemical scrubbing towards membrane separation of the plants that started operations in 2020 – 47% of the total number of newly installed plants that year – are known to use membrane separation as their upgrading technology.

In general, high concentrated CO2 (up to 99% purity) can be obtained with any of the alternatives.

- Physical or chemical absorption are mature technologies that provide a spectrum of separation

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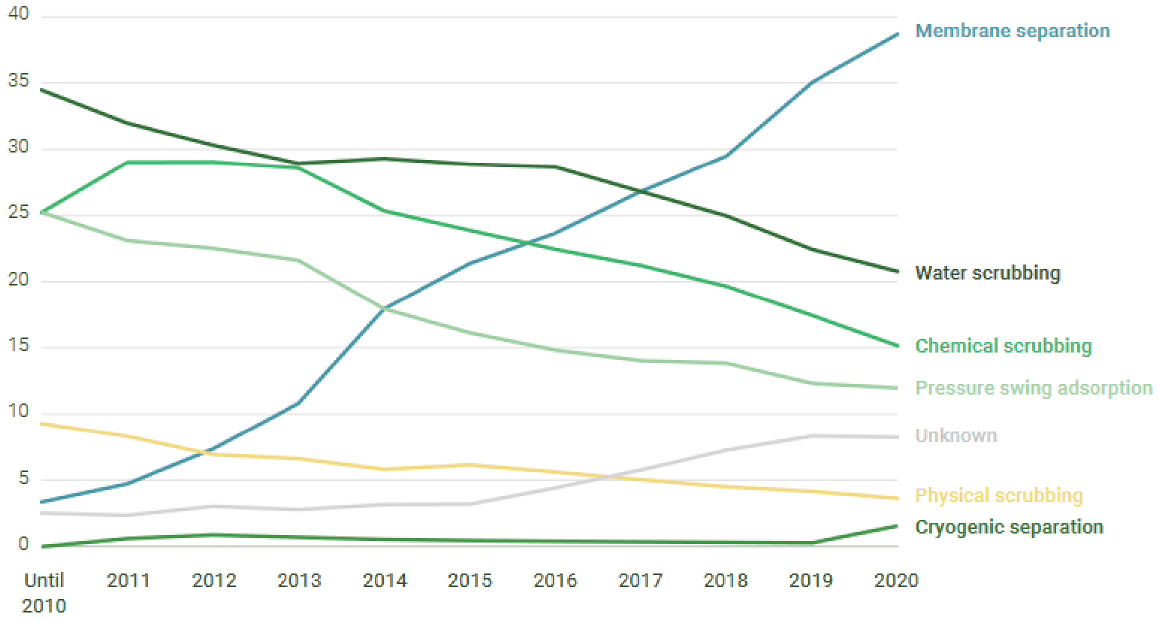
options. For instance, amine (chemical absorption) has high affinity for CO2, which allows its capture from biogas, and, after the process, the rich amine is further heated in the regeneration still column, where the CO2 is liberated, regenerating the amine.

- Membrane systems are extremely adaptable to various gas volumes, CO2 concentrations, and/or product-gas specifications. Using a membrane for biogas upgrading, the feed stream is separated into a methane-rich (residual) stream on the exterior of the membrane fibre and a carbon dioxide-rich (permeate) stream on the interior of the membrane fibre, easy to recover for further applications.
- Cryogenic separation has the advantage of enabling direct production of liquid CO2, which is needed for certain transport options, such as long-distance haulage. However, a disadvantage of cryogenic separation of CO2 is the amount of energy required to provide the refrigeration necessary for the process.



3.4 Simplified classification of pathways for CO2 use

Various CO2 utilization pathways co-exist today. These processes can be divided into the pathways without conversion (direct use of the CO2 as feedstock), and those with conversion (which requires specific processing or chemical treatment of the CO2 before utilization)

Some processes have been established for decades, such as the use of CO2 in beverage carbonation and urea production. Conversion pathways are in constant development, examples of end-products include methanol and construction materials.

Examples of such pathways are reported in Figure 2

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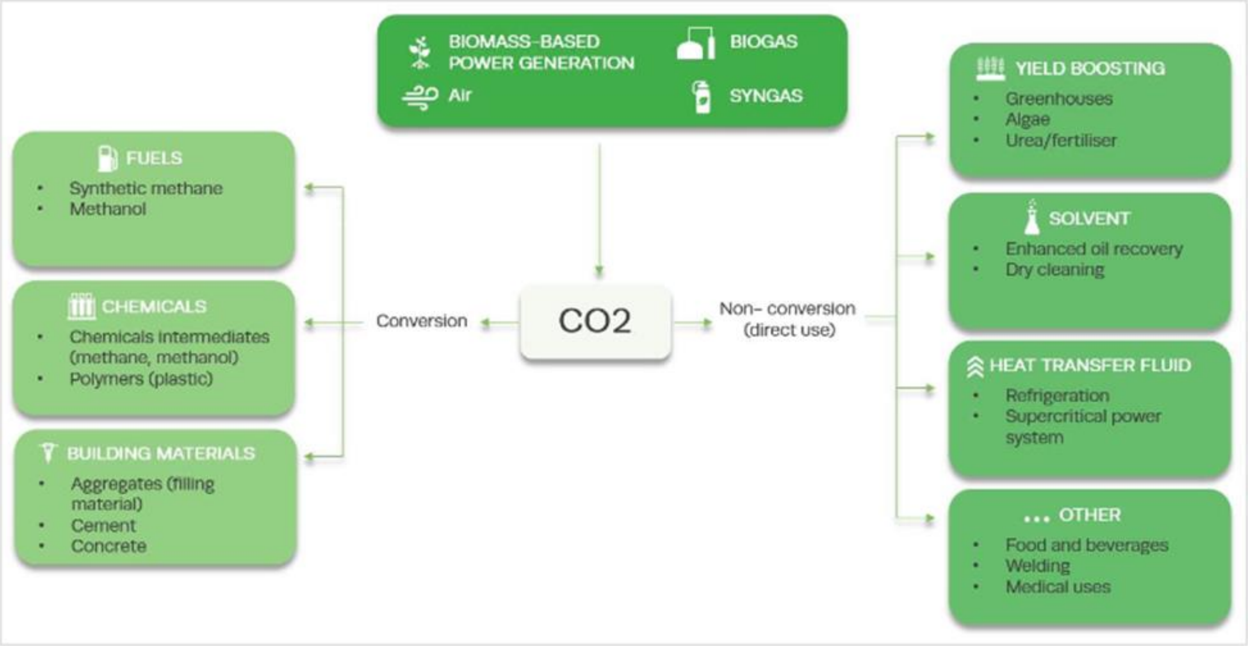

Figure 2. CO2 valorization pathways leveraging conversion or direct use.

Table 1. Concentration potentials and capture costs of CO2 from various sources.

CO_2 source	CO_2 concentration [%]	Capture cost [USD/tCO_2]
Natural gas processing	96 – 100	15 – 25
Coal to chemicals (gasification)	98 – 100	15 – 25
Ammonia	98 – 100	25 – 35
Bioethanol	98 – 100	25 – 35
Ethylene oxide 98 – 100	98 – 100	25 – 35
Hydrogen (SMR)	30 – 100	15 – 60
Iron and steel	21 – 27	60 – 100
Cement	15 – 30	60 – 12

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Table 2. Existing European biomethane facilities combined with bio-CCU(S)

Country	Name or Location	Feedstock type	Use of biogas	CO_2 end use	CO2 production
UK	Guy&Wright Farm	Waste crops	CHP	Greenhouses	
UK	UK Wight Farm	Crops	Upgrading	Food grade CO2	
Ireland	Greenville	Agri waste	Bio-LNG	Dry ice	5 T /d
Italy	Coop Speranza	Agri residues	Bio-LNG	Food grade CO2	8,5 T/d
Italy	Montello SpA	OFMSW[60]	Upgrading	Food grade CO2	200 T/d
Italy	SESA SpA	OFMSW	Upgrading	Food grade CO2	45 T/d
Italy	Caviro SpA	Agri residues	Upgrading	Food grade CO2	45 t/d
Italy	Biogas Wipptal (project)	Manure	Bio-LNG	Food grade CO2	15 /T d
France	Metha Treil SAS	Agri waste	Upgrading	Greenhouses	3.5 T/d
France	Agrogas pays de Trie	Agri waste	Upgrading	Food grade CO2 (ongoing)	8 T/d
Norway	Stord Island (project)	Salmon	Bio-LNG	Dry ice	11 T/d
Switzerland	Dietikon (project)	WWTP[61]	Methanation	SNG	100 Nm3/h
France	Pau	WWTP	Upgrading	SNG	50 Nm3/h
Germany	Augsburg	Biowaste	Upgrading + liquefaction	Dry ice, wastewater neutralization, snow jets, fire extinguishers	5 T/year
The Netherlands	Luttelgeest	Agri-residues and biowaste	Upgrading	Greenhouses	
The Netherlands	Westdorpe	Manure and organic by-products	Upgrading	Greenhouses	20,000 tonnes/year

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4 Developments in plant integration with AD systems

4.1 Biochar production plants

Biochar is a unique and versatile substance that is produced through a slow pyrolysis process. It is a form of charcoal that is specifically created from the thermal decomposition of organic biomass materials such as agricultural waste, wood chips, or plant residues, in the absence of oxygen. This process, known as pyrolysis, involves heating the biomass at high temperatures (typically between 400 to 800 degrees Celsius) in a controlled environment.

Biochar has a range of beneficial properties and applications. Firstly, it is highly porous, which gives it an impressive surface area that can absorb and retain water, nutrients, and other substances. This makes it an excellent soil amendment, enhancing water and nutrient retention in agricultural and gardening practices. Biochar can improve the structure and fertility of soils, promote microbial life, and increase the availability of essential nutrients for plants.

Furthermore, biochar has the ability to sequester carbon in the soil for a long period of time. When biochar is applied to the soil, it can remain stable and retain carbon for hundreds, or even thousands, of years. This makes it an effective tool for carbon sequestration and can help mitigate climate change by reducing greenhouse gas emissions.
In addition to its soil benefits, biochar also has the potential to be used as a renewable energy source. During the pyrolysis process, biochar produces a flammable gas called syngas, which can be used as a fuel for heat and power generation. This makes biochar production a potentially sustainable and carbon-neutral energy solution.

Overall, biochar is a valuable and multifaceted product with great potential for various applications. Its ability to improve soil quality, sequester carbon, and provide renewable energy makes it an exciting and important component in the sustainable agriculture and climate change mitigation efforts. As researchers and practitioners continue to explore and refine its uses, biochar is expected to play a significant role in creating a more sustainable and resilient future.

A slow pyrolysis process for the production of biochar can be successfully coupled with an AD process, either fed with agricultural feedstock or biowaste, yielding positive synergies both under a process and systemic perspective. For example, the introduction of a biochar production section instead of the traditional aerobic management practice of solid digestate via composting largely increases the value of the product and opens up the possibility to adhere to carbon removal certification frameworks, due to peculiar nature and properties of the produced biochar. The advantages are not limited to the economics, however, since composting of digestate requires a large amount of space, whereas the footprint of the biochar plant, notably for containerized designs, is much more compact.

For an AD process producing either biogas or biomethane and fed with agro- (cover crops, manure) or agro-industrial feedstock, a typical integration layout entails the addition of a dryer downstream of the digestate dewatering station, a buffer storage for dried digestate, the actual pyrolysis plant and biochar handling. Provided an effective digestate dewatering (typically for TS above 25%), and depending on the specific digestate properties, the pyrolysis plant can provide the heat required for its operation and that required by

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the dryer; this is achieved by combusting the pyrolysis gas produced in the conversion of the digestate and using the flue gases to exchange heat with the pyrolysis reactor, before releasing the residual heat content to an heat exchanger, where the recovered heat is ultimately provided to the dryer. Under certain conditions, there might also be some residual heat that could be used for the thermostatic control of the digestors, especially in colder climate and during the winter season.

In this example, it is typical to recirculate the condensate obtained from the dryer back to the liquid digestate management system of the plant, which will see its duty increased by 5-15%. Recovery of ammonium sulfate, its grade depending on the specific plant's arrangement, could be further pursued, potentially providing an additional product that can be traded to the market.

In the case of biowaste, for example those originating from the separate collection of municipal solid waste, a pyrolysis plant could be integrated in two distinct sections of the process. The first and most straightforward option follows the same steps described for agro-industrial AD plants; besides the option already mentioned, a pyrolysis plant can also be integrated upstream of the digestor, as more extensively discussed in the following paragraph.

Biowaste plants normally features a bag opening and pretreatment section, that originates a stream, rich in plastics, totaling up to 5% of the incoming feedstock. These materials, pretty heterogeneous and rich in inerts, can be conveniently pyrolyzed to yield a char that cannot be used in agricultural production, but could favorably find other end uses as coal substitute, after an upgrading step better explained in the following paragraphs. Besides, the pyrolysis process placed upstream of the digestors could potentially

Another technological advancement worth to mention in the context of coupling AD with a pyrolysis process for char/biochar production, pertain to the post processing of the produced char to increase its quality to meet more demanding and more economically rewarding applications.

Pretty much specific to AD processes operating on biowaste, is the fact that the digestate originating from such plant is normally higher in ashes and exhibits lower calorific value than the corresponding digestate obtained by agro and agro-industrial AD plants. While these characteristics do not preclude *per se* the production of biochar via pyrolysis, the carbon content of the produced biochar is much lower, restricting the potential application of the product.

It this respect, a new process for post processing the char/biochar is the one developed and patented by RE-CORD, which aims at drastically reducing the their ash content, recovering separately a low-ash char/biochar with increased carbon content and precursors for fertilizers from the inorganics previously in the char, including valuable nutrients such as P and K, either as liquids of salts. By the application of said process, one can obtain a tradable *bio* substitute for coal, also called *biocoal*, which can offset the former in a broad range of applications, including a number of coal grades currently adopted in steel and iron making. Further detail of the process can be found elsewhere.

4.2 SAF production via Fischer-Tropsch synthesis

The production of sustainable aviation fuel via gas-to-liquid pathways can be accomplished by gasification/Fischer-Tropsch (FT) synthesis to convert biomass into liquids. The basic steps to produce FT products include syngas production, gas purification, FT synthesis, and product upgrading. A syngas can be obtained either via gasification of biomass, or through reforming or partial oxidation of methane. The syngas then undergoes FT synthesis in an FT reactor to obtain liquid hydrocarbons. Jet fuel produced by the FT pathway was certified by ASTM in September 2009 and is called Fischer-Tropsch synthetic paraffinic kerosene

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(FT-SPK). Moreover, research and development of aromatic-containing fuel (FT-SPK) were continued and in 2015, the Fischer-Tropsch synthetic kerosene with aromatics (FT-SPK/A) was certified by ASTM[4].
As per ASTM D7566, the maximum blending content of FT-SPK and FT-SPK/A compounds in Jet A1 is currently up to 50% by volume.

Maniatis et al[5] reported in 2016 that natural gas-derived FT jet fuel has been commercially produced since 2012 and is routinely used in blends of up to 25% by Shell. There are different process unit options for the reforming of methane; steam methane reforming (SMR), dry methane reforming (DMR), catalytic partial oxidation (CPOX) and autothermal reforming (ATR). These process units may be operated in series or simultaneously to achieve the desired H2/CO ratio. Reverse water-gas shift (RWGS) processes can also be utilized to further control the H2/CO ratio[6].

Baltrusaitis and Luyben[7] explored several possible scenarios of adjusting the H2/CO ratio for FT synthesis with particular emphasis on incorporating the DMR reaction because it results in a net CO2 consuming process. Combinations explored included ATR with and without preceding SMR, as well as combined SMR/RWGS and SMR/DMR processes. The process flow diagram of one of these units using SMR with RWGS to produce syngas for FT is shown in the following figure.

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[4] Gunerhan, A., Altuntas, O., & Caliskan, H. (2023). Utilization of renewable and sustainable aviation biofuels from waste tyres for sustainable aviation transport sector. *Energy*, 276, 127566.

[5] K Maniatis, M Weitz and A Zschocke, *eds.* (2013), 2 million tons per year: A performing biofuels supply chain for EU aviation. European Commission, Brussels.

[6] J. Rahikka (2022) Conceptual design of a sustainable aviation fuel production route from biomethane, School of Chemical Engineering, Aalto University

[7] Baltrusaitis, J., & Luyben, W. L. (2015). Methane conversion to syngas for gas-to-liquids (GTL): is sustainable CO2 reuse via dry methane reforming (DMR) cost competitive with SMR and ATR processes?. *ACS Sustainable Chemistry & Engineering*, *3*(9), 2100-2111.

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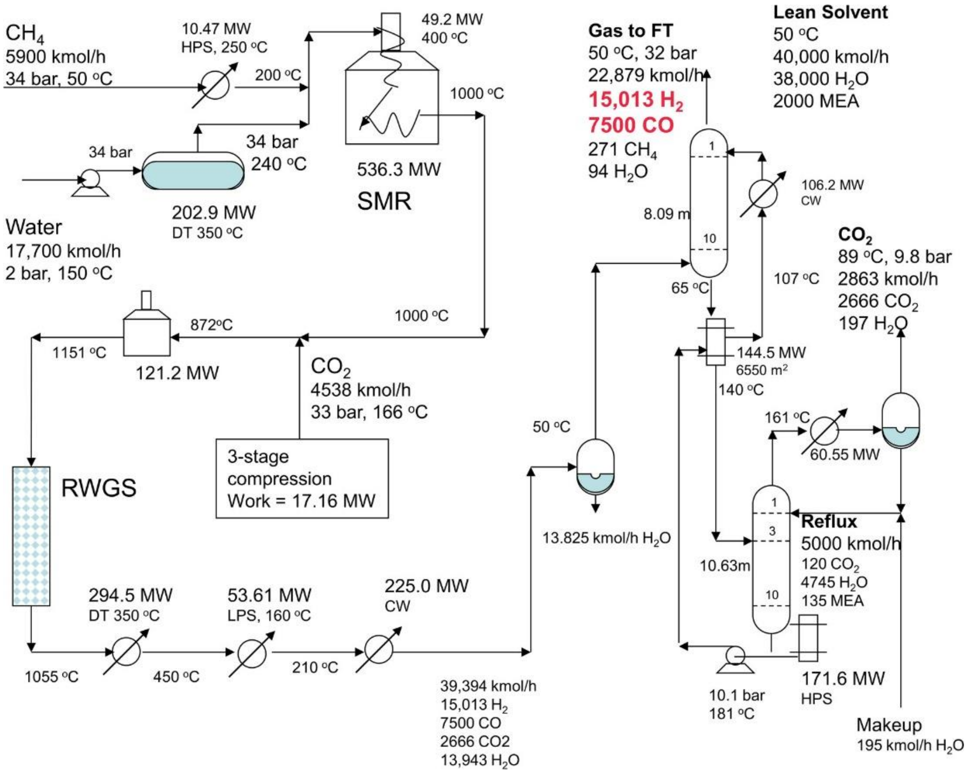

Figure 3. Example of PFD of SMR integration with RWGS for syngas production.

Another process unit for methane reforming is the Plasma Boudouard Reactor (PBR), that MAN ENERGY is currently constructing on its basis for an industrial scale plant owned by CAPHENIA in Industriepark Höchst in Frankfurt am Main, Germany. The process uses biomethane to produce syngas that is then used as a feedstock to produce SAF via FT [8].

In 2022, Jones et al. Showed the importance of FT processes to produce renewable fuels such as SAF in the schematics below, highlighting the role of methane and biomethane at the core of those processes, and the integration of the various sectors[9].

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[8] https://www.man-es.com/docs/default-source/press-releases-new/man-es_pr_caphenia_eng.pdf?sfvrsn=e146ccb2_2

[9] Jones, M. P., Krexner, T., & Bismarck, A. (2022). Repurposing Fischer-Tropsch and natural gas as bridging technologies for the energy revolution. *Energy Conversion and Management*, *267*, 115882.

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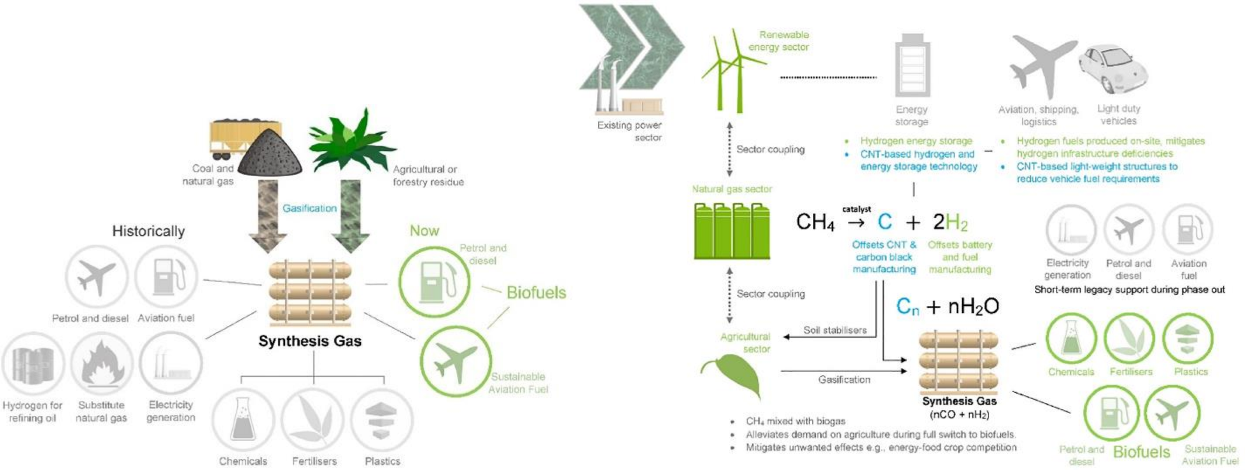

Figure 4. Appraisal of the use of biomethane for the synthesis of sustainable aviation fuel via FT.

4.3 e-methane (in-situ H2 injection, Sabatier, etc)

Biogas typically consists of 25-50 vol% carbon dioxide. These CO2 effluents as well as other intermediate products from AD and gasification can be combined with renewable hydrogen or renewable electricity to increase the overall biomethane yield. The conversion of CO2 effluents from biogas upgrading can significantly increase the biomethane potential in Europe. Using renewable hydrogen to increase biomethane yield in AD plants is promising, for instance, when large quantities of excess renewable electricity become available in areas with a high penetration of non-dispatchable renewables (or in future power system scenarios dominated by intermittent renewables), and where the development of a dedicated hydrogen infrastructure is not cost-effective. Green hydrogen can then be produced from excess renewable electricity, after which it is integrated into the AD process and combined with CO2 present in the biogas to increase biomethane yield.[10] There are two main categories of methanation; biological methanation and catalytic methanation.

4.3.1 Biological Methanation

Biological methanation, also termed methanogenesis, applies this transformative process of converting carbon dioxide and hydrogen into methane and water. This intricate conversion is achieved by hydrogenotrophic methanogenic archaea as catalysts, thriving optimally at temperatures between 55 - 65°C. Notably, this process boasts of a lower operational temperature compared to catalytic methanation, a feature shared with both being exothermic reactions generating considerable excess heat, which can be harnessed for ancillary processes.

Biological methanation, leveraging CO2 as a feedstock for microorganisms, emerges as an advantageous solution for smaller plants, capitalizing on waste heat for process sustenance. Its appeal is heightened using cost-effective biocatalysts, more lenient operational conditions, increased tolerance to syngas impurities, and superior product selectivity, simplifying the gas cleaning process. In contrast to catalytic methanation, the biological counterpart remains unaffected by the C/H ratio. The biological and catalytic methanation methods align in their utilization of the Sabatier reaction. Biological methanation unfolds through either in-

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[10] EBA Statistical Report 2023.

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situ injection of hydrogen into an Anaerobic Digestion (AD) reactor or ex-situ implementation in a dedicated reactor housing methanogenic bacteria and nutrients.

4.3.2 Catalytic Methanation

Catalytic methanation, akin to its biological counterpart , transforms CO_2 and H_2 or CO and H_2 into methane and water. Diverging from biological methanation, catalytic methanation employs a metal catalyst instead of microorganisms, necessitating higher temperature and pressure . Nickel stands out as the most prevalent catalyst due to its suitable properties and cost-effectiveness, with other metals like iron, cobalt, molybdenum, ruthenium, rhodium, palladium, and platinum also viable for the process. Operational parameters include a temperature range of 250 – 400 °C and 20 bar pressure, making catalytic methanation ideal for ex-situ applications post-biogas upgrading. This contrasts with anaerobic digestion, which operates at lower temperature and pressure. A prerequisite for catalytic methanation involves meticulous impurity separation, particularly removing H_2S, known to compromise reactivity and CO_2 conversion into methane. Ex-situ applications offer versatility, enabling the use of CO_2 from diverse sources, not confined to biogas.
Innovations have sought to enhance the catalytic methanation process. Combining different catalysts, such as adding a small amount of iron to a nickel catalyst, has been explored to boost methane conversion. Another innovative approach is Sorption-Enhanced Methanation (SEM), involving the introduction of a sorption material to extract water from the reaction and facilitate full methanation at reduced pressure.

BIOMETHAVERSE Horizon Europe Project: *In-situ and ex-Situ Methanation Technologies*
The ongoing BIOMETHAVERSE project[11] presents a good example of demonstrating methanation technologies. The project is exploring five technologies encompassing both catalytic and biological methanation processes. The demonstrated technologies have a TRL (Technology Readiness Level) 3 - 5 but the objective of the project is to move them to TRL 6 and 7. The aim is to surpass current commercial-scale implementations and increase the efficiency and yield of methane production, with demonstrated concepts including:

- In-situ and Ex-Situ ElectroMethanoGenesis (EMG): Electricity enhanced biomethane production.
- Ex-situ Thermochemical/catalytic Methanation (ETM): Thermochemical/catalytic upgrading of biogas using hydrogen.
- Ex-Situ Biological Methanation (EBM): Biological upgrading of biogas using hydrogen, including feedstock pre-treatment via ozonolysis.
- Ex-Situ Syngas Biological methanation (ESB): Biological methanation of syngas from thermal gasification.
- In-situ Biological Methanation (IBM): Hydrogen integration in the AD reactor

4.4 Biomethanol

Methanol, a versatile chemical commodity, finds applications in both the chemical and fuel industries on a global scale. At room temperature, methanol, characterized by the chemical formula CH_3OH, is a clear, lightweight, and easily flammable liquid with the additional properties of water solubility and

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[11] Biomethaverse Project.

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biodegradability. It is a component in a lot of products and is therefore produced, processed and used in many locations all around the world.[12] More than 60% of the global demand of methanol is allocated to the chemical sector, where methanol serves as a crucial intermediate for producing chemicals like formaldehyde, acetic acid, and methanol-to-olefins. These chemicals are integral in the creation of end products such as paints, plastics, and automotive components.[12] Simultaneously, over 40% of methanol is utilized in the fuel industry, functioning as a vital energy carrier in various forms, including pure methanol, methyl tert-butyl ether (MTBE), biodiesel, dimethyl ether (DME), and methanol-to-gasoline (MTG).[12,13]

Biomethanol, derived from renewable sources like agricultural feedstocks, sewage, municipal solid waste (MSW), and industrial waste products, distinguishes itself as a sustainable alternative due to its eco-friendly production methods associated with biomass. Conversely, e-methane refers to methanol sourced from carbon dioxide and green hydrogen generated through renewable electricity. The emergence of biomethanol and e-methanol, sourced from renewable processes, offers chemically identical alternatives to methanol with significantly lower greenhouse gas emissions throughout their life cycles. The production pathways for biomethanol, including gasification, reformer-based methods from biogas, and processes in pulp mills, share similarities with well-established routes for non-renewable methanol. The key steps involve the production of synthesis gas, methanol synthesis, and product purification. The crucial distinction among the pathways lies in the syngas generation step, highlighting the importance of cost and energy-efficient syngas production from renewable feedstocks for successful biomethanol production. For biogas reforming, requiring upgrading and cleaning, the removal of CO2 and elimination of toxic and corrosive components are integral processes as illustrated in figure 1 below. A process design with the possibility of purging the CO_2 separated into the synthesis stage is also included. Another alternative is the "dry reforming" process which replaces a part of the steam with CO2 for methane reforming[12]. This production method is demonstrated in the eQATOR project which is described in the next section.

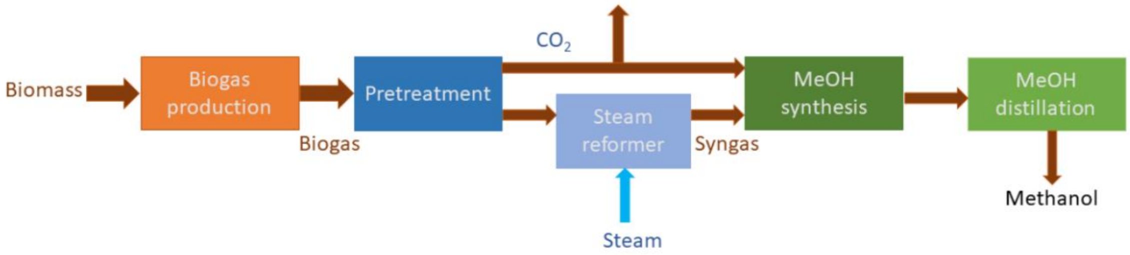

Figure 5. Example of simplified methanol production pathway.

eQATOR Horizon Europe Project: *electrically heated catalytic reactor technologies*

The eQATOR project demonstrates an example of an industrially relevant, environment scalable, electrically heated catalytic reactor technologies, that will allow the conversion of biogas into syngas. The central innovation in ēQATOR is the integrated development of catalysts and reactors, and two different,

Figure 6 Schematic process of biomethanol production from biogas[12]

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[12] https://www.etipbioenergy.eu/images/ETIP_Bioenergy_Biomethanol_production_and_use_as_fuel.pdf

[13] Biogenic-CO2-from-the-biogas-industry_Sept2022-1.pdf (europeanbiogas.eu)

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complementary electrical heating technologies: resistive heating (RH) and microwave heating (MWH), leading to a disruptive electrically heated reactor technology for syngas production.

As mentioned earlier, production of methanol (MeOH) makes use of fossil resources for heating the reactors. Mostly burners and furnaces are utilized in the dry reforming process. This leads to the high thermal mass production with inhomogeneous temperature distribution in the reactor/catalyst. Coking is formed in the process and due to the nature of the entire process, larger reactors are required to undertake them.[14]
The technology demonstrated by the eQATOR project will utilize an electrically heated reactor, with electricity from biogas. This eliminates the need for burners or furnaces. The reactor design will be modified to allow for sectional heating combined with contact points. Providing a more homogeneous temperature distribution, improvement in conversion and selectivity. The overall methanol production process will be more efficient by decreasing the reactor size by 90% and catalyst volume by 50-75%.[14] Implementation of the ēQATOR technology aim at decreasing life-cycle CO2 emissions in syngas production by 60-80% and save from 7Mt CO2/year in 2030. The project aims to achieve TRL 9 for the catalytic process for methanol production.

4.5 Biohydrogen

Biohydrogen refers to hydrogen obtained from biogenic sources (for example, biogases and biomass) using a variety of technologies, including biological, thermochemical and bioelectrochemical processes. Dark fermentation, photofermentation and biophotolysis are examples of biological processes. Thermochemical processes include gasification, biomethane/biogas steam reforming (BMSR) and pyrolysis. Microbial electrolysis (ME) is an example of a bioelectrochemical process.[15]

4.5.1 Dark Fermentation

During dark fermentation, microorganisms generate hydrogen, biogenic carbon dioxide, organic acids, and alcohols from biomass, under anaerobic conditions. The metabolic stages of dark fermentation include hydrolysis, acidogenesis and acetogenesis. These three steps are identical to the biogas production process but, in dark fermentation, the methanogenesis stage (the fourth step in the biogas production process), is prevented. Hydrogen and carbon dioxide are therefore mainly produced during acido- and acetogenesis. Dark fermentation is an alternative biohydrogen technology that is still under development (with a TRL of 3-4): it requires a greater level of maturity for market prices to be established.

4.5.2 Biophotolysis and Photofermentation

Biophotolysis includes all hydrogen production by photosynthesis under aerobic conditions. In principle, all photosynthetically active algae and cyanobacteria can produce hydrogen[16]. Two variants of biophotolysis exist today: direct and indirect biophotolysis. During direct biophotolysis, the transfer of excess electrons to protons occurs directly during light irradiation. During indirect biophotolysis, the electrons are first used for the biosynthesis of hydrocarbons (starch, glycogen) and only converted to hydrogen in a subsequent step.

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[14] ēQATOR - EU Project (eqator.eu)
[15] Decarbonising Europe's hydrogen production with biohydrogen | European Biogas Association
[16] McKinlay, J. B., & Harwood, C. S. (June 2010). Carbon dioxide fixation as a central redox cofactor recycling mechanism in bacteria. *Proceedings of the National Academy of Sciences*, *107*(26), 11669–11675. https://doi.org/10.1073/pnas.1006175107

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Photofermenation in purple non-sulfur bacteria that perform a specific variation of photosynthesis under anaerobic conditions is also considered a biohydrogen production technology. These bacteria need organic substrates and light to grow and produce hydrogen.

4.5.3 Gasification

Gasification is a versatile technology that converts biomass and other solid wastes into a gas (named syngas) at high temperatures (800 – 1,200 °C). The presence of oxygen or steam as oxidising agents is limited, preventing complete combustion to carbon dioxide and water. Although syngas is the main product, other solid and liquid by-products are also generated (namely biochar and tars after gas condensation). Syngas cleaning and upgrading processes (including water-gas shift and pressure swing adsorption) are currently well-developed: they use proven technologies, which are available on the open market. The integration of gasification technology with established gas conditioning operations needs to be further advanced, however, in order to consolidate gasification as a sustainable technology for biohydrogen production.

4.5.4 Raw Biogas and Biomethane Steam Reforming (BMSR)

Steam methane reforming (SMR) is the most common industrial hydrogen production process in use. The process requires high temperatures and a catalyst to facilitate the reaction of methane with steam (water) to produce hydrogen and carbon dioxide. The process is typically carried out in high-temperature reactors using top-fired reformers along with a subsequent water-gas shift process. In the reformer, methane reacts to form mostly hydrogen and carbon monoxide. The water-gas shift process follows to convert carbon monoxide to carbon dioxide while increasing the hydrogen yield from the steam. Steam reforming can also be applied to raw biogas (or biomethane), in which case it is referred to as BMSR. Raw biogas steam reforming can be conducted in compact reformers on-site at biogas plants. Biomethane on the other hand can be injected into the gas grid and used at a central large-scale steam reformer.

4.5.5 Microbial Electrolysis

Microbial electrolysis is based on the same principle as electrochemical water electrolysis. The main difference is the oxidation of organic substances instead of water at the anode of the electrolysis cell. In microbial electrolysis, biological catalysts, i.e. electroactive bacteria, oxidise organic substances such as volatile fatty acids and transfer electrons directly to the anode. The hydrogen evolution reaction at the cathode is identical to water electrolysis (abiotic) but can also be completed using a biological catalyst. The cell voltage generated by the oxidation of the carbon source is usually complemented by an additional voltage. However, this additional voltage is much lower (around 0.123 V) than the theoretical cell voltage of 1.23 V required for water electrolysis. In terms of practical application, it is possible to use aqueous organic waste streams such as wastewater or liquid digestate as a substrate for microbial electrolysis.[17]

TITAN Horizon Europe Project: *Microwave Catalytic Conversion*
The European project, TITAN, is developing an innovative catalyst- and microwave-heated reactor that will offer a high biohydrogen yield and facilitate electrical self-sufficiency. The TITAN technology aims to convert

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[17] [17] Rousseau, R., Etcheverry, L., Roubaud, E., Basséguy, R., Délia, M.-L., & Bergel, A. (1 January 2020). Microbial electrolysis cell (MEC): Strengths, weaknesses and research needs from electrochemical engineering standpoint. *Applied Energy*, *257*, 113938. https://doi.org/10.1016/j.apenergy.2019.113938

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biogas directly into biohydrogen, without greenhouse gas emissions. The technology is expected to rise from TRL 3 to TRL 5 by the end of the project. Thanks to its efficient process and significant reductions in expenditure, TITAN will yield biohydrogen at a competitive cost. The co-produced carbon material may be used for soil amendment at nearby delocalised biogas plants, allowing long term carbon sequestration and a sustainable circular economy. The project started in September 2022 and has a duration of 48 months.[15]

The technology readiness level (TRL) of biohydrogen production technologies varies. Some technologies are well developed, such as thermochemical production processes. Other technologies, including biological and bioelectrochemical processes, are still in the early stages of development. Thermochemical technologies have been implemented in the industry for several years, using fossil natural gas as the energy source. These mature technologies were easily adapted to use sustainable and carbon-neutral energy sources like biomethane and therefore, already rate highly in terms of their TRL. In contrast, processes such as biophotolysis, photofermentation and dark fermentation are emerging technologies still under development.

5 Challenges for large scale injection of biomethane into gas grid

The European natural gas network refers to the interconnected system of pipelines and infrastructure that enables the transportation and distribution of natural gas across Europe. It plays a crucial role in ensuring a reliable and efficient supply of natural gas to meet the energy demands of European countries.

The network consists of various pipelines that connect gas production facilities, storage facilities, import terminals, and end-users such as residential, commercial, and industrial consumers. These pipelines span across different countries and regions, creating a vast and intricate network.

In terms of extension, the European natural gas network is continuously expanding and evolving. New pipelines and interconnections are being constructed to enhance connectivity between different countries and regions. This expansion aims to improve energy security, promote competition, and facilitate the diversification of gas supply sources.

Given the limited amount of production, EU imports the vast majority of natural gas from abroad. Snam[18] provided a synthetic description of the intricated European gas network, which is reported in the following paragraphs. The *Transmed* and *Green Stream* depart from **northern Africa**, directed toward Italy, to Mazara del Vallo and Gela respectively; also beginning in Africa are the *Medgaz*, which connects Algeria to the Spanish coasts, and the *Maghreb-Europe Gas (MEG)*, which crosses Morocco, linking Algeria and Spain. Prior to the outbreak of the Russian-Ukrainian conflict, major gas supplies to Europe came from **Russia** through an extensive pipeline network. Departing from Russia are: the *Nord Stream*, more than 1200 km long and crossing the Baltic Sea over Poland to arrive in **Germany**; the *Yamal-Europe*, almost 4200 km long, crossing through Belarus and **Poland** to arrive in **Germany**; the *Trans Austria Gas Pipeline (TAG)*, running through **Austria** to arrive in **Italy** (Tarvisio); and the *Blue Stream*, which crosses the Black Sea transporting natural gas to **Türkiye**. The network of underwater gas pipelines active in the **North Sea** (among which, *Langeled, Europipe, Zeepipe, Franpipe, Interconnector*) connects **Norway**, **Great Britain** and The Netherlands to the other countries of **continental Europe**. The *Baltic Pipe*, operational since 2022, is a new key route to carry gas from Norway through Denmark to Poland and neighbouring countries. For **Central Europe**, the *Tenp-*

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[18] http://www.snamatlas.it/

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Transitgas system departs from **The Netherlands**, crosses **Germany** and brings Dutch gas and gas from the North Sea to **Switzerland** and **Italy** (Passo Gries). The **Southern Gas Corridor**, nearly 3500 km long, allows the supply of natural gas from the **Caspian Sea** area: it consists of the *South Caucasus Pipeline (SCP)*, which links **Azerbaijan**, **Georgia** and **Türkiye**, the *Trans-Anatolian Pipeline (Tanap)*, which crosses **Türkiye** from east to west, and the *Trans Adriatic Pipeline (TAP)*, which passes through **Greece**, **Albania** and **Italy**. The EU gas network also includes a number of entry points for LNG vessels, which de facto act as “connectors” with LNG exporters countries overseas such as US, Qatar.

The European natural gas network plays a vital role in enabling the flow of natural gas across the continent, ensuring a stable and resilient energy supply. It consists of two interconnected components: the transmission network and the distribution network.

The transmission network is responsible for transporting large quantities of natural gas over long distances, typically from production and import facilities to distribution networks or major industrial consumers. This network consists of high-pressure pipelines, compressor stations, and interconnection points. These pipelines are designed to transport large volumes of natural gas efficiently and at high pressures, often exceeding 70 bar.

The distribution network, on the other hand, operates at lower pressures and is responsible for delivering natural gas to residential, commercial, and smaller industrial consumers. It consists of medium and low-pressure pipelines, local distribution stations, and metering points. These pipelines are designed to ensure the safe and efficient delivery of natural gas to end-users, with pressure levels ranging from a few bars to around 1 bar.

The natural gas grid is interconnected to enable the transfer of gas between different countries, ensuring a reliable and diverse supply of natural gas across Europe. This interconnectedness also allows for flexibility in responding to changes in demand and supply, ensuring a continuous and stable supply of natural gas to consumers.

Provided that the product of biogas upgrading, i.e. biomethane, meets the quality criteria for injection into the local natural gas network, thus ruling out any potential compatibility issue with the existing infrastructure, biomethane is in the unique position of being able to leverage the extensive NG grid to foster the deployment of production plants and attain the ambitious biomethane production capacity target set forth by RePowerEU.

However, the large-scale introduction of biomethane into the European natural gas grid poses several challenges. One major challenge is the need for infrastructure modifications to accommodate biomethane injection points and ensure compatibility with existing pipelines. Additionally, ensuring the quality and consistency of biomethane produced from different sources is crucial for seamless integration into the grid, and the burden of meeting such quality criteria is on the shoulders of each single biomethane producer, since each plant constitutes an injection point into the grid. Balancing biomethane supply and demand, as well as addressing potential regulatory and legal barriers, are also important considerations for the successful integration of biomethane into the natural gas grid.

In November 2023, two officers with one of the largest italian DSO were interviewed within the framework of GreenMeUp project. The DSO officers, currently managing over 600000 end-users served by 8000 km of network and a number of biomethane injection point (to date less than 10), identified two measures of utmost importance, from a network standpoint, to let the grid accommodate the largest number of biomethane installations possible.

The first, is the installation of reverse flow stations (a.k.a. *rebours* or *grid reverse flow*). These apparatuses, already diffused in Germany and France, where at least 4 large rebours are in operation and 20 in test[19], but only experimentally tested in Italy at the time of writing, provide a workaround to the limited capacity of single-ended distribution networks. In fact, in the absence of gas storages the maximum injection capacity of biomethane shall equate the consumption in the subnetwork where the injection takes plane, i.e. the sum of the amounts withdrawn by all the end-users in the sub network.

Grid reverse flow consists in **compressing unconsumed biomethane on a distribution network and then injecting it into the higher-pressure network**. This allows the biomethane to be piped to a more distant consumption area, avoiding burning it or venting it into the atmosphere. **Its operation is automatic**: when the network pressure reaches a high threshold (as a result of low consumption), the compressor unit starts up automatically; by compressing the biomethane, it causes the pressure to increase and the excess is channelled into another network, allowing the initial network pressure to be reduced until the minimum threshold is reached, at which point the compressor will stop. These compression systems make it possible to **maximise the efficiency of the entire energy system** since, by means of pressure changes, they enable the circulation of any surplus gas on upstream networks for immediate consumption or, alternatively, into storage units for future consumption.

The bare module cost for the substitution of a single traditional stations with a reverse flow one rated approximately for 500 Nm3/h was assessed at around 1 M€, and the interviewed DSO alone currently manage in excess of 120 traditional stations.

The second measure that the interviewed DSO pinpointed was grid interconnection, as for the process of interconnecting terminations of independent network sections. This process is meant, on the one hand, to extend the number of end-users under the same distrubution network, thus providing a larger users base for the plants injecting biomethane into the grid; on the other hand, it increases the potential size (capacity) of the single injection point. However, infrastructural extensions are costly, and conversely by the simplicity offered by the installation of reverse flow stations, are subject to much more lengthy permitting.

6 Status and perspective on fugitive methane emissions

Monitoring of fugitive methane emission is of paramount importance along the natural gas value chain, given the sheer scale of consumption and extensive supply network of the commodity worldwide. In the context of the successful establishment of a biogas and biomethane industry in leading EU countries and taking into account the ambitus biomethane production target to 2030, an acceleration in the deployment of an increasing number of biomethane production plants is expected to take place in EU, and with this the interest – both from within and outside the sector, in addressing the curtailment of biomethane fugitive emissions.

A large number of studies have been undertaken since the early developments of the sector, aiming at providing plant operators and stakeholder with the most appropriate instruments to tackle this issue, and now the body of knowledge in the subject is relevant.

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[19] https://www.grtgaz.com/en/medias/news/reverse-flow-stations-to-optimise-production

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Notwithstanding its origin, fugitive emissions of methane are ubiquitous, occurring in most of processes and contexts where anaerobic digestion of organic matter takes place, from wastewater treatment plants[20] to solid waste landfills[21]. In this respect, the sector of biogas and biomethane has carefully considered the implications of fugitive methane emissions since the early days, and the topic has been extensively covered by IEA task 37[22] and EBA[23], leveraging a significant corpus of results from researchers that addressed the quantification of methane emissions from biogas/biomethane plants for specific geographical contexts[24,25], measurement methods[26,27,28] , or specific sections of said plants[29].

Fugitive emission of methane occurs for a number of reason and in distinct sections of the biogas/biomethane plant. Along with point and area sources, leakages can be originated under specific operational conditions. Typical sources of leakage include handling compartments, gas engine exhaust, flares, leaking pipes and connectors, vent and compressors of upgrading units, tanks, pressure release valve. Sections of plants where leaks happen are feedstock intake and pre-processing, digestion process, gas utilization, digestate storage and post-treatment.

In their meta-analysis, a group or researchers at JRC[30] assessed the median and mean values of methane losses for the whole plant, thus including biogas processing, digestate storage, CHP and biogas upgrading, respectively at approx. 2.5 % and below 5% of produced methane.
EBA[23], in its recent report, provided estimates to what extend methane emissions can be curbed through technical and operational measures basing on a comprehensive dataset of literature. According to the report's finding, the main source of leakage is attributed to the digestate storage and post-treatment, with average and median values of 0.69 and 0.5% of produced methane. These values are in agreement with EBA's elaboration of a recent Danish Study, leading to an average total methane emission rate of biogas plants in Denmark equal to 1.31±0.16%.

Hence, it is clear the relevance and pertinence of tackling this source of emission both in the context of meeting the EU goal of scaling up biomethane production to 35 bcm by 2030, thus avoiding a direct loss of production capacity, and avoiding undesired emissions with green-house effect.

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[20] Daelman, M. R., van Voorthuizen, E. M., van Dongen, U. G., Volcke, E. I., & van Loosdrecht, M. C. (2012). Methane emission during municipal wastewater treatment. *Water research*, *46*(11), 3657-3670.

[21] Kumar, S., Gaikwad, S. A., Shekdar, A. V., Kshirsagar, P. S., & Singh, R. N. (2004). Estimation method for national methane emission from solid waste landfills. *Atmospheric environment*, *38*(21), 3481-3487.

[22] J. Liebetrau, T. Reinelt, A. Agostini, B. Linke, Methane emissions from biogas plants (2017). IEA Task 37.

[23] G. Papa, M. Decorte, G.L. Cancian, H. Dekker (2023). Design, build, and monitor biogas and biomethane plants to slash methane emissions, EBA.

[24] Bakkaloglu, S., Lowry, D., Fisher, R. E., France, J. L., Brunner, D., Chen, H., & Nisbet, E. G. (2021). Quantification of methane emissions from UK biogas plants. *Waste Management*, *124*, 82-93.

[25] Liebetrau, J., Reinelt, T., Clemens, J., Hafermann, C., Friehe, J., & Weiland, P. (2013). Analysis of greenhouse gas emissions from 10 biogas plants within the agricultural sector. *Water science and technology*, *67*(6), 1370-1379.

[26] Scheutz, C., & Fredenslund, A. M. (2019). Total methane emission rates and losses from 23 biogas plants. *Waste Management*, *97*, 38-46.

[27] Hrad, M., Huber-Humer, M., Reinelt, T., Spangl, B., Flandorfer, C., Innocenti, F., & Scheutz, C. (2022). Determination of methane emissions from biogas plants, using different quantification methods. *Agricultural and Forest Meteorology*, *326*, 109179.

[28] Hrad, M., Piringer, M., & Huber-Humer, M. (2015). Determining methane emissions from biogas plants–Operational and meteorological aspects. *Bioresource technology*, *191*, 234-243.

[29] Reinelt, T., Liebetrau, J., & Nelles, M. (2016). Analysis of operational methane emissions from pressure relief valves from biogas storages of biogas plants. *Bioresource technology*, *217*, 257-264.

[30] O. Hurting, M. Buffi, N. Scarlat, (2022). Fugitive emissions from anaerobic digestion: GHGs methodology, European Biogas Association Conference.

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There is a number of compelling arguments in support of deploying technical measures and management practices to tackle fugitive emission, including cost-efficiency (decrease of product sold), safety (possibility to originate an explosive atmosphere around the leak), and odor avoidance (being the leak of methane often associated to other compounds).

A number of projects and government-sponsored initiatives has contributed building a body of knowledge of best practices that shall be implemented at the plant level to curtail methane emission; sometimes, as it is the case of Denmark, these best practices have been endorsed by the government agency in charge of the sector's funding and their adoption elevated to a prerequisite for the plant owner/operator to receive state supports.

EBA provided a summary of the measures that can be implemented at the operator level to reduce and mitigate biomethane fugitive emissions, that includes[23]:

- Installing gas-tight covers on receiving tanks and on mixing/incorporation tanks
- Implementing appropriate T and pH control;
- Monitoring and regulating the filling level of the gasholder, aiming at flaring before pressure release valves set off;
- Use of an enclosed flare or gas burner;
- In upgrading, limit methane slip into off-gas by adopting regenerative thermal oxidizers or SlipRec Units (Airco Process Control);
- Ensure sufficient hydraulic residence time to attain the most complete breakdown of digestible organic matter;
- Adopt gas-tight, covered digestate storage tank, connected to the gas system;
- Implement leaks detection and repair (LDAR) campaigns regularly and frequently;
- Implement regular

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7 Conclusions

The report provides a detailed investigation into various aspects of biomethane production and utilization under the umbrella of the Horizon Europe project, GreenMeUp. It sheds light on diverse areas, segmenting the discourse into five prominent chapters.

Developments in AD Technologies explains the growing global recognition of biogas as a renewable energy source and advancements in anaerobic digestion technologies.
Developments in CO2 Management discusses the potential of the biogas and biomethane sector in reducing greenhouse gas emissions and introduces various methods for capturing biogenic CO2.

Developments in Plant Integration with AD systems emphasizes the significance of sustainable bioenergy production methods and explores the innovations in biochar production, sustainable aviation fuel, e-methane production, biological and catalytic methanation, biomethanol production, and biohydrogen production.

Challenges for Large Scale Injection of Biomethane into Gas Grid delves into the complexities and challenges involved in large-scale integration of biomethane into the European natural gas grid.
Status and Perspective on Fugitive Methane Emissions concludes the report with a section dedicated to the urgency of monitoring and curbing fugitive methane emissions, given the rapid expansion of the biomethane industry in the European Union.

In conclusion, the report clearly underlines the promising advancements, pertinent challenges, and potential opportunities in augmenting biomethane production and use across Europe. It lays substantial emphasis on the continuous development and implementation of renewable energy technologies, effective management strategies, and regulatory measures to ensure a sustainable and efficient increase of biomethane in Europe's energy landscape.