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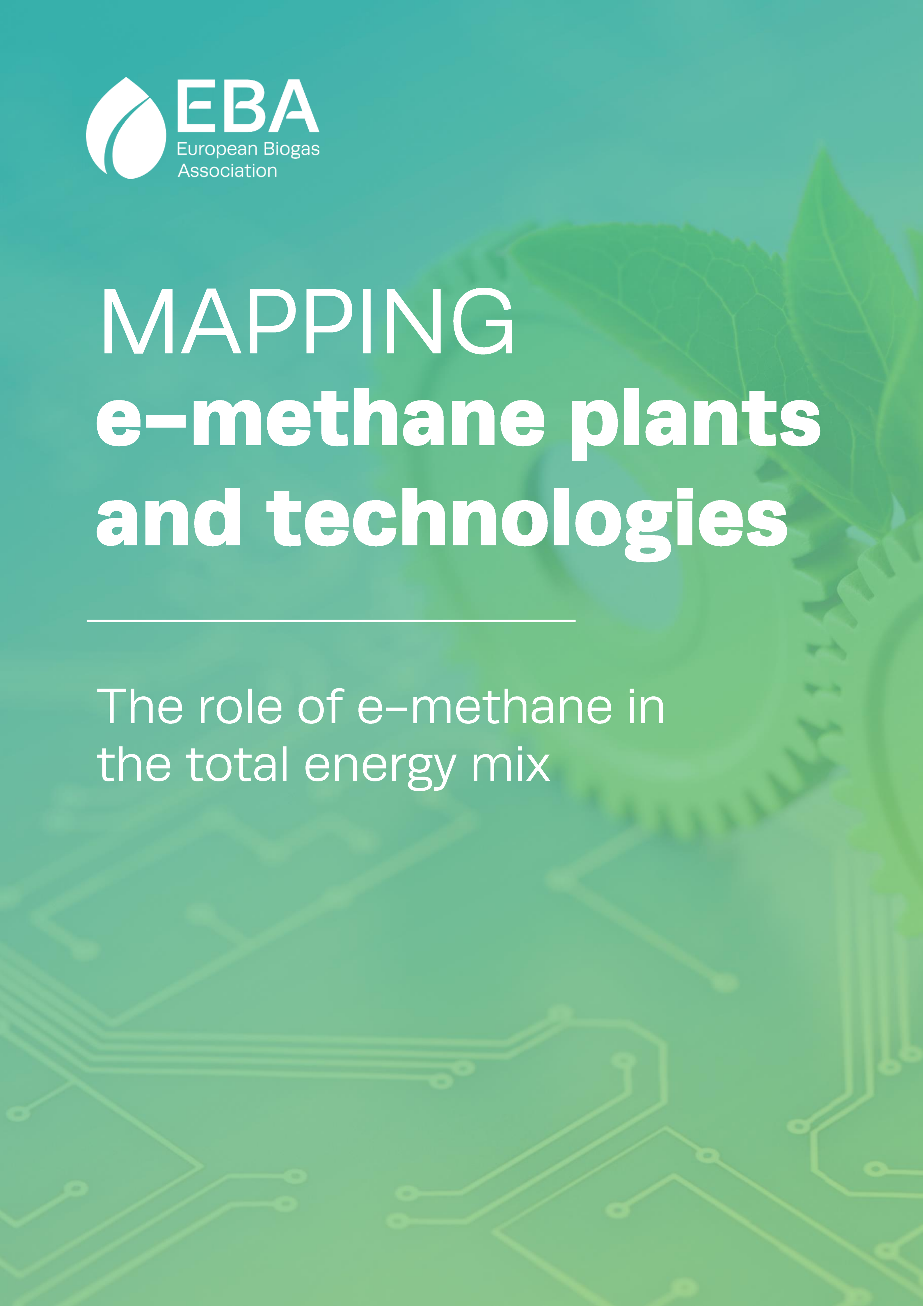

MAPPING e-methane plants and technologies

The role of e-methane in the total energy mix

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About EBA

Founded in 2009, the association is committed to the expansion of sustainable biogas production and their use across the continent. EBA counts on a well-established network of over 300 national associations and other organisations covering the whole biogas and biomethane value chain throughout Europe and further afield.

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Abbreviations

EII	Energy Intensive Industries
AD	Anaerobic Digestion
AEC	Alkaline electrolyser cells
AEM	Anion Exchange Membrane
BIP	Biomethane Industrial Partnership
CAPEX	Capital expense
CCS	Carbon Capture Sequestration
CCU	Carbon Capture Utilisation
CH_4	Methane
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2,	Carbon dioxide
CSTR	Continuous stirred-tank reactor
DAC	Direct air capture
ETS	Emission Trading System
GHGs	Greenhouse Gases
GO	Guarantee of Origin
GW	Giga Watt
H_2	Hydrogen
H_20	Water
H_2S	Hydrogen sulphide
LCA	Life Cycle Analysis
LCOE	Levelized cost of energy
LNG	Liquid Natural Gas
MW	Mega Watt
NECP	National Energy and Climate Plan
NG	Natural Gas
O_2	Oxygen
OPEX	Operating expenses
P2M	Power to Methane
PEM	Proton Exchange Membrane Electrolysers
PPA	Power-Purchase Agreement
REDIII	Renewable Energy Directive
RES	Renewable Energy Sources
RFNBO	Renewable Fuel of non-Biological Origin
ROI	Return of Investment
SAF	Sustainable Aviation Fuels
SOEC	Solid Oxide Electrolyte Cell
TRL	Technological Readiness Level
UDB	Union Data Base

Executive summary

In collaboration with biogas and methanation experts, the European Biogas Association (EBA) has drafted a paper to outline the role of the methanation process within the framework of energy system integration and its potential to increase renewable green gas production in Europe (*Chapter 1*). Insights are provided as to e-methane's place within renewable gas production, the technologies available and its production chain (*Chapter 2*). Furthermore, the European e-methane production plants are mapped, with the main figures and trends summarised. The mapping exercise provides insights into current e-methane production volumes and future growth, technology orientation, CO_2 sourcing, plant sizes and end use (*Chapter 3*). Market strategies and economic considerations are summarised in *Chapter 4*. Finally, considering the technical background and economic framework, policy perspectives and recommendations are formulated for an enabling EU regulatory framework (*Chapter 5*).

> *E-methane is a readily available solution that can help meet the EU's energy and climate goals and complete the integration of our energy system. Moreover, the synergy between biogas and methanation plants holds significant potential to valorise biogenic CO_2 and effectively increase methane production.*

Policy context

As the cornerstone of the European Green Deal, the Fit for 55 Package put forward several positive drivers for the development of biomethane, which are crucial to achieving the EU's climate targets.

For instance, the revised Renewable Energy Directive (REDIII) sets a 42.5% target for the renewables share in energy consumption, with a voluntary additional 2.5%. This directive mandates that Member States report on their progress, ensuring transparency and accountability in achieving EU renewable energy goals. These measures are designed to accelerate the transition to a greener energy system and support the EU's broader climate objectives.

To ensure that all areas of the economy contribute to the EU's climate goals, REDIII also includes sectors-specific targets for buildings, industry and transport, sectors in which renewable energy integration has been slower.

The buildings sector has an indicative target for a RES share set at 49%. For heating and cooling, there is a national binding target of a 0.8% annual increase in RES share until 2026, followed by a 1.1% annual increase until 2030.

For the industrial sector, there is an annual target increase in renewable energy sources (RES) of 1.6%, along with specific targets for hydrogen obtained from RFNBOs, aiming for 42% by 2030 and 60% by 2035, with some exceptions.

In the transport sector, Member States have the option to choose between a 14.5% reduction in greenhouse gas (GHG) intensity or ensuring a renewable energy share of at least 29% by 2030. Additionally, there is a combined sub-target of 5.5% for advanced biofuels and renewable fuels of non-biological origin (RFNBOs) in the renewable energy supplied to the transport sector.

In the REDIII framework, biomass gaseous fuels and RFNBOs are defined and treated differently (Table 1). This can in turn complicate compliance, especially for those biogas plants that produce both biomethane from anaerobic digestion (AD) and e-methane from methanation.

Table 1 Relevant REDIII definitions

REDIII Definition	Category
(27) 'biomass fuels' means gaseous and solid fuels produced from biomass;	Bio
(28) 'biogas' means gaseous fuels produced from biomass;	Bio
(33) 'biofuels' means liquid fuel for transport produced from biomass;	Bio
(34) 'advanced biofuels' means biofuels that are produced from the feedstock listed in Part A of Annex IX;	Bio
(36) 'renewable fuels of non-biological origin' means liquid and gaseous fuels whose energy content is derived from renewable sources other than biomass;	eFuel

The distinction between biomass fuels and RFNBO (eFuels) is especially relevant when looking at the criteria they have to fulfil in order to be considered sustainable and thus be eligible to contribute towards the targets set by REDIII (Table 2).

Table 2 Relevant distinction criteria according to the REDIII

Category	Criteria
Biofuel / Biomethane from AD	The **sustainability criteria** set out in RED Article 29 (par. 2 to 7), which are used to determine whether biogas can be considered sustainable or not depending on feedstock sourcing.
	The **greenhouse gas emission savings criteria** set out in REDIII Articles 27 and 29, which are used to determine whether biogas can be considered sustainable or not depending on the date on which the facilities came into operation and the end use for which the biogas or biomethane is destined. In addition, RED III specifies the methodology to calculate the greenhouse gas emission savings and provides default emission values to specific feedstocks and pathways (Annex VI).
eFuels / E-Methane from methanation	The **greenhouse gas emission savings criteria** in REDIII in Article 29a, which sets a greenhouse gas emissions saving of at least 70 %.

Together with REDIII sectoral sub-targets, other policies in the Fit for 55 Package drive the production ramp-up and utilisation of biomethane, as well as RFNBOs.

For instance, ReFuelEU Aviation[1] and FuelEU Maritime[2] regulations aim at increasing the share of renewable energy in the aviation and maritime segments by respectively: requiring fuel suppliers to provide EU airports with an increasing minimum share of sustainable aviation fuel (SAF) blends up to 70% by 2050; and limiting the GHG intensity of the energy used on board ships on an LCA basis up to 80% by 2050.

When talking of biomethane targets specifically, the REPowerEU plan aims to significantly enhance the production and use of biomethane in Europe. A key component of this strategy is the Biomethane Action Plan, which outlines various tools and measures to scale up the biomethane sector. The goal is to achieve a production capacity of 35 bcm per year of biomethane by 2030. To support this ambitious target, the plan also includes the establishment of a Biomethane Industrial Partnership, which will facilitate collaboration between industry stakeholders, policymakers and other relevant parties. This initiative is expected to drive investment, innovation and the adoption of best practices within the biomethane sector, thereby contributing to Europe's energy security and sustainability goals.

Moreover, since the publication of the RePowerEU Plan, the National Energy and Climate Plans (NECPs) must reflect the deployment strategies aligned with the 35 bcm target. Established in 2018, the NECPs are comprehensive strategies developed by the Member States to outline how they will achieve the EU's energy and climate targets for 2030 and delineate how EU countries aim to address the five dimensions of the energy union: decarbonisation; energy efficiency; energy security; internal energy market; research, innovation and competitiveness. The development of a European biogas and biomethane pathway towards 2030 offers promising medium-term prospects for the sector and can stimulate investment. However, the Commission should request that Member States include clear technological trajectories also for the production of methane from methanation.

The biogas sector also faces a number of legislative barriers that hinder the production scale-up and may jeopardise its business case. For instance, for plants producing both biomethane from AD and e-methane from methanation, the different methodologies to calculate the sustainability criteria of

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[1] Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (2023/2405/EU).

[2] Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC (2023/1805/EU).

biomass fuels and eFuels will imply the need for double certification, which will create a costly and unjustified administrative burden for biogases producers.

As per the Delegated Regulation (EU) 2023/1185[3], no time restrictions apply to the usage of CO_2 originating from biogenic in RFNBOs production. This will drive the demand of RFNBOs producers in biogenic CO_2. Specifically, from 2036 onwards, the CO_2 used in RFNBOs production will have to be either from Direct Air Capture or a biogenic source. Conversely, biogas plants capturing CO_2 will be able to claim Carbon Capture and Replacement credits only until the end of 2035.

Moreover, as per Delegated Regulation (EU) 2023/1184[4], RFNBO producers must adhere to specific power-purchase agreement (PPA) requirements, i.e. temporal[5] and geographic[6] correlation. These requirements introduce additional economic burdens that inevitably increase plant operational costs.

Taking into account the above-mentioned legislative game stoppers for the biogases industry, there is a need for EU legislation to treat biomethane from AD and e-methane from methanation equally by cutting costly and lengthy red tape for both biogas products, as well as introducing a clear trajectory for e-methane from methanation in the governance of the energy union.

Figure 1 Sustainable Criteria for RFNBOs as per Delegated Regulation (EU) 2023/1184[4] (Source: PtX Hub)[7]

Case 1: Direct connection
100% renewable H2/RFNBO

Renewable electricity facility must be new (time window of 36 months)

Case 2: Average grid electricity
100% renewable H2/RFNBO

Only if, the installation producing the RFNBO is located in a bidding zone where the average share of renewable electricity **exceeded 90%** in the previous calendar year [...]

Case 3: Renewable grid electricity (via PPAs)
100% renewable H2/RFNBO

Need to fulfil: 1)Additionality 2)Temporal correlation 3)Geographical correlation and other requirements

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[3] Commission Delegated Regulation (EU) 2023/1185 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a minimum threshold for greenhouse gas emissions savings of recycled carbon fuels and by specifying a methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels.

[4] Commission Delegated Regulation (EU) 2023/1184 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin.

[5] Until 31 December 2029, renewable electricity must be produced in the same calendar month as the hydrogen. Starting from 1 January 2030, renewable electricity must be produced within the same hour as the hydrogen.

[6] Hydrogen must be produced in the same or a nearby bidding zone as the renewable electricity installation.

[7] https://ptx-hub.org/delegated-acts-on-art-27-and-28-explained/.

Chapter 1 The role of methanation in achieving European energy system integration

The decarbonisation of the European economy requires the integration of various sectors and the use of multiple energy vectors. Enabling and encouraging different energy sectors to work together will optimise how the energy system functions as a whole: it is more effective than decarbonising and making separate efficiency gains in each sector individually. The cross-sectoral links in the EU's current energy system need to be strengthened to create the conditions, enabling and encouraging further integration, in which different energy carriers can compete on a level playing field and use every opportunity to reduce emissions. Better integration of the energy system is also necessary to achieve cost-effective decarbonisation of the EU economies. It will lead to the creation of a more flexible, decentralised and digital energy system, in which consumers are empowered to make energy choices. Achieving optimised integration opens the door to a better use of European-based resources, mitigating energy dependency in Europe.

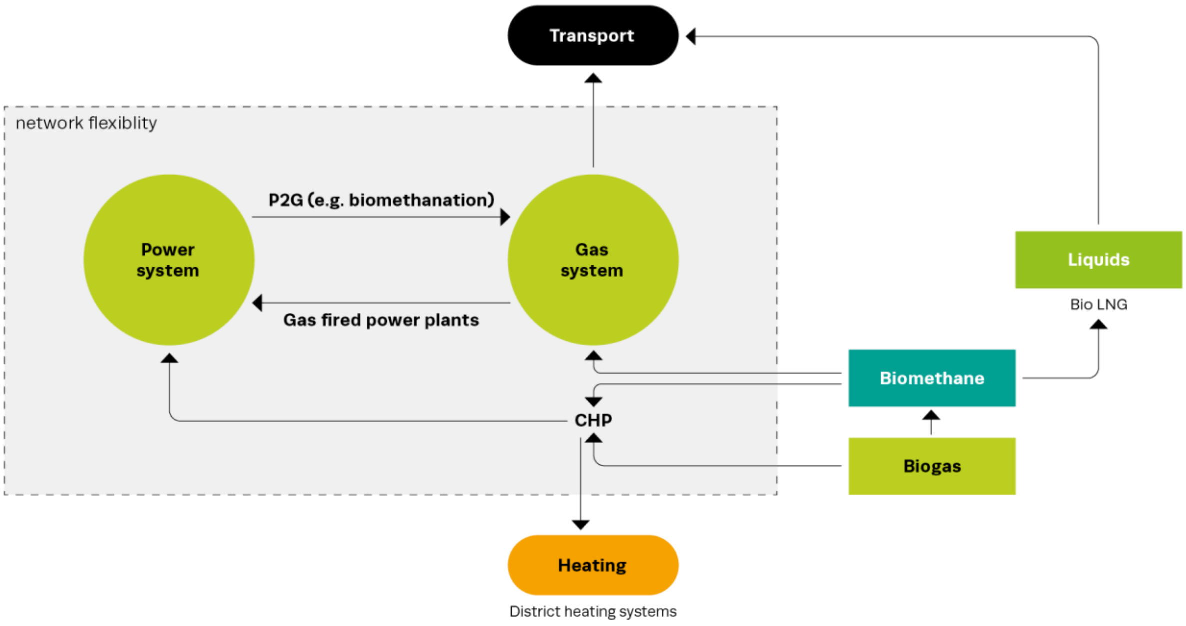
For example, the share of variable renewable electricity sources is on the rise. At the same time, dispatchable power generation capacity in the EU started to decrease in 2012: between 2012 and 2021, electricity capacity from combustible fuels dropped from 427 GW to 379 GW. Clean, dispatchable power generation capacity, for example from biogases, is essential to bridging periods with prolonged low solar and wind output. To compensate for the drop in dispatchable power, mitigate grid congestion and ensure grid stability, stronger connections between the electricity and gas systems are required.

Biogases play an important role in enhancing energy system integration: they provide both daily and seasonal flexibility to the energy system. They support the further integration of variable renewables via three main pathways:

- **The use of biogases in combined heat and power** plants is particularly well placed to provide short-term balancing of the electricity grid thanks to the flexibility in dispatching and controlling their energy output. CHP engines can be quickly tuned to produce more output when demand is high or less when demand is already being met by other renewables. In this way, biogas CHP engines contribute to electricity grid stability.
- **Biomethane** offers dispatchable power generation and the decarbonisation of existing fossil-based district heating systems, as well as greening the gas grid and supporting applications in industry and transport. Furthermore, biomethane is an important form of seasonal energy storage. It can be injected into existing gas infrastructure, which itself functions as a form of energy storage and has the capacity to hold enough for 2-3 months of current gas consumption in the EU.
- **The methanation process**: biomethane and hydrogen will increasingly play complementary roles in Europe's future energy mix. In the methanation process, renewable hydrogen, produced from excess renewable electricity, can be combined with biogenic CO_2 from raw biogas to produce e-methane. This process allows e-methane to function once again as an energy storage solution: excess renewable electricity is stored in the gas grid in the form of e-methane.

The role of methanation in achieving European energy system integration is illustrated in Figure 2.

Figure 2 The contribution of methanation to energy system integration



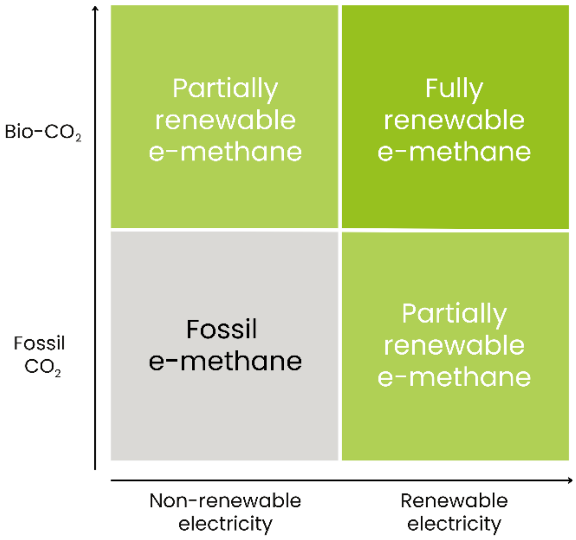
Chapter 2 E-methane categorisation and production chain

Categorisation of e-methane production

Power-to-Methane, or e-methane production, refers to a group of technologies that enables the conversion of electricity into the methane molecule, using CO_2 and H_2 as raw material. In this paper, e-methane is categorised based on the source of electricity and the CO_2 employed along the methane production chain:

- **Fully renewable e-methane**, when the electricity used for its production originates from renewable sources and the CO_2 stems from biogenic sources.
- **Partially renewable e-methane**, when either the electricity originates from renewable sources or the CO_2 from biogenic sources, but not both.
- **Non-renewable e-methane,** when both the electricity used is non-renewable[8] and the CO_2 used in the process is non-biogenic.

Figure 3 Categorisation of e-methane production



Thanks to the use of biogenic CO_2, fully renewable e-methane has the potential to be carbon negative, depending on the implementation of the production process. In particular, at the use-phase of e-methane, CCS can be applied. In the case of using biogenic CO_2 from AD and gasification, digestate and biochar can also enhance soil carbon sequestration, further improving the carbon footprint.

The e-methane production chain

The Power-to-Methane or e-methane production chain can be split into three main steps:

1) **Production of hydrogen (H_2)**, for example from excess green electricity. In some cases, the hydrogen production step is avoided by the direct use of electricity in the methanation process.
2) **Carbon dioxide (CO_2) recovery**, for example from biogas or syngas. Biogenic CO_2 can be separated before methanation takes place, or gas mixtures such as biogas and syngas can be used directly, depending on the technology requirements.
3) **E-methane production**, where H_2 and CO_2 are combined to form CH_4. Methanation technologies are further divided into biological methanation (in-situ and ex-situ) and catalytic methanation. Alternatively, e-methane can be produced via bio-electrochemical assisted AD.

These three stages are illustrated in Figure 4 and further detailed in the next sections.

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[8] including nuclear power

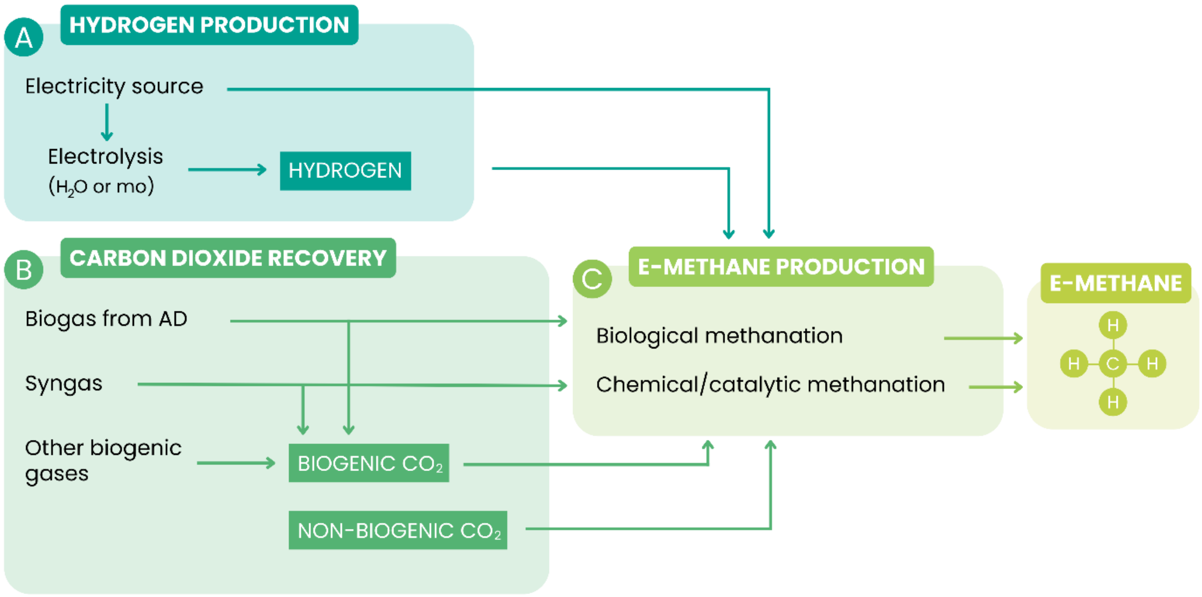

Figure 4 Main steps of the e-methane production chain

Production of hydrogen

The first step of the e-methane production chain is the production of hydrogen. There are several production pathways for hydrogen. These are categorised with colours according to the nature of the generation process. The EBA white paper "Decarbonising Europe's hydrogen production with biohydrogen" sets out the different categories of hydrogen production, together with their feedstock, energy source used during their production process and the products obtained. The most common route to sustainably produce hydrogen is the electrochemical electrolysis of water (H_2O) into hydrogen (H_2) and oxygen (O_2).[9]

Electrochemical water electrolysis is a widely recognised technique for splitting water into its basic elements, hydrogen and oxygen. This process uses electricity as an energy source and thus can be powered by renewable electricity, e.g. from wind and solar.

The chemical reaction is:

$$H_2O \xrightarrow{electricity} H_2 + \frac{1}{2}O_2$$

One mole of water thus yields one mole of hydrogen and half a mole of oxygen. In other words, 9 kg of water is required to obtain 1 kg of hydrogen and 8 kg of oxygen; an electrolyser typically consumes 1 L of water per Nm^3 of hydrogen produced.

In an electrolyser, two electrodes (an anode and a cathode) are immersed in water containing an electrolyte to enhance conductivity. When a voltage is applied across the electrodes, water molecules at the anode lose electrons and form oxygen and hydrogen ions. At the cathode, hydrogen ions gain electrons and form hydrogen gas. The overall reaction produces hydrogen and oxygen as byproducts. The main commercially available types of electrolysers are Alkaline electrolysers (AEC) and Proton Exchange Membrane Electrolysers (PEM), with a TRL of 9.

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[9] The most common process to produce hydrogen is steam methane reforming, but the most common way to sustainably produce H2 is electrolysis.

Other types such as Solid Oxide Electrolyte Cell (SOEC) and Anion Exchange Membrane (AEM) are within a TRL range of 5–7 [10] [11] [12] [13].

It should be noted that, in some cases, the hydrogen production step is avoided and replaced by the direct use of electricity via bio-electrochemical assisted AD (Section "E-methane production").

Carbon dioxide supply

Carbon dioxide (CO_2) supply marks the second step in e-methane production. The CO_2 source can be categorised into three main types: biogenic CO_2, fossil CO_2 and atmospheric CO_2.

Biogenic CO_2

Biogenic CO_2 originates from organic materials. These are themselves derived from biomass, directly (agricultural residues, intermediate crops, green waste etc.) or indirectly (sewage sludge, manure etc.). During its growth, this biomass captures a certain amount of CO_2 from the atmosphere for photosynthesis. When released, biogenic CO_2 does not contribute to atmospheric CO_2, but circulates in short carbon cycles.

Biogenic CO_2 can be captured from biogas or syngas, but also from other sources such as from biopower generation or bioethanol plants. Depending on technology requirements, biogenic CO_2 can be separated into a pure stream before methanation takes place, or gas mixtures such as biogas and syngas can be used directly.

Biogenic CO_2 from biogas is one of the most promising sources of CO_2 for e-methane production. This is first, because at biomethane plants, biogas separation into CO_2 and CH_4 already takes place to enable the injection of biomethane into the gas grid. Therefore, a concentrated CO_2 stream is already at hand. Second, because biogas from anaerobic digestion already contains a relatively large share of CO_2 (typically 25–50 vol%), it can also be used directly as an input stream for the methanation process.

The biogas upgrading process separates biogas into its main components, CO_2 and CH_4. Several types of biogas separation techniques are commercially available:

- **Pressure swing adsorption** separates carbon dioxide and methane molecules by using differences in their degree of attraction to a surface under elevated pressures.
- **Membrane separation** uses a permeable membrane to separate carbon dioxide and methane molecules based on their different physical characteristics.
- **Water scrubbing** dissolves the carbon dioxide molecules in water and thus separates them from the membrane molecules.
- **Chemical absorption** dissolves the carbon dioxide molecules in a chemical solvent and thus separates them from the methane molecules.
- **Physical absorption** dissolves the carbon dioxide molecules in a liquid under pressure and thus separates them from the methane molecules.
- **Cryogenic separation** cools the raw biogas to the condensation point of carbon dioxide. The methane molecules remain in their gaseous form, meaning that the liquid carbon dioxide stream can be easily separated.

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[10] Borge-Diez et al., (2023). Analysis of Power to Gas Technologies for Energy Intensive Industries in European Union Energies, 16, 538. https://doi.org/10.3390/en16010538

[11] Pinter G., 2023. The development of global power-to-methane potentials between 2000 and 2020: A comparative overview of international projects. Applied Energy 353, 122094 https://doi.org/10.1016/j.apenergy.2023.122094

[12] Murphy, J.D., Rusmanis, D., Gray, N., O'Shea, R. (2024) Circular economy approaches to integration of anaerobic digestion with Power to X technologies, Liebetrau, J. (Ed.) IEA Bioenergy Task 37, 2024:1.

[13] Ballal V., Cavalett O., Cherubini F., Watanabe M.D.B. (2023) Climate change impacts of e-fuels for aviation in Europe under present-day conditions and future policy scenarios Fuel 338127316; https://doi.org/10.1016/j.fuel.2022.127316

In 2022, the total availability of biogenic CO_2 from biogas and biomethane was calculated at 28 Mt CO_2/year[14]. The theoretical potential of biogenic CO_2 arising from biomethane production of 35 bcm (as targeted in the REPowerEU Plan) is estimated to be 46 Mt by 2030.

Fossil CO_2

Fossil CO_2 refers to CO_2 sourced from fossil fuels. For example, carbon dioxide can be captured from exhaust gases after fossil fuel combustion (post-combustion). Alternatively, pre-combustion CO_2 streams include CO_2 generated as a by-product in industries such as cement, iron, steel and chemical manufacturing. Industrial CO_2 has an overlap with fossil CO_2, however industrial CO_2 can also be biogenic in specific cases.

Atmospheric CO_2

Last, atmospheric CO_2 is extracted from ambient air, also referred to as Direct Air Capture (DAC). Like in all separation technologies, concentration significantly drives performance. Because CO_2 concentration in air is low (0.04 vol%), the recovery process poses challenges for optimal cost-efficiency and is still under development.

E-methane production

Thirdly, in the methanation process, H_2 and CO_2 are combined to form CH_4, water and heat. In some cases, for example when using syngas, both CO_2 and CO are used as inputs. CO_2 and CO reduction occurs and is facilitated by the presence of a chemical or biocatalyst. Methanation technologies are further divided into biological methanation (in-situ and ex-situ) and catalytic methanation. E-methane can also be produced via bio-electrochemical assisted AD, which is included as a third category below.

Methanation of biogas can be used to replace conventional upgrading, where the methane content is increased from 50-70 vol% towards nearly 100%. Therefore, methanation is also often referred to as hydrogen-assisted biogas upgrading.

The methanation process is not to be confused with methanisation.

- **Methanisation** is a biological process that occurs during the anaerobic digestion of organic matter and takes place in a digester. Naturally occurring microorganisms produce biomethane via a series of metabolic steps: hydrolysis, acidification, acetogenesis and methanogenesis.
- **Methanation** is the process that generates methane from gases, using hydrogen as a reducing agent. During the methanation reaction, CO_2¬- or CO-rich streams are converted to CH_4 according to the Sabatier reaction.

The different methanation technologies are further detailed in the following sections.

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[14] Theoretical potential of biogenic CO_2 based on biogas and biomethane production in Europe in 2022 (21 bcm).

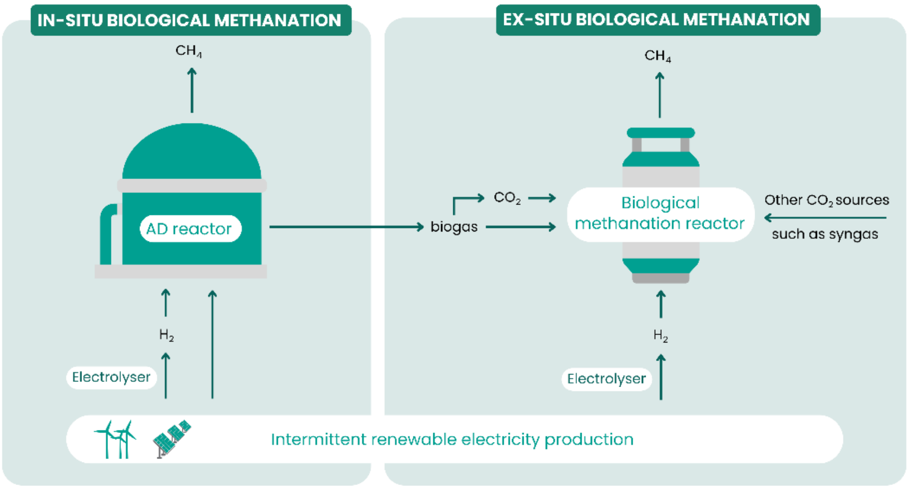
Biological methanation

In the biological methanation process, special microorganisms are used to convert H_2 and CO_2 into CH_4 and H_2O. These organisms capable of producing methane have been identified only from the domain *Archaea*. These *Archaea* are known as hydrogenotrophic and typically live in strict anaerobic environments. They can be cultivated in various reactor systems. Typically, this approach applies to biogenic CO_2 from AD plants. In a continuously stirred tank reactor (CSTR), the microorganisms are grown on an anaerobic medium, whereas, in a trickle bed reactor, the biocatalyst is present as a biofilm. In both cases, the biocatalyst consists of a combination of microorganisms, which facilitate the methanation reaction.

The main advantages of biological methanation include its operation at low temperature (30-60°C) and atmospheric to moderate pressure, along with a high tolerance to pollutants in the feed gas. However, biological methanation has slower kinetics compared to catalytic methanation due to a more limited mass transfer. As biological methanation uses microorganisms as a catalyst, a nutrient solution with essential macro and micronutrients must be supplied. The use of digester effluent or nutrient rich residual streams are being investigated to serve as a nutrient medium, providing all necessary nutrients for the microbial community[15]. Usage of anaerobic residual material such as sewage sludge or fermentation residue allows significant savings of consumables and operating costs for fresh water, disposal of wastewater and additives. Less effort for catalyst management and less equipment for handling catalysts is required. The low use of additives and their low hazardous effect (on the environment, health etc.) simplifies the approval process and requirements regarding safety equipment.

The TRL ranges from 4-8, depending on the setup[16] [17]. Biological methanation can be carried out in-situ or ex-situ (Figure 5). In both system configurations, the pressure and the temperatures are adjusted to the reactor type and the tolerance level of the microbial community.

Figure 5 Illustration of in-situ and ex-situ biological methanation



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[15] Jønson B.D, et al., (2022) Pilot-scale study of biomethanation in biological trickle bed reactors converting impure CO_2 from a full-scale biogas plant, Bioresource Technology, 365, 128160, https://doi.org/10.1016/j.biortech.2022.128160

[16] Vinardell S. et al., (2024) Exploring the potential of biological methanation for future defossilization scenarios: Techno-economic and environmental evaluation, Energy Conversion and Management, 307,118339, https://doi.org/10.1016/j.enconman.2024.118339.

[17] https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2020.00030/full

In-situ biological methanation

In the in-situ configuration, which only applies to recycling CO_2 from AD plants, the methanation reaction takes place in the biogas digester itself. Additional methane could be generated not only by converting the internally produced CO_2 during digestion, but also by stimulating the metabolic pathways of the microorganism present in the reactor. This results both in an overall increase of the biomethane yield per given amount of feedstock and a higher CH_4 concentration in the final biogas produced[18][19].

One of the main advantages of in-situ biological methanation is that there is no need for an additional system or reactor, as the methanation takes place in the AD reactor itself. This can significantly reduce the capital investment required for construction. Green hydrogen can be supplied to a running AD reactor, for example, using an existing gas circulation mixing system[20][21]. Biogas from the headspace of the reactor is pumped to the bottom of the fermenters to ensure the contents of the reactor are mixed and a high conversion of H_2 and CO_2 into CH_4.

The H_2 flow rate should be carefully controlled. On the one hand, due to the low solubility of H_2, a setup should be selected which ensures a sufficiently high H_2 transfer from the gaseous to the liquid phase[22]. On the other hand, overdosing H_2 can deplete CO_2 and thereby decrease the pH within the system towards levels unfavourable for the microbial community. Further influencing process parameters include reactor volume, temperature, hydraulic retention time and organic loading rate.
The TRL for biological methanation varies depending on the specific implementation, ranging between 6-8[23] .

Ex-situ biological methanation

In the ex-situ configuration, the reaction occurs in a separate methanation reactor containing the microbial culture and nutrients, necessary for the conversion[24][25]. The supply of CO_2 can either be a pure CO_2 stream or part of a gas mixture (such as biogas or syngas) and is supplied in stoichiometric ratio with H_2. In this process, the final CH_4 concentration is reportedly in the range of 79-98 vol%.

This configuration is simpler compared to in-situ, as the methanation step does not interfere with the digester. This increases the stability of the process. The ex-situ setup has broader industrial applications compared to in-situ, because the source of CO_2 can be diversified and does not necessarily need to come from biogas plants.

The TRL of ex-situ biological methanation varies depending on the reactor design, with higher TRL levels being achieved in continuous stirred tank reactors (TRL 8-9), trickle bed reactors (TRL 6-7) and stirred bubble columns (TRL 7)[26].

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Catalytic methanation

The catalytic methanation process is also referred to as chemical methanation or thermo-catalytic methanation. In this case, for the methanation reaction to take place, a chemical catalyst (typically ruthenium or nickel-based) are employed to facilitate the conversion[27] [28]. The required temperature ranges between 200–600°C, with applied pressures up to 40 bar[29]. Because of the high temperature and pressure applied, the feed gas (e.g. raw biogas) needs to be cleaned from impurities such as H_2S below 1 ppm[30]. The reaction is commonly carried out in fixed bed reactors, which are characterised by stationary setups where gases flow through a fixed catalyst bed. Alternatively, in a fluidised bed reactor, solid catalysts are suspended and kept in a fluid-like state by the upward flow of gas or liquid through the reactor.

The catalytic methanation reactor is an exothermic process; it thus produces excess heat which can be used to maintain the process itself. Catalytic methanation is a mature technology, with a TRL range of 7-9.

Bio-electrochemical assisted AD

In bio-electrochemical assisted AD, methane is formed via electroactive microbes. This process takes place, for example, when two electrodes are directly inserted into an AD reactor and driven by external electricity from renewable sources. As organics degrade at the anode, the released electrons can transfer to the cathode and drive CO_2 reduction to CH_4 generation[31]. Bio-electrochemical assisted AD is under investigation within the Biomethaverse project[32] and is expected to achieve a TRL of 6-7 by 2026.

As a technology, bio-electrochemical assisted AD is derived from microbial electrolysis. Microbial electrolysis is an electrical-driven hydrogen production technique, which uses oxidation of organic substances (as opposed to commonly used water) at the anode of the electrolysis cell. Here, electroactive bacteria act as biological catalysts, oxidising organic matter and transferring electrons directly to the cathode. In this case, hydrogen is formed at the cathode, instead of methane in bio-electrochemical methanation[33] [34]. Aqueous organic streams such as wastewater or liquid digestate can be used as substrate for microbial electrolysis.

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Recent advances in biological e-methane technologies

The potential of biological methanation as a leading technology for renewable energy storage and carbon recycling is increasingly being recognised. This is reflected in the surge of research focused on enhancing the efficiency and market readiness of the process. Research is focused on several key areas: improving operational stability and flexibility, boosting productivity, and reducing energy losses and operational costs. These are being tackled through advancements in reactor design, a deeper understanding of microbial community dynamics and the application of chemical and electrochemical mediators.

Operational stability and flexibility: To ensure that the process can consistently produce high-quality methane without the need for further upgrading, technologies are being developed that can adapt to varying operational conditions. This includes methods that maintain performance despite fluctuations in input variables such as hydrogen availability. Investigation into the resilience of methanogenic groups when these are subjected to prolonged starvation periods reveal that metabolic activity is resumed once conditions become favourable again without significant conversion capacity losses[35] [36] [37]. Studies on the effect of pressure on methanogenic cultures also suggests that apart from enhancing conversion rates, a pressure regulation mechanism can be employed as a means of stabilising methane production, particularly in scenarios where variable gas feeding rates may occur[38] [39] [40].

Enhancement of productivity rates: Mechanisms for maximising methane production rates include: microbial community management through the use of chemical components and materials that promote electron transfer[41] [42] [43] and through the regulation of environmental parameters such as pH, temperature and nutrient availability[44]. The increase of gas mass transfer rates is also explored through reactor design and the use of novel gas diffusion methods[45] [36] [46].

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Reduction of energy losses: Energy losses can occur due to the need for heating and mixing. Advanced reactor designs that promote gas mass transfer without using gas-liquid agitation are being increasingly explored. These include reactors that promote the creation of methanogenic biofilms[44 47 48 49 50] and the use of materials that retain a high concentration of biomass within the reactor[45 51]. A variety of other more novel designs is also on the rise[52 53 54]. The integration of electrochemical systems is also being explored to enhance microbial activity, as these can provide a controlled supply of electrons directly to the microbes[55 56].

Operational footprint: The minimisation of operational costs is explored through various mechanisms in a number of studies. These include the reduction of nutritional requirements through the exploitation of specific dynamics within a mixed methanogenic microbial community[35 44] and the direct or indirect coupling of biomethanation systems to other waste treatment processes[57 58 59 60].

Advanced product valorisation: Although biologically produced methane can be readily used as a fuel (heating/transport/industrial processes), its further valorisation to other products such as liquid biofuels, biochemicals or even single cell protein can further optimise resource efficiency and economic viability[61 62].

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Chapter 3 Mapping of European e-methane production plants

EBA ran research on existing e-methane production plants, providing an inventory of pilot and commercial plants operating and planned in Europe. The mapping exercise provides insights into current e-methane production volumes and future growth, technology orientation, CO_2 sourcing, plant size and end use. The inventory covers facilities that came on stream between 2015 and 2024 and those with an anticipated starting date between 2024 and 2027. Geographical distribution among EU countries is also mapped.

This inventory of e-methane production plants was compiled using a combination of direct outreach to project developers, technology providers and industry stakeholders and other data sources: existing databases[63] [64] [65] [66] [67], scientific papers and articles[17] and research projects[68]. Only projects with solid references were retained in the inventory. The established inventory provides insights into the characteristics of e-methane production and its market penetration. The data was subjected to thorough data analysis and the results are discussed in the following sections.

The full list of projects is presented in Annex 1.

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[68] Methanation Plant – Meri-Pori Rejlers Finland Oy | Y-tunnus 0765069-8 | Puh: +358 207 520 700 | www.rejlers.fi

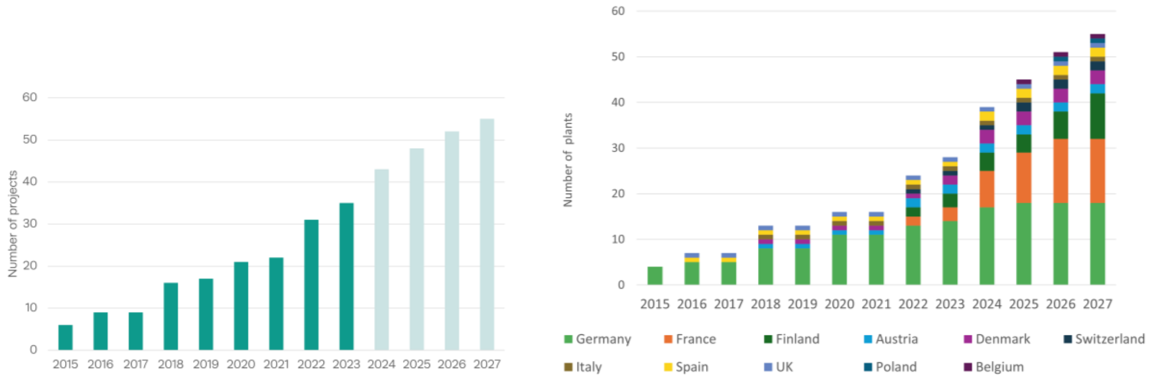
Number of plants

In Europe, by the end of 2023, there were 35 operational e-methane production plants (Figure 6, left), with the largest concentration of plants in 2023 in Germany (14 plants), as shown in Figure 6 (right).

Out of 55 plants and projects, 44 are classified as fully renewable, representing over 98% of total production capacity. The remaining 11 projects are partially renewable: six projects use renewable electricity or hydrogen in combination with fossil CO_2 and five projects use non-renewable electricity in combination with biogenic CO_2.

The years between 2015 and 2023 saw a fivefold increase in plant development and this growth trend will be sustained for the foreseeable future. Between 2024 and 2027, growth is expected to be driven by France (+11 plants), Finland (+8 plants) and Germany (+6 plants). 10 European countries currently have plants running or expected to come on stream in e-methane production by 2027 (Figure 6).

Figure 6 Growth in number of e-methane production plants in Europe (left) and per country (right)



Overall, 32 are active and fully renewable. 20 projects are planned for implementation before the end of 2027. Out of the 20 projects planned for implementation, 12 are already under construction. 47% of all plants and projects are active or planned on an industrial scale, the share of pilot and demonstration projects combined accounts for 47%[69] (Figure 7).

Table 3 Overview of e-methane production projects

Plant/Projects	n° methanation -projects plants	n° active in 2023	n° under development/plan	Production capacity (GWh/year)
Fully renewable	44	32	12	2,773
Partially renewable[1]	6	3	3	36
Partially renewable[2]	5	0	5	12
Non-renewable	na	na	na	na
Total	55	35	20	2,820

[1] fossil CO_2 + green hydrogen/ electricity
[2] biogenic CO_2 + non-renewable hydrogen /electricity

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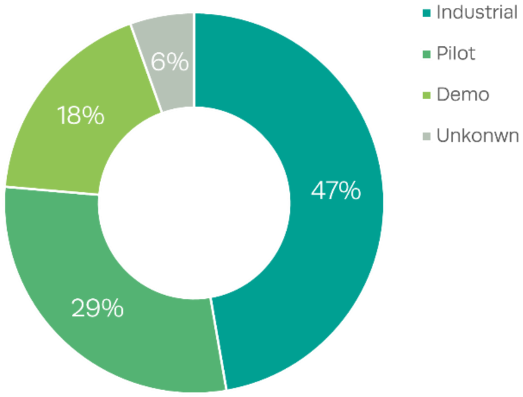
[69] According to classification: pilot (TRL 4-5), demo (TRL 6-7) and pre-commercial (industrial demo) and commercial (TRL 8-9); Eligibility of technology readiness levels (TRL) – UKRI

Figure 7 Type of e-methane production plant in the total number

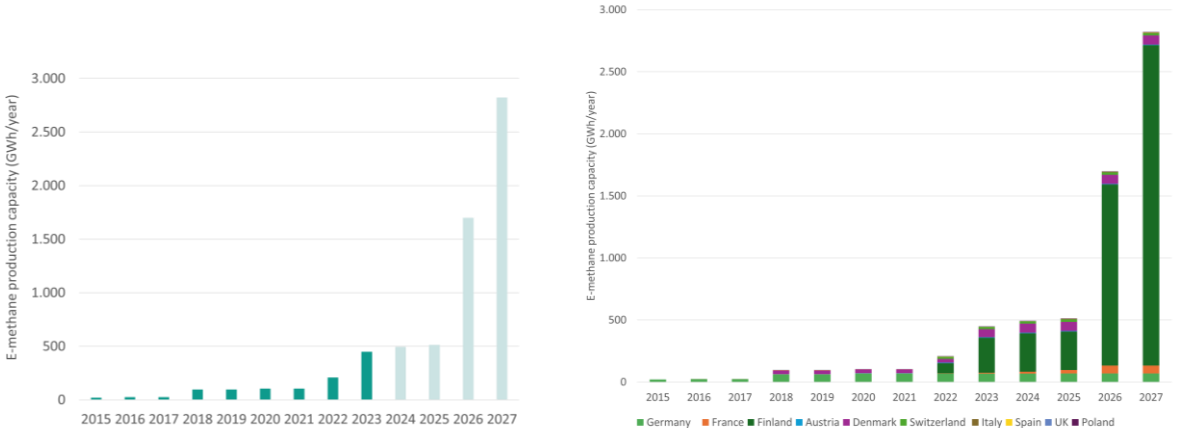


E-methane production capacity

In the past eight years, e-methane production capacity in Europe has increased from 20 GWh/year to 449 GWh/year in 2023 (Figure 8). By 2027, production capacity is expected to reach almost 3,000 GWh or 0.27 bcm per year.

At the end of 2023, Finland (282 GWh/year), Germany (68 GWh/year) and Denmark (64 GWh/year) were the countries with the biggest production capacities in place, followed by Switzerland (18 GWh/ year) and France (7 GWh/year). Finland is expected to register sharp growth in e-methane production capacity, reaching over 2 TWh/year in 2027.

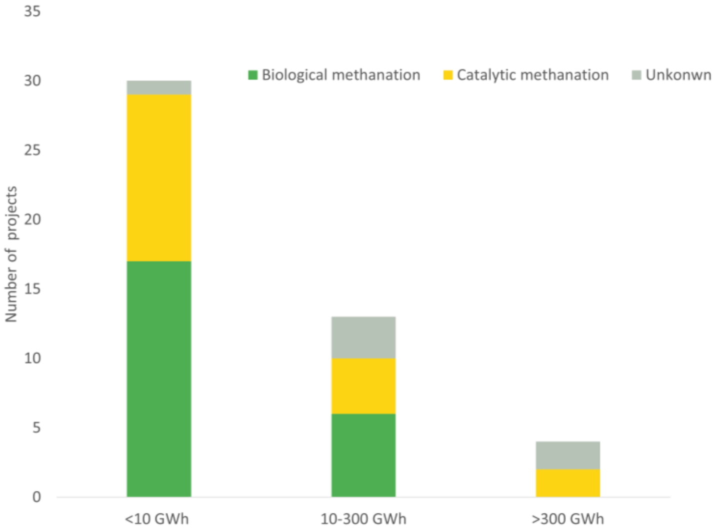
Figure 8 E-methane production capacity in Europe (left) and per country (right)



Plant size distribution

Most of the inventoried plants (64%) have a plant size below 10 GWh/year. This is mostly due to the fact that a large proportion of the plants is on a pilot or demonstration scale. About 30% of the projects have a size of between 10-300 GWh/year production capacity and 8% of the plants exceed 300 GWh/year (Figure 9). In terms of methanation technology employed, the inventory shows that for projects below 200 GWh/year, biological methanation projects are more prevalent. For projects above 200 GWh/year, there is a tendency to opt more for catalytic methanation. Biological methanation plays out its advantages when operated on a decentralised basis, in flexible operation and at biogas plants which typically have available a biogenic CO_2 stream of 100–800 Nm^3CO_2 per hour, thus, resulting in smaller biomethanation plants. Conversely, catalytic methanation plants play out their advantages on a larger scale at industrial CO_2 emitters (e.g. cement, biomass power plants) where, for instance, high temperature steam can be used. Thus, catalytic methanation plants are generally expected to be bigger.

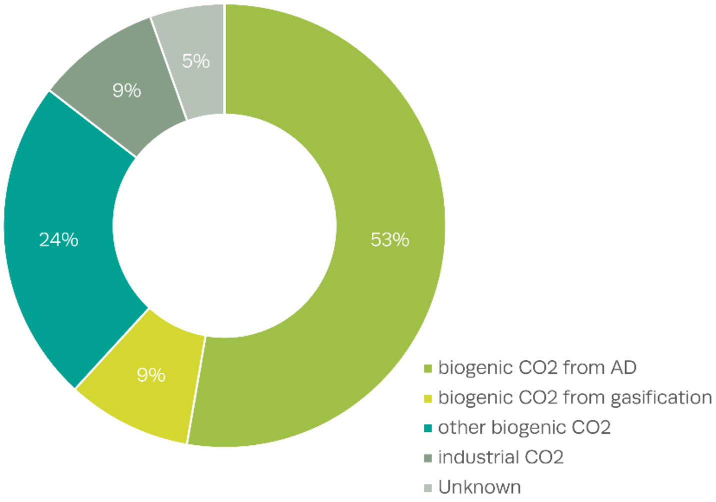
Figure 9 Size distribution of e-methane production plants



CO_2 sourcing

Figure 10 shows the classification of projects with regards to their CO_2 sourcing. More than 80% of all plants identified use biogenic CO_2 in the production process: 53% from anaerobic digestion, 9% from gasification and 24% use other types of biogenic CO_2. In Finland, several plants are under construction that will use biogenic CO_2 from waste-to-energy plants. 9% of the plants do not use biogenic CO_2 sources but CO_2 from industrial processes, and for the remaining 5%, CO_2 sourcing is currently unknown to EBA database.

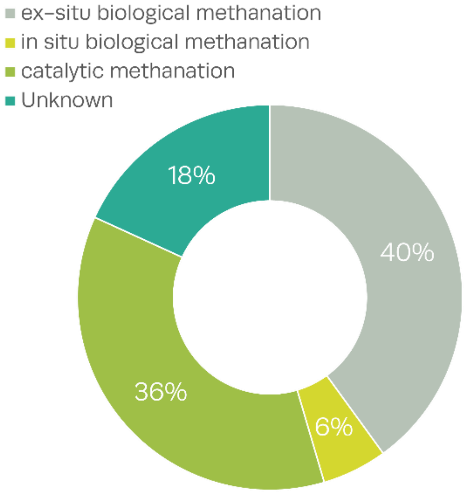
Figure 10 Distribution of the projects by CO_2 sourcing for e-methane production



E-methane production technology

As shown in Figure 11, the technology of the identified projects is shared between catalytic methanation (36%) and biological methanation (46%). Among these, ex-situ is mostly used, accounting for 40% of the total share, compared to in-situ methanation, which represents 6%.

Figure 11 Share of projects by technology for e-methane production

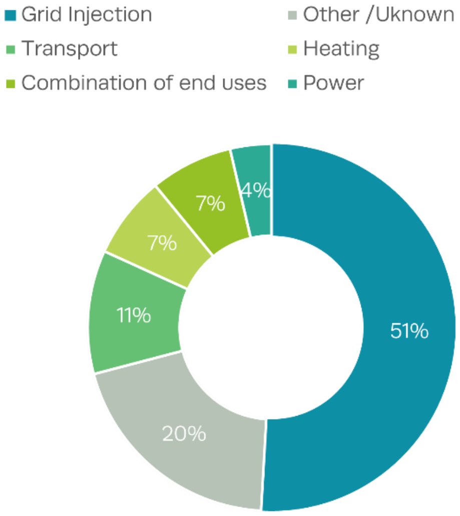


End uses

The majority of e-methane production projects inject or will inject the e-methane into the gas grid (51%), as depicted in Figure 12.

11% of the e-methane projects have transport as a destination, 7% heating, while 4% is used for power generation. Final end uses vary between countries. While most of the plants in Germany and France inject e-methane into the gas grid, in Finland, projects focus on its use as a transport fuel (Bio-CNG or Bio-LNG).

Figure 12 End uses of e-methane



Examples – Case Studies – Main Players

Hybridkraftwerk Limeco (Dietikon, Switzerland)

Technology: ex-situ biological methanation
Production capacity: 18 GWh/year

In a collaborative partnership with eight Swiss energy providers and the municipal utility alliance Swisspower, Limeco has constructed the first industrial power-to-gas plant in Switzerland in Dietikon. The 2.5 MW capacity of a PEM electrolyser fed with renewable power from a waste to energy plant is able to produce 450 Nm^3/h of H_2 which is combined with raw biogas from a waste water treatment plant via ex-situ methanation for injection of up to 270 Nm^3/h CH_4.

Hitachi Zosen Inova Schmack is a global leader in methanation technology and built the facility in Dietikon, which has been in operation since 2022.

Partners involved: Limeco Swiss Power, Eniwa, Stadt Dietikon, Stadt Schlieren, ewb, SWL Energie AG Lenzburg, IBI Ihre Energie, sgsw St. Galler Stadtwerke, Energie Zürichsee Linth, Hitachi Zosen Inova Schmack.

P2X Solutions (Harjavalta, Finland)

Technology: ex-situ biological methanation
Production capacity: 28 GWh/year

The Finnish green technology pioneer company Q Power supplies an industrial-scale renewable synthetic methane production unit to P2X Solutions' production site in Harjavalta. The plant uses 20 MWel of alkaline electrolysis to generate hydrogen from renewable power. The electrolyser can produce 4,400 Nm^3/h of hydrogen, part of which is then combined with CO_2 via ex-situ biological methanation. This process can inject up to 360 Nm^3/h of synthetic methane into the gas grid.

Partners involved: Q Power, P2X Solutions.

e-gas ATLANTIS (Werlte, Germany)

Technology: ex-situ catalytic methanation
Production capacity: 16 GWh/year

Audi has been operating the plant commercially in Werte since 2013. CO_2 is recovered from biogas obtained after AD of residual and waste materials. The electrolytic hydrogen is generated from wind power, via alkaline electrolysis with a capacity of 6 MWel. The catalytic methanation produces 325 Nm3/h of synthetic methane to be injected into the grid in a compressed (CNG) or liquefied (LNG) state.

Partners involved: Audi AG, Hitachi Zosen Inova ETOGAS (SolarFuel), Zentrum für Sonnenenergie und Wasserstoff-Forschung (ZSW), Fraunhofer Institut für Windenergie und Energiesystemtechnik, EWE Energie; McPhy electrolysers EWE Energie AG - the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) - Centre for Solar Energy and Hydrogen Research (ZSW), HY2Gen.

Biofactory Pau (Lescar, France)

Technology: ex-situ catalytic methanation
Production capacity: 6.2 GWh/year

The facility under construction in Pau-Lescar aims to convert CO_2 from AD treating urban waste water in renewable methane using green hydrogen produced from an electrolyser of 1.3 MW. Innovative technologies like ultra-dewatering by hydrothermal carbonisation and catalytic methanation are to be employed for production of 68 Nm^3/h of e-methane.

Partners involved: CAPB Communauté d'agglo Pau Béarn Pyrénées, Suez Eau France – Storengy, Egis, Sogea/Vinci.

Glansager P2X project (Glansager Sønderborg, Denmark)

Technology: ex-situ biological methanation
Production capacity: 35 GWh/year

Inaugurated in 2023, the Power-to-X facility in the Municipality of Sønderborg next to Nature Energy's biogas plant in Glansager, uses surplus renewable electricity to generate hydrogen through an alkaline electrolyser with a power capacity of 20 MWel. The hydrogen is combined with biogenic CO_2 to produce, via biological methanation, e-methane which is injected into grid. When fully operational, the plant is expected to boost green gas production contributing to 35 GWh/year.

Partners involved: Nature Energy, Andel.

Renewable Gasfield (Gabersdorf, Austria)

Technology: ex-situ catalytic methanation
Production capacity: 1.8 GWh/year

The catalytic methanation plant in Gabersdorf is part of "Renewable Gasfield", a research project for a carbon-neutral Austria. It implements a holistic power-to-gas approach, combining multiple renewable energy technologies and taking regional conditions into account, to enable green power to be stored. Renewable electricity from solar power is used to produce green hydrogen by electrolysis. This in turn is used to produce renewable natural gas, for the first time through the direct methanation of raw biogas: in the integrated catalytic methanation system that Hitachi Zosen Inova AG incorporated into the overall design, the CO_2 contained in the biogas reacts with the hydrogen to form synthetic methane, a renewable natural gas substitute.

Partners involved: Energie Steiermark, Montanuniversität Leoben, HyCentA Research GmbH, Energieinstitut an der JKU Linz, WIVA P&G, Energienetze Steiermark, Energieagentur Steiermark Amt der Steiermärkischen Landesregierung, A15 – Fachabteilung Energie und Wohnbau, Hitachi Zosen Inova AG.

BioFARM (Straubing, Germany)

Technology: ex-situ catalytic methanation
Production capacity: 0.2 GWh/year

Inaugurated in 2023 and operated by MycroPyros (Pietro Fiorentini Gorup) and BioEnerTecTM, this pioneering research facility is successfully implementing the process to generate fully green synthetic methane. The innovative anionic exchange membrane water electrolyser (AEM) produces 8 Nm3/ h of H2, which combines with biogenic CO2 from biogas (gasification) for an output of 2 Nm3/h CH4. Since the BioFarm project is not a commercial plant, the output is reinjected for local consumption.

Partners involved: Pietro Fiorentini, Hyter, BioKomp.

Chapter 4 Market strategies and economic considerations

Methanation has proven itself successfully in various pilot and demonstration projects and under relevant operating conditions. The technology shows convincing results under both continuous and flexible operation. It has been successfully tested with biogases (mixtures of CO_2 and CH_4) as well as with a pure CO_2 stream. The first methanation projects on an industrial scale and under commercial conditions have come on stream, indicating that methanation technology is ready to be introduced onto the market.

The technology has significant potential where existing biomethane plants are already in place: it can increase methane output by up to 40–60%, with no modification in the feedstock inputting the process. E-methane production contributes significantly to developing synergies between the renewable gases biomethane and hydrogen: using green hydrogen to increase biomethane yield in anaerobic digestion plants is promising, for instance, when large quantities of excess renewable electricity become available in areas with high penetration of non-dispatchable renewables, or in future power system scenarios dominated by intermittent renewables, and where the development of dedicated hydrogen infrastructure Is not cost-effective[70].

Factors influencing the productions costs

As e-methane production technologies deploy the use of hydrogen or power to generate additional biomethane, the production costs of the biomethane produced is highly dependent on hydrogen or power costs. Therefore, the profitability of e-methane production depends on the cost of surplus power from renewables and the value of power grid stability in the future power grid system. It is anticipated that production costs for e-methane will thus come down when large volumes of intermitted renewable electricity become available at low prices. Current studies indicate that the cost of electricity represents 72-86% of operating costs[71].

Secondly, the number of operation hours have a strong impact on e-methane production costs. An e-methane plant operator can opt either to operate for a few hours with cheap electricity or run for longer durations even if electricity prices are higher. In the first case, a larger unit and thus higher CAPEX is needed, whereas in the second case, smaller systems can be used, reducing CAPEX.

The cost of renewable e-methane production is furthermore influenced by factors such as the CAPEX and OPEX of the electrolyser and methanation plant, its efficiency as well as CO_2 recovery costs. Reduction in electrolysers and hydrogen equipment costs, which are likely given current research efforts, will further bring down e-methane production costs.

Due to these many variables, defining a cost for e-methane is challenging. Nevertheless, the methanation process itself is relatively inexpensive, once the carbon is captured and the hydrogen produced.

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[70] Bendikova V., Patterson T., Savvas S., Esteves S., Economic and policy requirements for the deployment of Power to Methane (P2M) for grid-scale energy management, Energy Reports, 10, 2023, Pages 4271-4285, ISSN 2352-4847, https://doi.org/10.1016/j.egyr.2023.10.049

[71] T.T.Q. Vo, D.M. Wall, D. Ring, K. Rajendran, J.D. Murphy Techno-economic analysis of biogas upgrading via amine scrubber, carbon capture and ex-situ methanation Appl. Energy, 212 (2018), pp. 1191-1202, 10.1016/j.apenergy.2017.12.099.

Factors influencing the business case

Apart from the specific production costs for e-methane, the overall business case is further influenced by factors such as revenues of e-methane sales, revenues of GHG certificates and the usage of waste heat and water.

The economics of e-methane production will furthermore depend on how Member States internalise the added values of power grid stability, security of supply and intra-seasonal energy storage (the biomethane produced with excess power in summer can be stored for use in winter in the natural gas grid). Thus, the cost of additional e-methane produced with power or hydrogen should be compared with the cost of long-term energy storage or other power-to-gas technologies (e.g. in comparison to batteries or H_2 storage).

Policy interventions, such as the RFNBO sub-target, incentives from the EU hydrogen bank Auction or national measures providing CAPEX and OPEX support further improve the business case.

> *The first methanation projects on an industrial scale and under commercial conditions have come on stream, indicating that methanation technology is ready to be introduced onto the market.*

Chapter 5 Outlook and perspectives

As showcased in this paper, e-methane is a readily available solution that can help meet the EU's energy and climate goals and complete the integration of our energy system. Moreover, the synergy between biogas and methanation plants holds significant potential to valorise biogenic CO_2 and effectively increase methane production. Nevertheless, a sound legislative framework is still needed in order to untap the full potential of both biomethane and e-methane.

Overview of the EU framework applicable to RFNBO

Several policies within the Fit for 55 Package, along with the REDIII sectoral sub-targets, are crucial for promoting the ramp-up and utilisation of e-methane. REDIII sets an indicative target for renewable energy used in the industry sector and an RFNBOs sub-target against which e-methane can be counted: in each Member State, at least 42% of hydrogen used in industry shall be RFNBOs in 2030, and 60% in 2035.

REDIII also establishes a binding combined sub-target of 5.5% for advanced biofuels (Annex IX, Part A) and renewable fuels of non-biological origin (RFNBOs), which primarily include renewable hydrogen and its derivatives, in the energy supplied to the transport sector. Within this target, there is a minimum requirement of 1% specifically for RFNBOs.

Moreover, regulations on strengthening CO_2 emission performance standards for both new light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) encourage the shift towards zero-emission vehicles, such as fuel cell electric vehicles (FCEVs), which can run on e-methane. Additionally, the ReFuelEU Aviation and FuelEU Maritime Regulations aim at increasing the share of renewable energy in the aviation and maritime transport sectors, which have the potential to become an attractive market for e-methane.

Policy Recommendations

In order to unleash e-methane's full potential and expedite the widespread adoption of methanation solutions, EBA identified a set of recommendations that should be integrated in future policies.

1) **Ensure legal certainty and a level playing field among renewable vectors**: as per RED III, biomass fuels and RFNBOs are defined and treated differently, creating administrative burdens for those plants producing both biomethane from AD and e-methane from methanation, especially when it comes to the calculation of their respective GHG emissions savings. Thanks to their low greenhouse gas footprint, both biomethane and synthetic methane can significantly displace fossil CO_2 emissions, particularly in those sectors that are more challenging to decarbonise. For the EU to achieve its energy and climate objectives, policymakers should establish regulatory conditions that support the profitable production and use of both.
2) **Set higher biomethane and e-methane targets to unlock their rollout and ensure political commitment over time**: large amounts of green vectors are necessary to achieve the EU's climate neutrality goal. Translating regulatory drivers into tangible market developments requires time. Therefore, it is crucial to establish specific targets

for both biomethane and e-methane to ensure long-term legal certainty and encourage investment, allowing for increased production and deployment for their use in all sectors. Moreover, since the release of the RePowerEU Plan, the European Commission recommended Member States to incorporate deployment strategies that align with the 35 bcm/year target in their National Energy and Climate Plans (NECPs). Establishing a European biogas and biomethane trajectory towards 2030 presents promising medium-term opportunities for the sector and can attract investment. However, policymakers should require Member States to set higher national targets and ensure they include clear technological pathways, including the production of methane from methanation, to maintain sustained political commitment.

3) **Develop policy measures able to internalise the costs of daily and seasonal energy storage, flexibility, peak shaving and waste management**: biomethane and e-methane are highly flexible green energy sources, offering numerous socio-economic and environmental benefits. They can be easily stored and deployed throughout the energy system using existing gas infrastructure and end-use technologies. As a dispatchable energy carrier, biomethane – and its synthetic counterpart – can balance intermittent renewable energy generation, offering dynamic electricity production able to accommodate the fluctuations in electricity demand while promoting grid stability and seasonal energy storage. The potential of these green gases goes way beyond renewable energy provision, offering substantial, long-term benefits for the entire economy. This supports the European Green Deal and the transition to a more sustainable and circular economy. Policymakers should recognise these additional benefits and ensure that agricultural, climate, energy and waste policies allow the sector to fully realise them.
4) **Further incentivise the use of both biomethane and e-methane as feedstock**: biomethane and e-methane can and should be allowed to significantly contribute to the decarbonisation of all sectors of our economy. EU legislation should introduce additional economic incentives for the use of biomethane and e-methane in end uses not currently covered by EU ETS and with low or no energy tax as well as the CO_2 tax. This is the case in the chemical and metallurgical industry where biomethane is used as feedstock or a reductor.
5) **Set-up harmonised rules across Registries of Guarantees of Origin for the handling of GO in energy conversions:** GO Registries should adapt their processes to energy conversion, while the harmonisation of rules will avoid double counting and confusion in the market. To this end, the REGATRACE Project[72] made technical recommendations that should be taken into account by GO Registries. This will facilitate market uptake and trade of e-methane when Guarantees of Origin are issued for the purpose of consumer disclosure.
6) **Design a consistent energy system framework**: EU policymakers should design a long-perspective and comprehensive market environment that encourages investment, innovation and growth within the biogas industry. Avoiding a silos approach and taking stock of the sector's real needs will enhance the sector's contribution to renewable energy targets and support broader climate and environmental goals.

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[72] See REGATRACE, D7.3 Recommendations for EU and national policy makers (2022). See Recommendations 5 and 6.

Annex 1

The list of projects includes the following information per plant: name of plant, country, city, methanation process, CO2 source, plant size, status of plant (active, under construction, planned), type of plant (industrial, pilot, demo), starting or anticipated starting year of operation.

Table A1 Plants fully renewable (biogenic CO2 + renewable hydrogen /electricity)

EU country	Location	Name/project/ plant name/company	Methanation process type	Start year operation	Status	End use	CO_2 source	CO_2 converted t/year	Energy production capacity GWh/year	H Source	Electricity source	Electrolysis tech	Total Electrolyser power (MW)	Hydrogen production [Nm3 H_2/hr]	Type	Partners	Links
AU	Gabersdorf	Renewable Gasfield	ex situ catalytic	2022	active	grid injection	biogas (AD)	342	2.0	electrolysis	wind / solar PV	PEM	2	385	industrial	Energie Steiermark Technik GmbH (Projektleitung), HyCentA Research GmbH, Energieagentur Steiermark GmbH, Energieinstitut an der Johannes Kepler Universität Linz, Energienetze Steiermark, Montanuniversität Leoben, WIVA P&G, Land Steiermark, Fachabteilung A15: Energie und Wohnbau; Energie Steiermark, Christian Purrer and Martin Graf	Link
CH	Dietikon	Hybridkraftwerk Limeco	ex-situ biological	2022	active	grid injection	biogas (AD)	3,100	18	electrolysis	waste incineration	PEM	2.5	450	industrial	Hitachi Zosen Inova Schmack -HZI	Link Link Link
DE	Falkenhagen	STORE&GOWindgas/Demonstrationsanlage Falkenhagen des InnovationsprojektsSTORE&GO	ex situ catalytic	2018	active	grid injection	Other	906	5.2	electrolysis	wind	PEM	1.0	180	demo	Uniper Energy Storage GmbH, thyssenkrupp Industrial Solutions AG, DVGW (German Association for Gas and Water), Karlsruhe Institute of Technology (KIT) Uniper Energy Solutions Storage GmbH, Climeworks AG, DBI GUT, DVGW, GWI, HSR Rapperswill, KIT	Link
DE	Straubing	BioFARM/MicroPyros	ex-situ biological	2024	constructed	power	gasification	32	0.2	electrolysis	wind / solar PV	AEM	0.04	8	demo	Pietro Fiorentini, Hyter, BioKomp	Link
DE	Pirmasens-Winzeln	PFI - Pirmasens-Winzeln	ex-situ biological	2015	active	grid injection	biogas (AD)	874	5.0	electrolysis	wind / solar PV	na	2.5	556	pilot	PFI	Link; Link
DE	Schwandorf	Eucolino	in-situ biological	2012	constructed	power	biogas (AD)	84	0.5	na	na	na	0.10	21	pilot	MicrobEnergy GmbH	Link
DE	Flensburg	WeMetBio2 / consortium	ex-situ biological	2025	planned	transport + heating	biogas (AD)	318	1.8	ns	wind	na	na	na	demo	GICON GmbH, Nissen Biogas GmbH, BTU Cottbus-Senftenberg, HS Flensburg	Link
DE	Werlte	Audi e-gas ATLANTIS	ex situ catalytic	2013	active	Mobility / transport	biogas (AD)	2,800	15	electrolysis	wind / solar PV	Alkaline	6.3	1402	industrial	Audi, ETOGAS (SolarFuel), Zentrum für Sonnenenergie und Wasserstoff-Forschung	Link Link

																(ZSW), Fraunhofer Institut für Windenergie und Energiesystemtechnik, EWE Energie; McPhy electrolyzers	
DE	Allendorf, Giessen	BioPower2Gas	ex-situ biological	2016	constructed	grid Injection	biogas (AD)	na	2.8	electrolysis	wind / solar PV	PEM	0.3	67	demo	Carbotech, BION technology, MicrobEnergy GmbH, Viessmann Werke GmbH &Co.KG, Hitachi Zosen Inova, Viessmann Werke GmbH & Co. KG, microbEnergy GmbH	Link Link Link
DE	Mainz	Power-to-Gas-Anlage, Sektorenkopplung	na	2018	active	grid Injection	biogas (AD)	5,509	32	electrolysis	wind / solar PV	PEM	6.3	1402	industrial	Stadtwerke Mainz, Linde, Siemens, Hochschule RheinMain	Link Link Link
DE	Eggenstein-Leopoldshafen	Energy Lab 2.0 am KIT	ex situ catalytic	na	constructed	grid Injection	biogas (AD)	159	0.9	electrolysis	wind / solar PV	PEM	0.1	22	pilot	Karlsruhe Institute of Technology (KIT), the Helmholtz Center Forschungszentrum Jülich (FZJ) and the German Aerospace Center (DLR). Sunfire Forschungszentrum Jülich	Link Link
DE	Sassenburg	Nachhaltige Enregieversorgung Bernsteinsee	ex situ catalytic	2020	constructed	grid Injection	gasification	130	na	na	solar PV	na	na	na	na	EXYTRON	Link
DE	Goldenstedt	BiRG (BioReststoffGas)	ex-situ biological	2023	constructed	other	gasification	na	0.2	pyrolisis	na	na	0.1	24	demo	Power Pack, the Jülich Research Centre and the Fraunhofer Institute UMSICHT, OGE	Link Link Link
DE	Dörentrup	Forschungsprojekt - KraftwerkLand project	ex situ catalytic	2018	active	na	other	na	na	electrolysis	wind / solar PV	PEM	na	na	pilot	Technical University of Ostwestfalen-Lippe (TH OWL)	Link Link
DE	Brandenburg	Turn2X	na	2024	under construction	grid Injection	na	na	na	na	na	na	na	na	industrial	Karlsruher Institut für Technologie (KIT) Turn2X	Link
DE	Pfaffenhofen an der Ilm	Infinity 1	ex-situ biological	2020	active	grid Injection	biogas (AD)	na	7.52	electrolysis	wind / solar PV	na	1	223	industrial	Electrochaea GmbH	Link
DE	Cottbus	RB-HTWP / GICON GmbH	ex-situ biological	2022	constructed	grid Injection	biogas (AD)	8	0.05	na	na	na	na	na	demo	GICON GmbH, energiequelle GmbH, BTU Cottbus-Senftenberg, DLR e.V., YADOS GmbH	Link
DK	Hjørring	PowerLBG/Aarhus University-MissionGreen Fuel	in-situ biological	2024	active	transport + power	biogas (AD)	1,752	9.17	electrolysis	wind	PEM	2		360	Full list available here	Link
DK	Sønderborg	Glansager PtG	ex-situ biological	2023	active	grid injection	biogas (AD)	8,760	35	electrolysis	wind / solar PV	Alkaline	6	1335	demo	Nature Energy	Link
DK	Rooslepa	BioCat	ex-situ biological	2018	active	grid injection	biogas (AD)	6,360	30	electrolysis	wind / solar PV	na	10	2225	industrial	Full list available here	Link; Link
ES	Sabadell-	CoSin Project — Combustibles Sintètics	other (plasma)	2016	constructed	na	biogas (AD)	318	1.8	electrolysis	na	SOEC	0.05	9	pilot	Ineratec Gas Natural Fenosa, AGBAR	Link Link Link Link
ES	Elche	Naturgy and Greene	ex-situ biological	2024	planned	grid injection	Other	na	0.29	electrolysis	renewable unknown	na			pilot	Naturgy, Greene	Link

FIN	Kerava	Keravan Energia Bio-CHP	ex-situ biological	2027	under construction	transport + heating	Other	37,000	180	electrolysis	renewable unknown	na	34	7621	industrial	Q Power Oy	Link Link
FIN	Tampere	e-methane project	ex situ catalytic methanation	2023	under construction	mobility / transport	Other	39,885	201	electrolysis	wind/solar PV	Alkaline	45	23099	industrial	Ren-Gas-	Link
FIN	Lahti	Lahti	na	2027	under construction	heating	Other	70,000	360	electrolysis	na	na	68	15241	industrial	Ren-Gas-	Link
FIN	Kotka	Kotka	na	2026	under review/feasability study	heating	Other	110,000	200	electrolysis	na	na	104	23099	industrial	Ren-Gas	Link Link
FIN	Mikkeli	Mikkeli	na	2027	under construction	heating	Other	37,000	200	electrolysis	na	na	34	7621	industrial	Etelä-Savon Energia.	Link Link
FIN	Pori	Pori	na	2027	under construction	Mobility / transport	Other	100,000	382	electrolysis	na	na	68	15241	industrial	Ren-Gas	Link Link
FIN	Kristinestad	Power-to-X plant	ex situ catalytic	2026	under review/feasability study	transport + power	Other	181,332	949	electrolysis	wind/solar PV	Alkaline	200	41419	industrial	Koppö Energy	Link Link
FIN	Riihimäki	Carbon2x	ex situ catalytic	2022	planned	na	Other	14	0.055	electrolysis	renewable unknown	na		2	industrial	Fortum	Link Link
FIN	Vantaa	Vantaa Energia renewable methane	ex situ catalytic	2022	planned	mobility / transport	Other	13,992	81	electrolysis	wind	na	20	4450	industrial	Vantaa Energy, Vantaa Energy Ltd., Wärtsilä	Link
FR	Ludiès	Occi-Biome	ex-situ biological	2025	under review/feasability study	grid injection	biogas (AD)	1,161	6.7	electrolysis	solar PV	PEM	1.4	312	industrial	Arkolia Energies, Ariege Biométhane - AREC Innovation	Link
FR	Angé	MéthyCentre (Storengy)	ex-situ biological	2024	under construction	grid injection	biogas (AD)	199	1.15	electrolysis	renewable unknown	PEM	0.25	56	pilot	Storengy, EA, Elogen, Khimod, Prodeval, and La Sablière	Link Link
FR	Audun-le-Tiche	METHA2	ex situ catalytic	2022	under construction	mobility / transport	biogas (AD)	41	0.24	electrolysis	wind + gasification	na			pilot	EPA Alzette-Belval et la CCPHVA, Khimod, Prodeval, McPhy	Link Link
FR	Saint-Pierre-d'Eyraud	CUMA des éleveurs du Bergeracois	in-situ biological	2026	under review/feasability study	grid injection	biogas (AD)	2,067	11.92	electrolysis	renewable unknown	na	2.3	520	industrial	CUMA des éleveurs du Bergeracois, Bouygues Energies et Services - Chambre d'agriculture de la Dordogne	Link
FR	Lescar	Biofactory Pau	ex situ catalytic	2024	under construction	grid injection	biogas (AD)	3,143	6.23	electrolysis	waste incineration + PV	PEM	1.3	289	industrial	CAPB Communauté d'agglo Pau Béarn Pyrénées, Suez Eau France - Storengy	Link Link
FR	Marmagne, Cher	MarHySol	ex situ catalytic	2026	under review/feasability study	grid injection	biogas (AD)	2,385	13.75	electrolysis	renewable unknown	na	2.7	600	industrial	Engie	Link
FR	Bonneuil-en-France	STEP de Bonneuil	na	2025	under review/feasability study	grid injection	biogas (AD)	636	3.67	electrolysis	renewable unknown	na	0.7	160	industrial	SIAH Croult et Petit Rosne	Link Link
FR	Perpignan	STEP Perpignan	ex-situ biological	2023	under review/feasability study	grid injection	biogas (AD)	795	5	electrolysis	renewable unknown	na	1	200	industrial	Terega	Link
FR	Sempigny	ENERGO	other (plasma-catalysis)	2022	active	na	biogas (AD)	na	0.28	electrolysis	renewable unknown	na	0.1	12	industrial	ENERGO	Link Link Link
FR	Paris	COMETHA / GICON GmbH	ex-situ biological	2024	active	na	biogas (AD)	1.6	0.01	na	renewable unknown	na	na	na	demo	GICON GmbH, tilia, france biogaz, DBFZ, Fraunhofer IGB	Link
UK	Pontypridd	University of South Wales, Aeriogen Ltd. Pilot systems	ex-situ biological	2016	active	na	biogas (AD)	1.56	0.01	electrolysis	renewable unknown	PEM	0.0028	0.4	pilot	University of South Wales, Aeriogen Ltd	Link Link

																	Link Link Link
IT	Corticella	SynBioS/MicroPyros	ex-situ biological	2025	planned	grid injection	gasification	795	4.53	electrolysis	na	AEM	1	200	industrial	Pietro Fiorentini, Hyter, BioKomp	Link

Table A2 Plants partially renewable (i.e industrial CO_2 + green hydrogen/ electricity)

EU Country	Location	Name /project / plant name/company	Methanation process type	Start Year operation	STATUS	End Use	CO_2 source	CO_2 converted t/y	Energy production GWh/year	H Source	Electricity source	Electrolysis tech	Total Electrolyser power (MW)	Hydrogen production [Nm3 H_2/hour]	Type	Partners involved	Link
AU	Gampern	Underground Sun Storage	ex-situ biological	2018	under construction	grid injection	fossil / industrial CO_2	477	2.8	electrolysis	solar-wind	**Alkaline**	**0.6**	**100**	na	Axiom, Energy institue, acib, Boku, MUL, RAGRAG Austria, AG AXIOM angewandte Prozesstechnik GesmbH VERBUND AG MONTANUNIVERSITÄT LEOBEN UNIVERSITÄT für Bodenkultur Wien ENERGIEINSTITUT an der Johannes Kepler Universität Linz: Axiom Applied Process Technology GmbH, Energie AG, Energy Institute at the Johannes Kepler University Linz, EVN AG, HyCentA Research GmbH, K1-MET GmbH TU Vienna ICEBE, TU Vienna EEG, University of Natural Resources and Life Sciences IFA Tulln, Verbund AG, WIVA P&G, voestalpine Stahl GmbH	**Link** **Link** **Link** **Link**
CH	Aigle	Gaznat methanation project	ex situ catalytic	2023	active	grid injection	fossil / industrial CO_2	11	0.07	electrolysis	solar PV	Alkaline	0.5	109	na	Swiss Federal Institute of Technology Lausanne (EPFL);	Link Link
DE	Pfaffenhofen	Orbit II	ex-situ biological	2022	active	na	mix CO_2 from other sources than biogas	4	0.03	electrolysis	renewable unknown	PEM	0.005	1	pilot	Regensburg University of Applied Sciences (OTH Regensburg)	Link
FR	Fos-sur-Mer	Jupiter 1000	ex situ catalytic	2024	under construction	grid injection	fossil / industrial CO_2	397	2.29	electrolysis		Alkaline& PEM	1	223	pilot	GRTgas, Khimod, McPhy, CEA, CNR, RTE, ADEME	Link Link Link
FIN	Harjavalta	Harjavalta P2X Solutions	ex-situ biological	2024	under construction	na	fossil / industrial CO_2	na	28	electrolysis	renewable unknown	Alkaline	20	4450	industrial	Q Power	Link
PL	Łaziska Górne	TAURON	ex situ catalytic methanation	2025	planned	mobility / transport	fossil / industrial CO_2	72	2.11	electrolysis	PV-wind	Alkaline	0.081	18	pilot	Tauron, CEA, Atmostat, AGHUST, IChPW, Rafako, WT&T Polska DROENERGY S.p.A EIT InnoEnergy; CEA and ATMOSTAT Exergon; IChPW (Institute for Chemical Processing of Coal); RAFAKO S.A; WTT; AGH University of Science and Technology	Link Link Link Link

																ATMOSTAT (Alcen group); CEA (French Alternatives Energies and Atomic Energy Commission)	

Table A3 Plants partially renewable (biogenic CO2 + non-renewable hydrogen /electricity)

EU Country	Location	Name/project / plant name/company	Methanation process type	Start Year operation	STATUS	End Use	CO_2 source	CO_2 converted t/y	Energy production capacity GWh/year	H Source	Electricity source	Electrolysis tech	Total Electrolyser power (MW)	H production [Nm3 H_2/hour]	Type	Partners involved	Link
DE	Zolling	Energiepark Zolling	na	2026	planned	heating	other biogenic CO_2	na	na	coal	na	na	na		industrial	Onyx Power	Link
FR	Lesquielles-Saint-Germain	Denobio-Enosis	ex-situ biological methanation	2024	under construction	grid injection	biogenic CO_2 from (AD)	318	1.83	electricity	na	na	0.4	80	pilot	Denobio-Enosis	Link Link
FR	Le Havre	Methan'Up	ex situ catalytic methanation	2024	under review / feasibility study	grid injection	biogenic CO_2 from (AD)	1,749	10.09	na	na	na	1.98	440	pilot	Urbeez, Smart Port City Le Havre	Link Link Link
FR	Épinal	BIMOTEP - Enosis	ex-situ biological methanation	2022	active	na	biogenic CO_2 from (gasification)	na	na	na	na	na	na	na	demo	Enosis	Link Link
FR	Toulouse	SOLIDIA - Enosis	ex-situ biological methanation	2018	active	na	biogenic CO_2 from (AD)	na	na	electrolysis	network	Alkaline	0.05	na	demo	Enosis, TBI, Teréga, Trify	Link

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