[D4.2] Biomethane Planning Decision Guide

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Deliverable:	Biomethane Planning Decision Guide
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GLOSSARY and ABBREVIATIONS

AD	Anaerobic Digestion
CAPEX	Capital expense
CCS	Carbon Capture Sequestration
CH_4	Methane
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2,	Carbon dioxide
CSTR	Continuous stirred-tank reactor
EBM	Ex-Situ Biological Methanation
EMG	In-situ and Ex-situ Electro Methanogenesis
ESB	Ex-Situ syngas and biogas methanation
ETM	Ex-situ Thermochemical/catalytic Methanation
ETS	Emission Trading System
GHGs	Greenhouse Gases
GO	Guarantee of Origin
GW	Giga Watt
GWh	Giga Watt Hour
ATEX	Atmospheres Explosible
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
H_2	Hydrogen
H_20	Water
H_2S	Hydrogen sulphide
IBM	In-situ Biological Methanation
LCOE	Levelized cost of energy
LDAR	Leak Detection and Repair
LNG	Liquid Natural Gas
MW	Mega Watt
MWh	Mega Watt hour
NECP	National Energy and Climate Plan
NZIA	Net-Zero Industry Act
NG	Natural Gas
O_2	Oxygen
OLR	Organic Loading Rate
OPEX	Operational expenses
PtG	Power to Gas
REDIII	Renewable Energy Directive
RFNBO	Renewable Fuel of non-Biological Origin
ROI	Return of Investment
TBR	Trickle Bed Reactor
TRL	Technology Readiness Leve
UDB	Union Data Base

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Executive Summary

BIOMETHAVERSE project showcases five innovative biomethane production and upgrading pathways, currently under implementation at a demonstration scale in France, Greece, Italy, Sweden and Ukraine. The pathways combine thermochemical, biochemical, electrochemical and biological conversion processes. The demonstrators are showing how biogenic CO_2 rich stream effluents in biogas or syngas combined with green hydrogen or renewable power, is used as an input stream for the methanation to increase the overall yield of renewable methane while addressing the circular approach by CO_2 recycle and valorisation. The demo activities currently in progress are focusing on how to address and implement process parameters and design the pilot construction including operational preparation to reach TRL 6-7.

Implementing these pathways requires a comprehensive evaluation that integrates technical, market, policy, business, and social considerations. To support this, Deliverable 4.2 (Biomethane Planning Decision Guide) is intended as document within Task 4.2 (Assisting future planning decisions) as practical guidance to evaluate whether and how these technologies could be implemented. Its goal is to facilitate the commercial exploitation of promising technologies by ensuring they reach the market, find practical applications, generate value and supports not only technological diffusion but also sustainable industrial innovation, bridging the gap between research and market uptake.

The results highlight that market demand fulfilment and cost efficiency are prioritized over environmental sustainability in investments in these innovative technologies, though environmental concerns remain a key driver. Regulatory policy instability and energy market volatility are the primary investment risks top concerns seen as significant hurdles. Adoption is mostly driven by sustainability incentives and general energy demand, with waste management and technological efficiency also crucial. The preferred ROI range is 5–10%, with investment sizes mainly between 1–10 million EUR, and smaller investments under 1 million EUR also valued. Incentives like blending mandates and biomethane subsidies are crucial to enhance competitiveness and support innovation in grid capacity and flexibility.

The guide is designed to facilitate project developers in evaluating a range of interrelated factors essential for determining the feasibility, scalability, and long-term viability of a given technological solution. Based on analysis of decision-making criteria, insight from project partners, e-methane producers, project developers and field experts, the Guide highlights key technical, economic, political, socio-environmental aspects for successfully deploying e-methane technologies emphasizing the importance of aligning with market needs, regulatory framework and industrial integration potential. This structured, multidimensional approach support early-stage decision-making and strategic planning informed reflection. It also serves as foundation for replication analysis which will help further to identify where and under what conditions each technology is most likely to succeed, towards the broader deployment of renewable methane technologies across Europe.

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Summary of Considerations impacting the decision for e-methane production

1. INPUT

- Biomass Feedstock: no specific limitation, bio-electrochemical assisted AD has requirements for DM
- Biogases Quality biomethanation are generally more robust to variation in gas quality compared to catalytic methanation. Elements influencing the yield of the AD and gasification are substrate/reactor type/temperature/pH/HRT/ORL/C,N
- Electricity for H_2 and reactor operation ranges 0.01-2.7 kWh el/kWh CH_4 produced
- Nutrients ex situ bio-methanation requires nutrients for microorganism growth
- Water: is necessary for H_2 production~9 L /kgH_2)

2. PLANT SIZE

- Methanation is scaled to match the biogas output
- There is no minimum or maximum plant size
- Plants installing an overcapacity can adjust their production volumes to electricity prices

3. BIOGAS PROCESSING

There might be further requirements regarding gas quality from the off-takers (e.g N and H_2S removal)

4. PLANT FLEXIBILITY

On-site gas storages (both for renewable methane and hydrogen) allows plant operator to profit from energy price fluctuations. To produce hydrogen during low electricity prices and sell renewable methane during high gas prices.

5. MINIMIZING GAS LEAKAGES

Leak Detection and Repair LDAR and optimized plant management can effectively reduce fugitive emissions

6. REVENUES FROM BY-PRODUCTS

spent nutrient solution can be used as fertilizer
oxygen produced in addition to hydrogen during electrolysis can be used

7. SITE SELECTION

Sites near renewable electricity sources, ensuring cost-effective hydrogen production
Ideal near existing plants (gasification plant or AD plants) with hydrogen and biogas supply

8. SAFETY

HAZID HAZOP ATEX study must be conducted before commissioning and start up.

Technical factors

Market and commercial factors

9. POLITICAL SIGNALS REGULATORY STABILITY

REDIII, and RNFBO target, REPower EU, Duration of support schemes, FuelEU Maritime Regulation

10. ACCESS TO MARKET

RED sustainability compliance, Gas Directive and Gas Regulation (Right to grid access and Gas GO Registry), Energy Taxation Directive (ETD), EU Emissions Trading Scheme (ETS), Net-Zero Industry Act (NZIA)

12. COMMERCIAL

- Energy related revenues
- Support Schemes, quota GOs, ETS, certification , tax benefits, access to the gas grid
- Revenues from flexible ops
- By product revenues
- CAPEX OPEX

13. SOCIAL ENVIRONMENTAL CONSIDERATION

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1. BIOMETHAVERSE in a nutshell

BIOMETHAVERSE project aims to advance the development and deployment of innovative biomethane technologies across diverse geographical and operational settings.
To this purpose 5 innovative biomethane production pathways are being demonstrated in France, Greece, Italy, Sweden, and Ukraine **Figure 1 1**
In the BIOMETHAVERSE demonstrators, the biogenic CO_2 in the biogas from anaerobic digestion (AD) or from gasification are combined directly with renewable power or in synergy with hydrogen to increase the overall biomethane yield.
The production routes include one or a combination of thermochemical, biochemical, electrochemical and biological conversion processes.

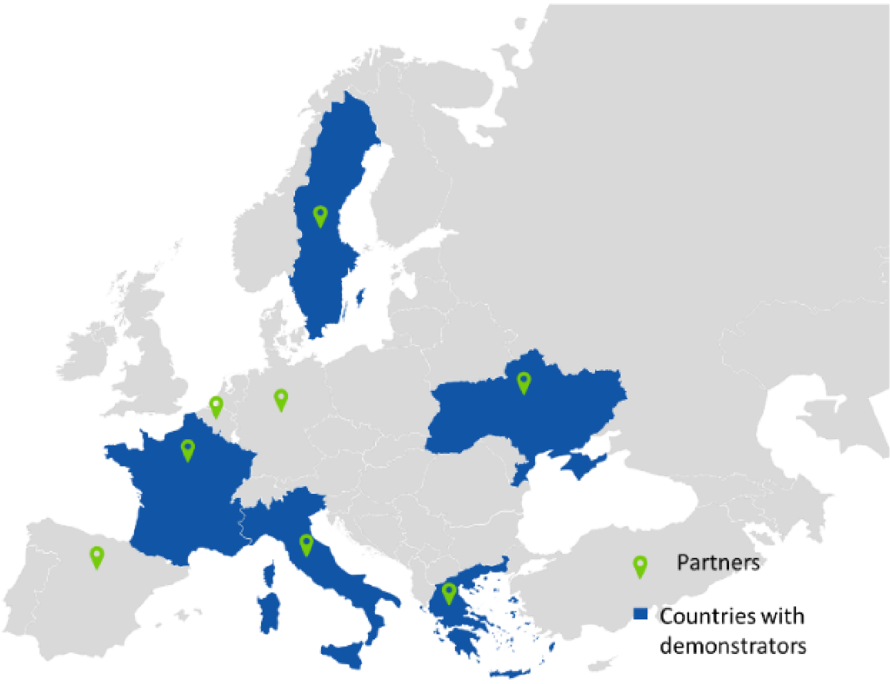

Figure 1 1 BIOMETHAVERSE countries and partners

The five innovative technological concepts that are demonstrated and implemented are listed in **Table 1** ***1*** and an overview of the concept is given in **Figure 1 2**

Technological Innovation	Country	Demo leader
• *In-situ* and *Ex-situ* Electro Methanogenesis **(EMG):** Electricity enhanced biomethane production	France	ENGIE
• *Ex-situ* Thermochemical/catalytic Methanation **(ETM)**: Thermochemical/catalytic upgrading of biogas using renewable hydrogen	Greece	BLAG
• *Ex-Situ* Biological Methanation **(EBM):** Biological upgrading of biogas using renewable hydrogen, including feedstock pre-treatment via ozonolysis	Italy	CAP

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• *Ex-Situ* syngas and biogas Biological methanation **(ESB):** a two-step process that links biomass gasification with biological methanation	Sweden	RISE
• *In-situ* Biological Methanation **(IBM):** Renewable hydrogen integration in the AD reactor	Ukraine	MHP

Table 1 1 Innovative Technology Demonstrations

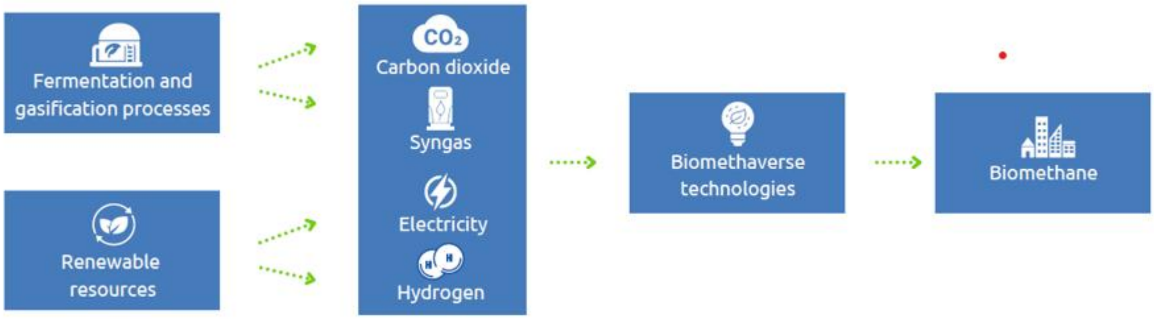

Figure 1 2 Overview of innovative technological concepts in BIOMETHAVERSE

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2. Introduction

2.1. Purpose of this guide

The goal of this guide is to facilitate the commercial exploitation of the innovative technology pathways to produce renewable methane by ensuring they reach the market, find practical applications, and generate concrete value. This approach supports not only technological diffusion but also sustainable industrial innovation, bridging the gap between research and market uptake.

The implementation of innovative technologies requires a comprehensive, multi-dimensional assessment that integrates technical, market, policy, business, and social considerations. Project developers must evaluate a range of interrelated factors to determine the feasibility, scalability, and long-term viability of a given technological solution. To support this process, we have developed a structured framework designed to guide informed decision-making regarding the e-methane technology deployment.

This framework outlines key technical, economic, and socio-environmental criteria that should be considered. It identifies what aspects should be assessed, why they are critical, and how they influence the likelihood of successful implementation. Particular emphasis is placed on ensuring that these technological innovations are aligned with market demands, regulatory frameworks, industrial integration potential, and societal acceptance.

Central to this effort is the construction of a practical guide to evaluate whether and how technology could be implemented. This assists stakeholders in navigating the complexity of commercialization by clarifying the steps necessary to go from development to deployment. It provides a logical sequence of decision points and evaluation criteria that inform whether the innovation is ready for scaling and under what conditions.

The general structure of this guide includes several fundamental nodes, each addressing a critical aspect of the evaluation process:

(i) Technology Description: an overview of the technology, highlighting its key features and operational principles.

(ii) Industry and Market Relevance: consideration of current and emerging market needs, identifying opportunities technology could address and outlining its potential applications across relevant industrial sectors.

(iii) Commercial Dimension: general insights into economics, including indicative costs, business risks, and scalability potential, to support early-stage investment and strategic planning.

(iv) An evaluation of the broader system in which the technology would operate, including supply chains, supporting infrastructure, and logistical requirements.

(v) Societal aspects and contributions to overall productivity and sustainability.

The Biomethane Planning Decision Guide was developed based on an analysis of the criteria and factors that influence decision-makers to implement the technology for producing additional renewable methane.

It draws on the expertise of project partners, as well on the experience of e-methane producers, project developers and experts in the field. It intends to explain the technical, economic, political, and social aspects that should be considered, as well as the key factors that determine whether to implement the technology and the necessary steps to take.

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The information in this guide is also complemented with insights derived from a questionnaire distributed to 50 organizations and private sector and pioneering companies in the renewable energy and biomethane production. The majority of respondents provided detailed answers, offering a representative base of experience from which this decision guide has been developed. In the Annex II the questionnaire with the first part related to technical and the second to market-commercial policy factors and Annex III contains and the script of the workshop.

The comparison of the different configurations and innovative methanation pathways presented in this guide illustrates how P2X facilities can be established and how successful e-methane production can support the system integration of low-emissions gases.

However, each innovation has unique characteristics that may not apply universally.

The chapters of this guide address various aspects of renewable methane production.

After introducing fundamental concepts of the biomethane and e-methane production pathways, the following sections focus specifically on technical elements and explore the key factors involved in the decision to begin production using the described innovative technologies outlining fundamentals on economics and policy dimension.

Complementing the Guide with a replicability assessment

This Planning Decision Guide offers a structured, multidimensional framework to support early-stage decision-making and strategic planning for the deployment of innovative biomethane technologies. Building on this foundation, the BIOMETHAVERSE project has carried out a dedicated replication assessment under Task 4.1, presented in **Deliverable D4.4 – Report on Replicability of Demonstrators**.

The two tools are highly complementary. While the Guide provides a **qualitative and narrative evaluation** of critical factors—such as technological maturity, market relevance, regulatory frameworks, and societal acceptance—the **INSPIRE™ methodology** translates these same dimensions into a **quantitative, evidence-based assessment**.

INSPIRE considers both solution-specific and site-specific variables, enabling the calculation of replicability scores and comparative rankings across different geographical and operational contexts.

By combining insights from both instruments, BIOMETHAVERSE offers a robust decision-support ecosystem. The Guide facilitates informed reflection and planning, while INSPIRE enhances this process with analytical depth, helping identify where and under what conditions each technology is most likely to succeed.

Together, they provide a comprehensive and coherent framework to support the effective deployment and scaling of renewable methane technologies across Europe.

For further details and results of the replicability assessment, see Deliverable D4.4 – Report on Replicability of Demonstrators, when available (November 2026).

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3. Biogases upgrading: biomethane and e-methane production pathways

3.1. Conventional Biogas Upgrading techniques

Upgrading biogas refers to the process of enriching its methane (CH_4) content to obtain a gas with a high CH_4 concentration – called biomethane. This process primarily involves the removal of carbon dioxide (CO_2), which is the most abundant impurity in raw biogas after methane.

Beyond CO_2, upgrading processes also aim to remove other undesirable components. These include:

- **Hydrogen sulfide (H_2S):** A corrosive and toxic compound.
- **Siloxanes:** Silicon-containing compounds that can form abrasive deposits in engines.
- **Water vapor:** Which can lead to corrosion and ice formation at low temperatures.
- **Other trace impurities:** Such as ammonia (NH_3), volatile organic compounds (VOCs), and particulate matter, which can also be present depending on the feedstock and digester operation."

Upgrading usually involves 2 key steps: first, contaminants are removed, and CO_2 is separated from the biogas.

Upgrading increases the energy content to natural gas quality, which is needed for gas grid injection or for use as a vehicle fuel. Upgraded biogas can also be liquified by cooling the gas down to around -162°C.

Biogas upgrading technologies commercially available are:

- **Pressure swing adsorption** separates CO_2 and CH_4 molecules by using differences in their degree of attraction to a surface under elevated pressures.
- **Membrane separation** uses a permeable membrane to separate CO_2 and CH_4 molecules based on their different physical characteristics.
- **Water scrubbing is one step process that** dissolves the CO_2 molecules in water and thus separating the CO_2 and H_2S since are more soluble in water than CH_4.
- **Chemical absorption** dissolves the CO_2 molecules in a chemical solvent and thus separates them from the CH_4 molecules.
- **Physical absorption** dissolves the CO_2 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 CO_2. The methane molecules remain in their gaseous form, meaning that the liquid CO_2 stream can be easily separated.

The relative use of different upgrading techniques in Europe today is shown in Figure 3 1

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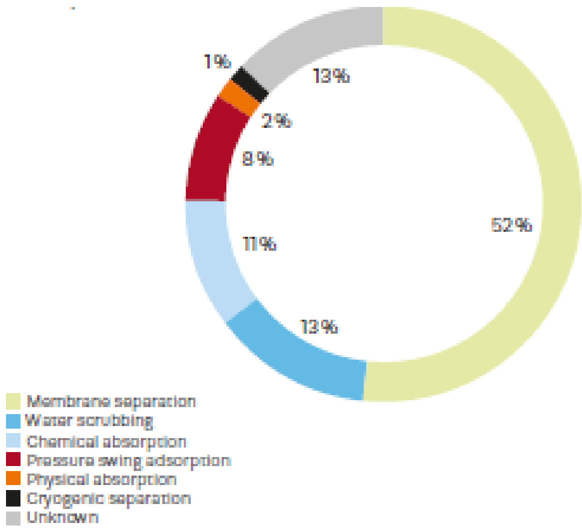

Figure 3 1 Relative use of different upgrading techniques in Europe in 2023 (Source: EBA statistical report 2024) [1]

According to EBA, today most new biogas plants are upgrading the biogas to biomethane. An increasing number of plants, not connected to a gas grid, are producing liquefied biogas (LBG) which can be used for instance in heavy duty vehicles (HDV), in the maritime sector or at off grid industries – replacing LNG.
The Figure 3 2 shows the substances that are removed using different methods involving the combination of upgrading methods to achieve both CO_2 and separation and cleaning.

Methods of removal / Substances to be removed	Pathogenic substances	Siloxanes	Water	Nitrogen	Hydrogen sulphide	Carbon dioxide
Water scrubbing		X	X	X	X	X
Pressure swing absorption (carbon molucar sieves)			X		X	X
Drying			X			
Use of biocide	X					
Chemical scrubbing (absorption amines)		X			X	
Adsorption filter	X	X	X		X	X
Heat exchanger		X	X			
Chemical absorption in desulphuration tower				X		
Stripping						X

Figure 3 2Substances that are removed using different methods from BIOGASMAX [2] project

In the future it is likely that a large part of the CO_2 (called biogenic CO_2) that today is removed at the upgrading units is combined with green H_2 to produce more CH_4, so called e-methane.

[1] EBA Statistical Report 2024
[2] BIOGASMAX project

3.2. Methanation - an alternative to upgrading

Methanation of CO_2 constitutes a large potential for increased biomethane production by using the same amount of initial biomass feedstock.

Methanation of biogas can be used to replace conventional upgrading, where the methane content is increased from 50-70 vol% towards nearly 100%. This can be done either *in-situ* (where methanation takes place already in the digestor) or *ex-situ* (where methanation takes place after the biogas production by conversion of the CO_2 in the off-gas).
Therefore, methanation is also often referred to as hydrogen-assisted biogas upgrading.

The role of methanation in supporting European energy system integration was thoroughly examined in the recently published paper *'Mapping e-methane Plants and Technologies'*.[3] The study highlights the potential of methanation to enhance renewable green gas production and presents policy recommendations for establishing an enabling EU regulatory framework.

The different methanation technologies, including the configurations under development within the BIOMETHAVERSE project, are further detailed in the following sections.

3.3. E-methane production via biological methanation

In the biological methanation process, special microorganisms are used to convert H_2 and CO_2 into CH_4 and H_2O. Methane-producing organisms, exclusively from the domain *Archaea*, are uniquely adapted to anaerobic conditions necessary for methanation.

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.

Key advantages of biological methanation include its low operating temperature (30–60°C), moderate pressure, and resilience to feed gas impurities. 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. Ongoing research investigates the use of digester effluent or nutrient-rich residual streams as cost-effective nutrient media for microbial communities.[4] Usage of anaerobic residual material such as sewage sludge or fermentation residue reduce the need for consumables and operating costs for fresh water, disposal of wastewater and additives.

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[3] https://www.europeanbiogas.eu/mapping-e-methane-plants-and-technologies-2/
[4] 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://www.sciencedirect.com/science/article/pii/S0960852422014936?via%3Dihub

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Biological methanation also reduces costs associated with catalyst management and handling equipment. The low use of additives and their low impact on the environment or health simplifies the approval process and requirements regarding safety equipment.

The Technology Readiness Level (TRL) ranges from 4-8, depending on the setup.[5] [6] Biological methanation occurs either in-situ (directly within the biogas digester) or ex-situ (in a separate methanation reactor), each offering unique operational benefits.
In both system configurations, the pressure and the temperatures are adjusted to the reactor type and the tolerance level of the microbial community.

3.3.1. In Situ biological methanation

In the in-situ configuration, applicable only to anaerobic digestion (AD) plants, the methanation reaction occurs directly within the biogas digester. Methane production increases by converting internally produced CO_2 and enhancing bacterial activity within 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.

The H_2 flow rate should be carefully controlled. 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. 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. Other influencing process parameters include reactor volume, temperature, hydraulic retention time and organic loading rate. Additional challenges include managing gas mixing to prevent foaming, ensuring real-time monitoring of critical parameters, and maintaining operational flexibility to handle seasonal feedstock variations.

The TRL for biological methanation varies between 6-8. depending on the specific implementation.

In the BIOMETHAVERSE project in-situ biological methanation is demonstrated in the Ukrainian demo as followed described.

IBM -PILOT DEMONSTRATION in Ukraine

In situ biological methanation at the AD facility site processing manure and other agricultural residues is being demonstrated in Ukraine.

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 investment cost.

Green hydrogen is supplied to the running AD reactor via an existing gas circulation mixing system replacing conventional stirrers, to enhance substrate mixing and high conversion rates of H_2 and CO_2 into CH_4.

[5] 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.
[6] https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2020.00030/full

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Biogas from the headspace of the reactor is mixed with hydrogen and pumped back into the bottom of the reactor. This ensures good mixing with the contents of the reactor and a high conversion of H_2 and CO_2 into CH_4 is achieved.

Using an existing gas circulation mixing system enhances the carbon efficiency of the AD process, significantly increase the biomethane yield unit of feedstock, and resulting in a higher methane concentration in the final biogas.

This means an overall improvement in the carbon efficiency of the AD process as it results in overall increase of the biomethane yield per given amount of feedstock, and in a higher methane concentration in the final biogas produced.

Yield optimization is achieved through a straightforward, cost-effective approach suitable for existing biogas system.
This approach uses existing gas mixing systems and a mobile design to reduce costs and enable flexible deployment.

This process configuration is expected to achieve a TRL of 6-7 by 2026.

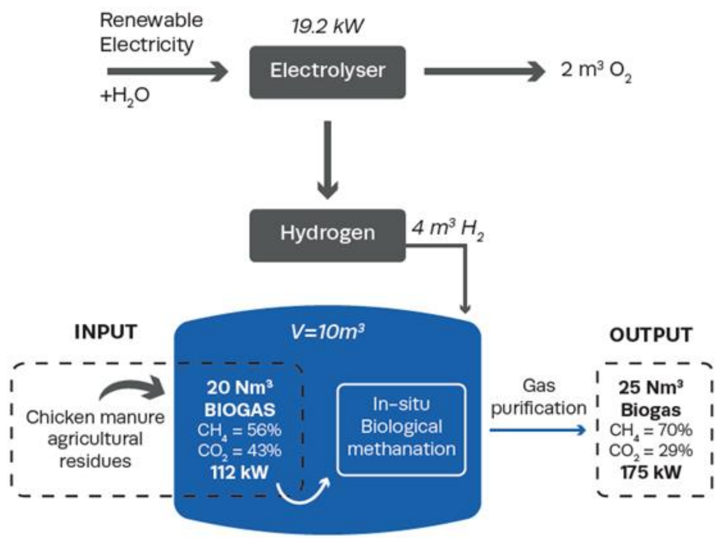
<table>
<tr><td>In-Situ biological methanation</td><td rowspan="3">
</td></tr>
<tr><td>TRL: 4→ 6-7</td></tr>
<tr><td>Technology:
Hydrogen assisted in situ biological biogas upgrading to biomethane</td></tr>
</table>

Figure 3 3 IBM -PILOT DEMONSTRATION in Ukraine

3.3.2. Ex Situ biological methanation

In the ex-situ configuration, the methanation reaction occurs in a separate methanation reactor containing the microbial culture and nutrients necessary for the conversion. The supply of CO_2 can either be a pure CO_2 stream from the biogas upgrading or part of a gas mixture (such as biogas or syngas).

A 4:1 H_2:CO_2 mixture is required for the methanation reaction. Three different demos in BIOMETHAVERSE are demonstrating ex-situ biological methanation pathways. The final CH4 concentration achieved is in the range of 79-98 vol%.

An advantage with ex-situ configuration is that it does not interfere with the processes in the digester which increases the stability of the process. The ex-situ setup has also 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 depends on the reactor design. The highest TRL is reached for continuous stirred tank reactors TRL 8-9, followed by trickle bed reactors (TBR) (TRL 6-7) and stirred bubble columns (TRL 7).

The White Paper titled '*Mapping e-methane plants and technologies' - The role of e-methane in the total energy mix'* [7]based on reaserch conducted by EBA in collaboration with biogas and methanation experts, presents an inventory of pilot and commercial plants operating and planned in Europe aiming to provide insights into current e-methane production volumes and future growth, technology orientation, CO_2 sourcing, plant size and end use.

Among full scale plants, currently active in Europe, the facility in Denmark operated by BiogasClean CycleØ[8] is particularly noteworthy, and good example of Ex-situ Biological Methanation (EBM). The plant was integrated into the raw biogas line on an existing full-scale biogas plant, with 7.5 MW electrolyzer – converting CO_2 and H_2 into e-CH_4.

The system was installed, and operation was initiated in October 2023. The system consists of:

- 7.5 MW electrolyzers (installed power)
- Capacity to convert at least 381 m^3/h CO_2
- Special designed and optimized gas system for inlet of raw biogas and H_2
- Three stainless tanks with total active volume of 914 m^3
- One process technical building, with modulized equipment

The system is built with biological trickling filters (BTF) for optimal mass transfer from gas to liquid, and simplicity of technology system. To the system, gas consisting of H_2 and raw biogas is supplied in stoichiometric levels along with nutrients, to supply the overall biology in the technology. The EBM utilizes natural found *Archaea* in digestate, formally known as *Hydrogenotrophic Methanogens*, which is the *Archaea* naturally accounting for ⅓ – ¼ of biogas production from an AD. The EBM operates under low conditions, with pressures <200 mbar and temperatures <80 °C, with minimal power requirements due to simplicity of BTF system.

The integration of the EBM was the first of its kind in full scale. The full-scale EBM is an upscaling from pilot scale, which validated the technology in TLR 4-5, utilizing raw biogas on a biogas plant. The full-scale system is fully operational and have proven the technology in TLR 8. (Figure 3.4)

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[7] Papa, G., Decorte, M., Venturini, A., Lamon, F., Cancian, G., Dekker, H., Boehm, R., Esteves, S. R., Clinkscales, A., Madoui-Barmasse, M., Karlsson, L.-E., Thibaut, O., Piepiora, V., & Bonse, D. (2024). Mapping e-methane plants and technologies: The role of e-methane in the total energy mix. European Biogas Association. https://www.europeanbiogas.eu/wp-content/uploads/2025/10/Mapping-e-methane-plants-and-technologies.pdf

[8] https://www.cycle0.com/what-is-e-methane; https://www.cycle0.com/biogasclean-acquired/

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Ex-Situ biological methanation	
TLR 8	
Conversion of CO_2 and H_2 to e-CH_4 through biological catalyst.	

Figure 3 4 Installed EBM facility at the biogas plant in Denmark. In operation since October 2023.

EBM - PILOT DEMONSTRATION in Italy

In the Ex-situ Biological Methanation (EBM) demonstration in Italy the demonstration plant is being implemented in one of two parallel AD lines. The set up is composed by four units:
(1) sewage sludge ozonolysis, which will serve as pre-treatment to enhance the feedstock digestibility and thus the biogas yield,
(2) ex-situ biological upgrading, to convert CO_2 into CH_4 and boost the biomethane yield,
(3) microalgae cultivation on the liquid fraction of digestate and
(4) co-digestion of pre-treated sludge, microalgae, and selected substrates.

The purpose of sludge treatment using ozone is to increase the anaerobic biodegradability of the substrate and its capacity to produce biogas while significantly reducing the digestate volume.
Biological ex-situ upgrading operates under mild conditions. Key factors include gas transfer efficiency and the ability of microbes to adapt to varying hydrogen loads. The biological hydrogenotrophic conversion of biogas to biomethane, is being demonstrated using *Archaea* in both suspended biomass and biofilm forms. H_2 and biogas are supplied through two methods: the biofilm receives nutrients by membrane diffusion, while oxygenating the suspended biomass to support its growth or metabolism.

This process configuration is expected to achieve a TRL of 7 by 2026.

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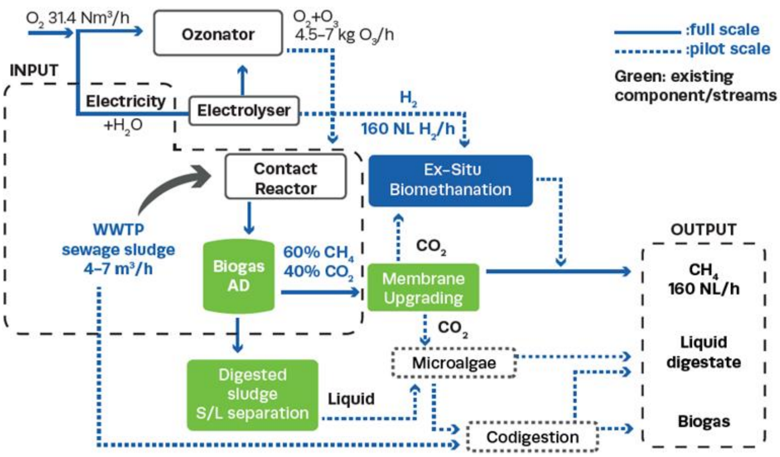
<table>
<tr><td>Ex Situ Biological Methanation</td><td rowspan="3">
</td></tr>
<tr><td>TRL: 3-4→ 7</td></tr>
<tr><td>Technology:
• Sludge pre-treatment via ozonolysis
• Hydrogen assisted biological biogas upgrading
• +2 auxiliary units: Microalgae production with the unconverted CO_2 and co-digestion unit</td></tr>
</table>

Figure 3 5 EBM -PILOT DEMONSTRATION in Italy

ESB - PILOT DEMONSTRATION in Sweden

In the Ex-Situ Syngas and Biogas Biological methanation (ESB) demonstration in Sweden syngas from thermal biomass gasification is converted to biomethane in a Trickle Bed Reactor (TBR).

The syngas, consisting of CO, H_2, CO_2 and some CH_4, is fed to the reactor together with a nutrient solution. Various nutrient solution can be used, such as digestate from a co-located conventional biogas plant or reject water from municipal wastewater sludge dewatering. The syngas meets a microbial biofilm and a continuous flow of nutrient rich solution. CO and H2 are consequently converted to CH_4 and CO_2. The TBR design allows for a high exchange rate between the gas and liquid phase.

Methanation of the remaining CO_2 can be done by adding H_2 to the input syngas. The methanation reaction between the additional H_2 and CO_2 takes place in the same TBR infrastructure facilitated by the same mix culture biofilm. The resulting final gas mix has very high CH_4 content and the need for a conventional upgrading step is therefore eliminated. This results in a high utilization of invested CAPEX with no need for investment in the CO_2 separation step required instead in conventional biomethane upgrading.

Biological methanation of syngas is demonstrated both without and with addition of external H_2.

This process configuration is expected to achieve a TRL of 6-7 by 2026.

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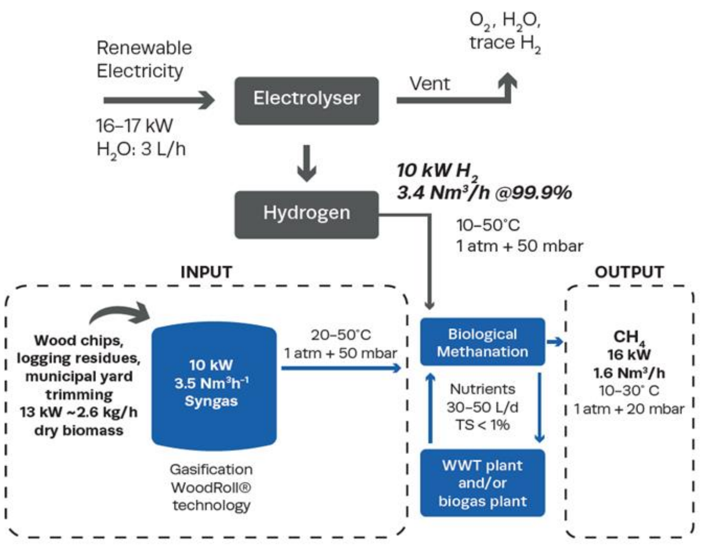
Ex Situ Syngas and Biogas Biological Methanation	
TRL: 4→ 6-7	
Technology: Biological methanation of syngas (CO, H_2) and nutrient solution with or without additional green H_2	

Figure 3 6 ESB -PILOT DEMONSTRATION in Sweden

EMG - PILOT DEMONSTRATION in France

In the bio-electrochemical assisted AD under investigation methane is formed via electroactive microbes. When two electrodes are directly inserted into an AD reactor and driven directly 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.[9]

Therefore, 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.[10] [11] Aqueous organic streams such as wastewater or liquid digestate are used as substrate for microbial electrolysis. The key factors include a stable pH of 7 in the cathodic chamber to keep the microbiology in optimal conditions

This process configuration is expected to achieve a TRL of 6-7 by 2026.

[9] Ning Xue et al., (2021) Emerging bioelectrochemical technologies for biogas production and upgrading in cascading circular bioenergy systems. iScience 24, 102998).
[10] Liu, H.; Grot, S.; Logan, B. E. (2005) Electrochemically assisted microbial production of hydrogen from acetate. Environmental science & technology, 39 (11), 4317–4320; DOI 10.1021/es050244p
[11] Rozendal, R.; Hamelers, H.; Euverink, G.; Metz, S.; Buisman, C. Principle and perspectives of hydrogen production through biocatalyzed electrolysis. International Journal of Hydrogen Energy 2006, 31 (12), 1632–1640; DOI 10.1016/j.ijhydene.2005.12.006.

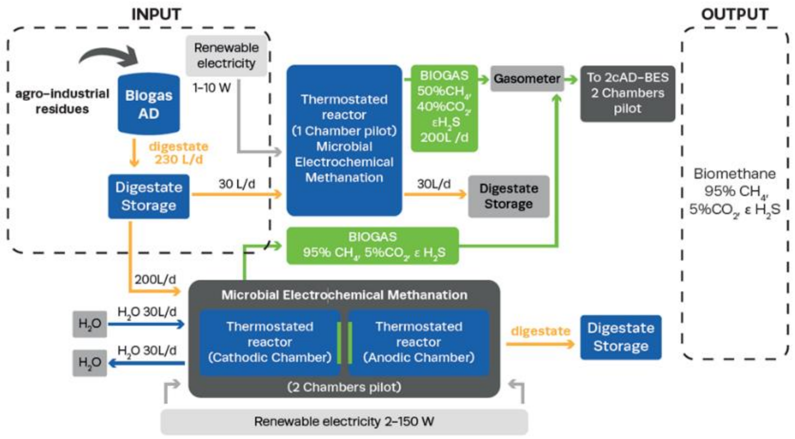
In-Situ and Ex Situ electro-methanogenesis	
TRL: 4→ 6-7	
Technology: Bio-electrochemically assisted AD. Electrodes into digestate; 2 sub-systems: boost biogas (1c-AD-BES) + biogas upgrading through bioelectrochemical conversion (2c AD-BES)	

Figure 3 7 EMG-PILOT DEMONSTRATION in France

3.4. E-methane production via thermochemical catalytic methanation

3.4.1. Ex-situ thermochemical/catalytic methanation

The catalytic methanation process, also referred to as chemical methanation or thermo-catalytic methanation, utilizes a chemical catalyst (typically ruthenium-based or nickel-based) to facilitate the conversion of CO_2 and H_2 into CH_4[12 13]. The required temperature ranges between 250-600°C, with applied pressures up to 40 bar[14]. Due to the high temperature and pressure conditions, the feed gas (e.g., raw biogas or syngas) must be purified from contaminants such as hydrogen sulphide (H_2S) (<1 ppm) to prevent catalyst deactivation.[15]

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 in a fluid-like state by the upward flow of gas or liquid through the reactor, allowing for enhanced mass and heat transfer.

The catalytic methanation process is highly exothermic, producing excess heat that can be recovered and reused to support the process itself or for external applications. Catalytic

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[12] Garbarino G., et al., (2015) Methanation of carbon dioxide on Ru/Al_2O_3 and Ni/Al_2O_3 catalysts at atmospheric pressure: Catalysts activation, behaviour and stability, Int. J. Hydrogen Energy, vol. 40, no. 30, pp. 9171–9182,doi: 10.1016/j.ijhydene.2015.05.059

[13] Hu D. *et al.*, (2012) Enhanced Investigation of CO Methanation over Ni/Al_2O_3 Catalysts for Synthetic Natural Gas Production, *Ind. Eng. Chem. Res.*, vol. 51, no. 13, pp. 4875–4886, doi: 10.1021/ie300049f.

[14] M. A. A. Aziz, A. A. Jalil, S. Triwahyono, and A. Ahmad, (2015) CO_2 methanation over heterogeneous catalysts: recent progress and future prospects, *Green Chem.*, vol. 17, no. 5, pp. 2647–2663, doi: 10.1039/C5GC00119F.

[15] Nieß S, Armbruster U, Dietrich S, Klemm M. (2022) Recent Advances in Catalysis for Methanation of $CO_2$from Biogas.*Catalysts.*; 12(4):374. https://doi.org/10.3390/catal12040374

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methanation is a mature technology, particularly in syngas-to-methane conversion, with a TRL range of 7-9. The catalytic reactor can directly process a mixture of CH_4 and CO_2 (raw biogas), eliminating the need for prior separation. The reaction takes place under controlled high-pressure and high-temperature conditions to ensure optimal methane yield.

The individual stages of the catalytic methanation process include:

- Biogas cleaning and compression, ensuring removal of contaminants before methanation.
- Catalytic methanation reaction, where CO_2 and H_2 react to form methane.
- Processing and purification of the final bioCH_4 stream for grid injection or direct use.

ETM -PILOT DEMONSTRATION in Greece

During the methanation procedure, the cool biogas stream is introduced into the reactor, where it absorbs excess process heat, ensuring thermal stability and efficient energy utilization. The heated biogas then enters the reactor tubes, where the Sabatier reaction ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$) takes place under controlled conditions.

In the Ex-situ Thermochemical/catalytic Methanation (ETM) demonstration in Greece, two distinct NiO/Al_2O_3 catalysts are being evaluated for CO_2 conversion efficiency and CH_4 selectivity, under optimized reaction conditions.

The optimization of the biogas cleaning system ensures the effective removal of sulphur compounds, mercaptans, and siloxanes, preventing catalyst degradation. The biogas is compressed, purified and then mixed with green hydrogen. The gases stream enters the reactors section at a pressure of 14 bar. The reactor operates at temperatures between 250-370 °C, with an optimal target range of 320-370 °C.

This process configuration is expected to achieve a TRL of 7 by 2026.

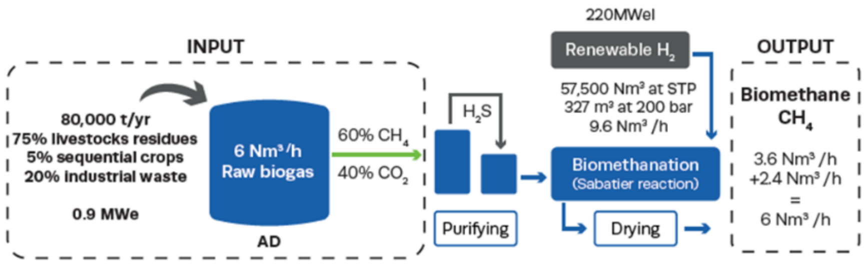
Ex -Situ thermo-catalytic methanation	
TRL: 5→ 7	
Technology: conversion of CO_2 in the biogas via its reaction with H_2 in a catalytic reactor	

Figure 3 8 ETM -PILOT DEMONSTRATION in Greece

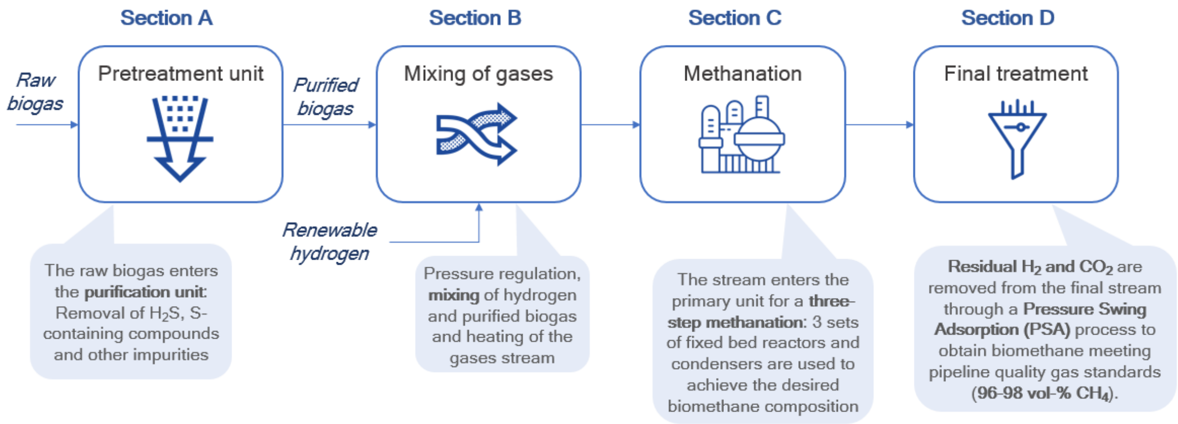


Figure 3 9 Simplified -scheme ETM -PILOT DEMONSTRATION in Greece

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4. Key factors impacting the choice of e-methane production technology

There are several technical and economic factors to consider for stakeholders considering investments in e-methane technology.
Assessing and comparing these factors might help identify emerging opportunities with the different technologies, determine the optimal timing for market entry, and support effective budget management. Additionally, they play a crucial role in shaping future investments and strategies in this rapidly growing field.
The following section explores both technical and market factors and examine commercial considerations along policy implications.

4.1. Technical considerations

During the development of a project and the evaluation of potential investments, it is essential to compare various technical considerations. This includes assessing the necessary inputs, the details of the processing stages, and the characteristics of the final outputs.
A thorough analysis of these factors helps to understand the efficiency, feasibility, and scalability of different technologies. Additionally, such comparisons provide insights into cost implications, resource requirements, and potential operational challenges, ultimately supporting well-informed decision-making.

4.1.1. Input

This section explores for what feedstocks different innovative technologies are suitable for and what inputs are needed. Such aspects are important as they could affect for instance the efficiency of logistics for sourcing feedstocks, material handling and storage requirements. The type of feedstock available affects both site location, plant scale and choice of technology. Additionally, the choice of feedstock might affect the gas composition and CO_2 content of the input gas. Depending on the feedstock availability over the year, the gas composition may vary depending on the type of biomass used and the season.
An overview of key inputs involved in the biomass to methane conversion process through methanation is provided, including (i) biomass feedstock, (ii) gas quality (iii) electricity (iv) water and nutrient source.
To consider the input requirements is a crucial first step to understand efficiency, production potential (carbon yield) and finally economics as inherently driven by feedstock prices.

Biomass Feedstock

All the demonstrated methanation technologies utilize sustainable waste-based feedstock sources, such as agricultural residues, livestock waste, chicken manure, sewage sludge, forest residues or municipal yard trimming.

The demonstrated in-situ methanation technologies where the methanation takes place in direct connection with the biomass have requirements regarding dry matter (DM) content of the biomass mix in the digestor (EMG and IBM):

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- **EMG**: the DM content needs to be below 10% for technology to be efficiently working. However further development would include working on adaptability to high DM%.
- **ETM:** since the catalytic methanation process is carried out ex-situ, no supplementary feedstock-related considerations are required beyond those already necessary to optimize the anaerobic digestion process.
- **EBM**: the DM content of the feedstock is currently ~2%. It should be noted that the application of both ozonolysis and anaerobic digestion (AD) could still be effective at higher DM concentrations (up to 4-5%). Ultimately, the achievable DM level is a direct function of the sludge pre-thickening procedure that precedes these treatments.
- **ESB**: higher moisture in biomass (20-60%) increases methane (CH_4) but reduces carbon monoxide (CO) and calorific value of syngas leading to lower overall biomethane output per unit of biomass (due to CO/H_2 for microbes). Excess moisture may also disrupt microbial health and CO_2 from wet syngas can acidify the reactor favoring unwanted bacteria (e.g., acidogens) and stressing microbes. Additional requirements of extra H_2 injection are also needed to balance reactions. Optimal moisture is a trade-off for stable performance.
- **IBM**: being in-situ, the methanation is fully integrated with the digester. Therefore, the bioreactor operative conditions and parameters are key drivers of microorganism performance during CH_4 production in AD. In general moisture content and high degradability of feedstock are ideal features for AD process but there are other elements that influence the yield and the effectiveness of the process in terms of biogas production. In practice, the maximum solid feedstock that can be processed efficiently in IBM systems is typically around 8–10% total solids (TS). Higher values may lead to mixing difficulties, mass transfer limitations, and inhibition effects, while lower values ensure smoother operation and stable microbial activity.
    - Substrate
    - Inoculum
    - Bioreactor Type
    - Anaerobic conditions and reducing agent
    - Temperature
    - pH value
    - Hydraulic retention time (HRT) and solid retention time (SRT)
    - Organic loading rate (OLR)
    - Carbon/nitrogen (C/N) ratio
    - Other parameters

In summary, to prevent inhibition in AD, it is crucial to ensure that high ammonium nitrogen levels, which can reduce system efficiency microbial activity, remains within acceptable limits thus helping to maintain optimal microbial performance. Additionally, controlling the organic load content to below 10% (i.e. OLR of ≥2.5 kg $TS/m^3/day$) is essential to ensure stable results and for preventing overloading, which can disrupt reactor stability and hinder digestion processes. Optimizing the process for high OLRs remains a critical area of implementation. By carefully monitoring these variables, smooth and efficient reactor operations can be maintained, leading to improved digestion performance.

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Gas input quality requirement

For the demonstrated ex-situ methanation technologies (ETM, EBM and ESB) there are some specific requirements on the resulting input gas (biogas or syngas) to consider:

- **EMG**: the cathodic biofilm is sensitive to impurities such as O_2 and H_2S, therefore monitoring and gas cleaning before methanation may be needed.
- **ETM**: impurities such as H_2S, mercaptans and siloxanes must be removed to prevent catalyst degradation. The required purity levels are below 1 ppm for H_2S and siloxanes. The CH_4 content should be at least 50-60%, while the CO_2 content must be in the 40-50% range to ensure efficient methanation. Additionally, the biogas must be dried to prevent condensation in the reactor system, ensuring stable reaction conditions. Finally, ammonia (NH_3), oxygen (O_2), and halogenated compounds should be minimized to avoid catalyst deactivation and equipment corrosion.
- **EBM**: The process has proven to be very robust and flexible with respect to the quality of the biogas used as feedstock. Being a biological process, it is capable of tolerating fluctuations in gas quality without being damaged. Furthermore, being catalyst-free, it does not suffer from deactivation caused by impurities in the biogas, such as sulphur compounds (e.g., H_2S)
- **ESB**: the methanation process is robust enough to deal with variations in gas quality and work with both biogas and syngas as microbial culture employed proved to be resistant to impurities from gasification. If pyrolysis gas is used purification from liquid impurities from pyrolysis process may be necessary to avoid the risk of clogging methanation plant. Syngas production is influenced by several key variables. For a more detailed understanding of these parameters, which are not covered in this report, one can refer to relevant review papers.[16] [17]
- **IBM**: the considerations are related to AD as described above and, as an in situ process, the methanation is fully integrated with the digester, and biogas quality is influenced by the AD process. The biogas should have a CH_4 content of at least 50% and a CO_2 content of 30–50% for efficient methanation. Although the process is tolerant to variations in biogas quality, impurities such as H_2S, NH_3, and siloxanes should be minimized to prevent inhibition of microbial activity and corrosion of equipment.

Electricity

Electricity is required for hydrogen production on-site. Availability of on demand electricity is needed for secure operations and for the possibility for flexible operation of the methanation.

Purchasing hydrogen from an external supplier is an option for all methanation technologies but is likely not cost-effective in most cases. There are some advantages with on-site hydrogen production such as possibility to flexible operation depending on electricity price, and potentially reduced cost for hydrogen transport and supply.

Electricity is also needed for reactor operation for most of the demonstrated technologies, for auxiliary equipment (e.g., compressor, pumps, control systems, heating, sensors) and for start-up.

[16] https://pmc.ncbi.nlm.nih.gov/articles/PMC10483670/
[17] Ramachandriya et al., *AIMS Bioengineering*, (2016), 3(2): 188-210.doi:10.3934/bioeng.2016.2.188

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Preliminary estimates[18] on specific electric consumption for each methanation configuration are:

- EMG: 2.71 kWh el/kWh CH_4 produced
- ETM: 0.010 kWh el/kWh CH_4 produced
- EBM: 0.010 kWh el/kWh CH_4 produced
- ESB: 0.02 kWh el/kWh CH_4 produced
- IBM: 0.01 kWh el/kWh CH_4 produced

Nutrient sources

Biological methanation technologies involve a nutrient source and the specific requirements for it differ depending on the configurations. Therefore, in addition to the gas stream entering the biomethanation reactor, the process relies on nutrients feeding the microorganisms.

- **EMG**: relies on biofilm composed of microorganisms sourced from digestate or an additional source (granular sludge).
- **ETM**: no nutrient source is needed since the reaction is catalyst-driven. However, the catalyst itself must be carefully maintained to ensure long-term activity and minimize deactivation risks.
- **EBM**: nutrient source is needed and pumped at dosage of 0.1-0.2 L/h.
- **ESB**: liquid residue streams are used as a flow of nutrient-rich solution sourced locally.This may include digestate from a conventional biogas plant or reject water from municipal treatment processes.
- **IMB** additional use of nutrients is not necessary, as digestate from the AD is a sufficient source.

4.1.2. Site selection

The plant's location can significantly impact the project's profitability and its potential for expansion. In general, the main factors to consider are:

1. Location, with respect to the marketing area
2. Feedstock supply
3. Transport facilities
4. Availability of labour
5. Availability of utilities: water, fuel, power
6. Availability of suitable land
7. Environmental impact, including effluent disposal
8. Local community considerations (social acceptance)
9. Climate
10. Political and strategic considerations

The availability and location of key inputs influence the selection of technological pathway which in turn affect the choice of location, technology, and scalability.

[18] From ENEA estimations - Preliminary Demos Flowsheeting (D3.2) . Empirical input data to the model were not considered.

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Even though none of the demonstrated technologies have specific technological requirements affecting the site selection, logistic considerations and synergies regarding the infrastructures for distribution to increase competitiveness should be kept in mind.

All the demonstrated technologies can be implemented at existing biogas (or syngas) plants. Therefore, the report does not address strategic considerations regarding options (centralized vs. decentralized) related to transport electricity to a combined bioCO_2 source and methanation facility, transport H_2 to the CO_2 source for methanation. transport CO_2 to a hydrogen production and methanation site transport the final e-methane product from a remotely located integrated plant.

When the demonstrated technologies are used in retrofitting existing facilities, the main consideration comes from the availability of sufficient space for installation of the hydrogen system (electrolyser and possibly gas storage) and the methanation reactor. Other aspects to consider are access to grid with sufficient electrical power capacity for hydrogen production, adjustments of monitoring and safety systems and possibility for increased logistics. In certain cases, units such as compressor and gas cleaning might be integrated into a container.

- **EMG**: requires the digestate, therefore it can be implemented at an AD plant or a WWTP
- **EBM**: offers various implementation options, suitable for AD facilities or any site providing CO_2 and water for hydrolysis.
- **ETM**: can be implemented at AD plants for biogas methanation or at gasification plants for syngas methanation (already been demonstrated e.g. in China). Ideal locations for ETM integration include a) existing biogas plants with sufficient hydrogen and biogas supply, b) sites near renewable electricity sources, ensuring cost-effective hydrogen production
- **ESB**: requires either a syngas or a biogas source, thus an ideal site would be at a gasification plant or an AD plant
- **IBM**: can only be implemented at an AD plant.

4.1.3. Plant size

In general, all the methanation pathways are scalable, and this is from a technological perspective not limited to a certain plant size. Depending on the size of the biogas or gasification plant the hydrogen production and the methanation system can be scaled to match the biogas output.
However, from an operation and cost perspective a larger scale may be favourable.

- **EMG**: scaling up may offer advantages.
- **ETM**: particularly relevant for biogas plants in the 500–1000 Nm^3/h range, which are the most common plant sizes. It can also be applied to partial upgrading in larger biogas plants, allowing gradual adoption without full facility retrofitting. The technology can be incrementally expanded, depending on hydrogen availability and biogas production levels.
- **EBM**: plant size is not critical, but as a biological process with long residence times, larger plants offer increased economic benefits.
- **ESB**: no minimum or maximum size is required.
- **IBM**: can be integrated into an existing biogas complex of any capacity.

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4.1.4. Additional equipment needs

General equipment needed at the plant for all the demonstrated methanation pathways include power, water system, hydrogen production and storage system, methanation reactor, cooling system and ancillary/supporting equipment and systems, such as secondary control energy reserves to maintain the proper flow and pressure conditions. Some of the demonstrated technologies require additional equipment beyond standard set up.

- **EMG**: a mixing selection to be adapted with the presence of electrode.
- **ETM**: a biogas purification unit is essential before the methanation process to remove sulphuric compounds, preventing catalyst degradation. A mixing valve is required to blend purified biogas and hydrogen before entering the methanation reactor, ensuring a homogeneous gas mixture for efficient reaction kinetics. Additionally, a membrane purification unit may be installed after methanation to remove residual H_2 and CO_2, ensuring high purity bioCH_4 before grid injection or direct utilization.
- **EBM**: membranes are the essential element to support the growth of methanogenic biofilms and to transfer H_2 without gas bubbling.
- **ESB**: packing media is of great importance, as it serves as a contact surface between microorganisms, gas and liquid.
- **IMB**: additional installed equipment for effective hydrogen dissolution is necessary.

4.1.5. Need for additional upgrading of e-methane/biomethane

Biological methanation may lead to variation in output gas quality.

There might be requirements from gas off takers regarding output gas composition that would demand additional processing. For example, in the case of ESB, using nitrogen containing syngas may require nitrogen removal in the product gas.

Moreover, gas quality in European countries is regulated at national level therefore some countries have more strict gas quality specifications than others, and this can hinder the physical trading of gas between countries' gas systems.[19] [20] [21]
H_2S content must be reduced below the acceptable level to meet the specifications of the engine suppliers and the environmental legislation. When injected to the gas grid, complete H_2S removal is necessary, and this is an integrated part of the upgrading process.

4.1.6. Plant flexibility (output side), including gas storages

Flexibility allows a e-methane plant to adjust how and when to produce and deliver the gas, depending on electricity price and gas demand. With flexible operation e-methane can be produced when electricity prices are low and turned off at peak demand, thus helping balance the electricity grid while generating more revenues. More gas can also be produced at times with higher gas demand (and thus higher gas prices). Key to achieve maximum flexibility is gas storage facilities at the site, both for hydrogen and for methane. This allows

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[19] https://www.marcogaz.org/publications/quality-of-biomethane-required-in-european-countries-for-injecting-into-natural-gas-grid/
[20] https://www.europeanbiogas.eu/biomethane-standards-facilitating-renewable-gas-uptake/
[21] GreenMeUP project: Development of Standardisation Processes for Biomethane Deliverable n. 1.4
CEN/CLC/JTC14/WG5 "Guarantees of Origin related to energy";SECT/SF GAS I/JWG GQS "Qas Quality Standards"; TF3 "Oxygen"; CEN/TC 408 "Natural gas and biomethane for use in transport and biomethane for injection in the natural gas grid.

the operator to balance supply and demand, thus store gas when production is high, but demand is low and release it when demand increases.
Additionally, it helps to avoid curtailment and keep production even when immediate delivery is not possible. Such flexible operation enables scheduled deliveries at set times and supports grid stability especially when integrated with variable renewables.

Generally, digestion plants are operated as a continuous process, but depending on plant set up feedstock and operational parameters can be changed.
A gasification plant can, depending on the type of plant, to some extent be run flexible (changing load/feedstock and/or product outputs), but is generally run continuously at steady state.
ETM plants are primarily designed for continuous operation, but their flexibility depends on hydrogen availability and biogas production rates. ETM can be integrated with flexible hydrogen supply models, allowing modulation of e-methane production based on hydrogen input variations.

Biogas-CHP

The combustion of biogas in combined heat and power (CHP) systems allows for the simultaneous production of electricity and heat. It is well recognized that electricity from biogas and biomethane CHP units contributes to stabilizing the grid.
The plant operator can adjust by switching on and off the CHP unit according to the demand for electricity in the grid after signals from the grid operator or electricity trader.
On the other hand, most biogas plant operators maximize operational duration. This is due to support scheme (FiT) providing incentives to the amount of electricity produced.
By installing excess electric capacity, more electricity can be generated during periods of high demand and less during low demand, while biomethane serves as a solution for seasonal energy storage.
In the context of the transition to a power system with fluctuating levels of electricity, the increase of such flexibility is key.
CHP plants using biomethane offer such flexibility in energy production and system integration, thus helping balancing supply and demand in the power grid with high non dispatchable electricity from renewables. By supplying stable and reliable process heat, CHP plants can adjust their output to balance variable renewable energy sources, helping modulate the operation of methanation plants that rely on renewable hydrogen availability.
In summary, CHP units could provide a degree of dispatchable power, with their output adjusted to coordinate with the operability of these technologies during electricity grid constraints, thus balancing the energy flows. However, the operation of CHP units is often primarily driven by heat demand, such as for district heating systems, which may not align with the operational schedules of methanation or Power-to-Gas (PtG) processes. Additionally, if CO_2 from CHP operations is to be utilized in methanation, its quality and composition must meet the compatibility requirements of the methanator to ensure efficient conversion.

4.1.7. Minimizing gas leakages

Minimizing methane leakages is crucial for both economic and environmental reasons.

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Regular maintenance, implementation of Leak Detection and Repair (LDAR)[22] and optimized plant management can effectively reduce fugitive emissions. Advanced gas-tight reactor designs and reinforced piping can further minimize methane slip.
The risks can be minimized with gas alarms and preventative safety work, such as continuous leak detection and training of staff. The implementation of these systems is crucial for technologies incorporating also hydrogen use such as ETM due to its high diffusivity and flammability. Automated safety protocols, such as real-time pressure monitoring and emergency shutdown systems, help mitigate risks associated with hydrogen and methane handling. Syngas storage (in case of ESB) can minimize risk of disturbed syngas feed.
Inherent CH_4 slip can be reduced by making use of the best available technique (BAT) combined with frequent monitoring. Perform mass balance calculations to identify losses, analyze residual gas potential, during the planning phase of plants consider proper dimensioning of pipes as well invest in improved leak detection and repair technologies are some of the strategies to avoid associated economic losses from fugitive methane emissions. For new plants, preference should be given to upgrading technologies with inherently low CH_4 emissions. Equipment for the post-treatment of the off-gas can further reduce CH_4 slip. Examples of innovative technologies to reduce slip are Regenerative Thermal Oxidizers (RTOs) or SlipRec units (Airco Process Control).
In particular, to oxidize the CH_4 by regenerative thermal or catalytic oxidation results in the lowest or negligible fugitive emissions. Additionally, if the CO_2-rich stream after upgrading is liquefied, the remaining CH_4 is recycled and CH_4 slip is reduced to almost 0.
Finally, piping connections, especially close to moving equipment, are susceptible to leaks and should be closely monitored.
The CH_4 formation process of the digestate can be reduced by cooling the digestate to temperatures below 17°C.[23] Furthermore, emissions from digestate can be reduced by a gas-tight, covered digestate storage tank that is connected to the gas system.

4.1.8. Recovery of by-products: System- Heat and Water Integration Strategies for Energy Efficiency

There are some by-products that could be recovered and utilized. Heat can be recovered and utilized in in various ways, water is produced as a byproduct as well and pure oxygen from the electrolyser could contribute to the overall profitability, although specifically at close distance.
The heat can be used within the same facility for operations reducing the overall energy costs. The thermal energy can be converted into power, providing an additional revenue stream.

- **EMG** does not produce any by products that require additional offtake.
- **ETM** demonstrated technology produces heat from exothermic reactions, which may be recovered for industrial use or district heating. Additionally, CO_2 captured after methanation can be marketed Additionally, excess CO_2 captured after the methanation

[22] Papa G., Decorte M., Cancian G.L., Dekker H., Prieur-Vernat A., de Veron A., Virolainen- Hynnä A.,Praz B., Briere R., G., Berengere, Rispoli E., Rigon E., Van Erp M., Maciejczyk M., Sander Nielsen B., (2023) Design, build, and monitor biogas and biomethane plants to slash methane emissions- *Pursuing an efficient and sustainable scale-up of the sector*. *https://www.europeanbiogas.eu/info-hub/publications/*
[23] Liebetrau, Jan; Reinelt, Torsten; Agostini, Alessandro; Linke, Bernd (2017): Methane emissions from biogas plants. Methods for measurement, results and effect on greenhouse gas balance of electricity produced. ed. by Jerry D. Murphy. IEA Bioenergy Task 37.
URL:http://task37.ieabioenergy.com/files/datenredaktion/download/Technical%20Brochures/Methane%20Emission_web_end_small.pdf

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reaction can either be recirculated within the biomethane plant or sold for various industrial applications.

- **EBM** The oxygen produced in addition to hydrogen during electrolysis can be used to produce ozone utilized for sludge pre-treatment. In particular, the hydrogen for the upgrading and the oxygen for ozone comes from the same electrolyser. The biomass from raceway ponds (microalgae) and the digestate from the AD stage can both be subjected to ozonolysis. This process converts them into new, biodegradable organic material that can be recycled as feedstock for the AD process. Furthermore, the CO_2 generated during AD can be redirected to act as a nutrient source for the microalgae, particularly when it's not required for methane production in the EBM (e.g., when there is an overproduction of CO_2).
- **ESB** process results in several by-products, such as nutrient solution and wastewater. The spent nutrient solution can be used as fertilizer. However, nutrient solution value may be reduced due to microorganism consumption of accessible nutrients (e.g., NH_4^+), which may add difficulty in locating an off taker. Whether this can be considered a product or rather a residue depends on local conditions, and whether there is a user within a short enough transport distance. Additionally, the methanation process produces wastewater that could be treated and used for the electrolysers and thus for H_2-production, but at an extra incurred cost but it's costly.
- **IMB** process produce digestate.

4.1.9. Safety considerations

The safety of an energy vector depends mainly on flammability, explosiveness, and toxicity. It is well known that e-methane is safe, due to its high autoignition temperature (>670 °C), small explosive range, and low toxicity.
However, hydrogen presents risks like flammability and pressure hazards, requiring strict safety measures during transportation storage and use, including leak detection, temperature and pressure monitoring, and safety assessments.
The demonstrated technologies typically do not need additional safety measures or storage beyond what is already in place, although biological methanation may require extra storage to handle downtimes in hydrogen or syngas production.
Extra storage is needed likewise for ETM for the process to run continuously.
HAZID HAZOP ATEX study must be conducted before commissioning and start up.
To assess the potential hazard of a new plant, the index is calculated after the piping and instrumentation, and equipment layout diagrams is prepared.
Additionally, obviously the countries require plants to be built and operated in accordance with national and industry standards.
The main safety risks associated with the ozonolysis process are connected to the nature of ozone and oxygen with their strong oxidizing characterization and, in case of ozone, its toxicity. In base of this element the design of the process considers all the safety measures in terms of minimum distance of oxygen tank from plants and buildings, compatibility of materials, sludge degassing, presence of ozone in air surrounding the plant and oxygen control in biogas. The ozonolysis plant integrated with anaerobic digestion is controlled by an automatic system that monitors all operating parameters and determines the plant stop in case of malfunctions. For further information about the risk assessment of the ozonolysis demo-plant, refer to the Safety Operational Plan (POS).

Digitalization and Modelling for Safety and Integration

In addition to conventional safety measures, simple digital tools are increasingly applied to improve safety and system integration.

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- Real-time monitoring and control: SCADA systems and sensors enable continuous tracking of hydrogen concentration, pressure and temperature, allowing early detection of abnormal conditions.
- Process modelling: Basic simulations can support testing of operating scenarios and improve coordination between hydrogen supply, AD reactors and storage.

These tools contribute to safe operation and facilitate efficient integration of methanation into existing biogas facilities.

4.2. Market and regulatory considerations

This chapter helps project developers and investors navigate and assess the complex regulatory landscape that surrounds the production of e-methane in the EU.
It provides a **structured overview of the main policy factors** influencing the market and regulatory environment, **both at EU and national levels**, and translates them into practical insights for investment decisions.

The rationale underpinning this structure is twofold:

- First, it introduces a framework to analyse the policy dimensions of a biomethane or e-methane project by categorising them into five areas (i.e., Political Signals, Regulatory Stability, Access to Market, Competitiveness, Regulatory Demand Drivers). These areas act as entry points to identify relevant regulations, incentives, and risks.
- Second, the chapter identifies concrete indicators. This is displayed in a handy checklist, guiding developers and investors in identifying what to check precisely in EU and national legislation.

The chapter is organised into three parts:

1. **Main policy factors and indicators**: An overview of five key categories that shape investment conditions – Political Signals, Regulatory Stability, Access to Market, Competitiveness, and Regulatory Demand Drivers.
2. **EU policy context**: A closer look at European legislation and strategies that determine much of the regulatory environment across Member States.
3. **Checklist**: A practical tool distinguishing EU and national indicators to help investors assess whether the conditions are favourable for project development in a given location.

4.2.1. Main policy factors and indicators to consider across EU and national levels

There are multiple reasons to opt to produce renewable methane: economic, political and environmental.
Political considerations play a part in the decision to implement the biomethane solutions. The political decisions are based on the environmental and economic aspects of the project herein discussed.
Investment decision-making will consider thoroughly how policies and legislation impact the e-methane market, both at production and consumption sides.

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The future of e-methane is significantly shaped by the EU's regulatory framework, which in turns influences heavily national policies.

Two cross-cutting factors should be considered:

- **Political signals**: Indicators such as binding or indicative objectives, strategic roadmaps, or other public commitments, that shape investor confidence and expectations in a given sector.
- **Regulatory stability**: The consistency and predictability of policies, laws, and enforcement mechanisms that reduce investment risks and create a secure business environment. Regulatory stability benefits from long-term stable policies, clear regulations that do not change frequently over the course of a decade, and from well implemented and enforced legislation.

Policies weigh a lot on three thematic categories:

- **Access to markets**: this category is about:
  - Access of your production plants to gas grids or - if liquified - to LNG infrastructure.
  - Having your e-methane product recognised in the energy market as a sustainable and renewable fuel, through certificates.
  - Export opportunities to other EU countries, based on the use of certificates.
- **Competitiveness**: Policies and law can shape the competitiveness of a commodity, often through tax policy, administrative requirements and public support mechanisms. such as consumption subsidies.
  In the energy sector, the carbon price of the regulated Emissions Trading Scheme (ETS) plays a key role in forcing phasing out fossil fuels and drive for renewables.
- **Regulatory demand drivers**: incentives, or mandatory supply targets, which create or enhance demand for specific products. This category of factors is heavy in the EU energy legislation.

These factors collectively impact the financial risk, return on investment, and overall attractiveness of biomethane and e-methane projects.

Effective legislation typically aims to provide a stable, long-term framework that reduces financial risks, offers clear incentives, and aligns with broader energy and climate goals.

The table below sums up how those factors are reflected in several defined regulatory/policy indicators **at both EU and national level**

Table 4 1 Summary of factors (political signals and regulatory stability) across defined EU and national policy indicators

		EU-level indicators	National indicators
META FACTORS	Political Signals	• EU renewable energy consumption target (RED) • REPower EU	• National renewable energy consumption targets (general and sectoral) • Overall climate policy ambition

	Regulatory Stability	• Stability of energy and climate policies • Implementation of adopted legislation • Forecasted policy revisions within the next 1-3 years.	• Stability of energy and climate policies • Implementation of adopted legislation • Forecasted policy revisions within the next 1-3 years. • Duration of support schemes
THEMATIC FACTORS	Access to Market	• RED sustainability compliance • Hydrogen and decarbonised gas market Package (common internal market for renewable gases) • Network/infrastructure access • Availability and tradability of gas guarantees of origin (GO) • Eligibility and accounting rules for renewable fuels in various regulations (e.g. EU ETS) and voluntary climate reporting frameworks (e.g. GHG Protocol)	• Any additional sustainability requirements • Availability of natural gas grids and hydrogen pipelines • Implementation of right to access the grids • Gas GO Registry and readiness for e-methane GO issuance. • Possibilities to export e-methane GO
	Competitiveness	• EU Energy Taxation Directive • EU Carbon price in EU ETS 1 and EU ETS 2 • Net Zero Industry Act (support manufacturing of clean technologies)	• Production and investment support schemes • Financial responsibility for building the grid connection • GO Issuance and GO value • Tax policy • Duration and estimated cost for the permitting process
	Regulatory Demand Drivers	• FuelEU Maritime Regulation: GHG intensity reduction obligation • Road transport: CO_2 emissions standards for cars and vans (No ICEs after 2035) and for heavy-duty vehicles (90% GHG emission reduction by 2040) • mandates, including shares of RFNBO	• Renewable energy or GHG intensity reduction obligation on fuel suppliers • Volatility of biofuel and biomethane price in compliance market • RFNBO mandates on fuel suppliers

4.2.2. EU Policy factors impacting market conditions

This subsection outlines the EU policies listed in the table above explaining why they are regulatory factors.

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4.2.2.1. Political signals and regulatory stability

The EU has adopted strong renewable energy ambition both through public commitment of the European Commission and adopted legislation.

REPowerEU plan

The REPower EU Plan aims at rapidly reducing the EU dependence on Russian fossil fuels and fast forward the green transition. Released in May 2022 at the request of the European Council, this is a **non-binding strategy from the European Commission**, which includes 3 main aspects:

- Energy savings increase.
- Diversification of energy imports into the EU (liquefied natural gas).
- Substitution of fossil energy through the accelerated expansion of power generation capacities from wind and PV, hydrogen (generation and import), and biomethane.

The REPowerEU Plan has been central to the EU's renewable energy acceleration strategy since 2022. It includes EU production targets for both biomethane and renewable hydrogen:

- 35 billion cubic meters of biomethane production.
- 14 million tons of renewable hydrogen production.

Previously, the European Commission's Hydrogen Strategy (2020) set an indicative target of 10 million tonnes of renewable hydrogen production per year by 2030 (equivalent to 333 TWh/year).

Moreover, the recently published REPower EU Roadmap in May 2025 by the Commission forecasts that renewable fuels, including biomethane and hydrogen, will remain essential to the EU energy mix through 2040 and 2050, particularly for hard-to-electrify sectors and as industrial feedstock. According to the Roadmap, total gas consumption in the EU is expected to range between 105 and 155 Mtoe by 2040, and between 70 and 80 Mtoe by 2050. Following this publication, the Commission foresees the inclusion of alternative energy sources to natural gas into the European energy mix. This also includes the promotion of biogas and biomethane and clean hydrogen in line with REPowerEU.

The Renewable Energy Directive (RED III)

The revised Renewable Energy Directive (RED III), published in October 2023, sets the overarching framework for renewable energy deployment in the EU. It mandates a renewable energy share of 42.5% in gross final consumption by 2030, with sectoral targets, including 29% for transport and 49% for buildings.

It also sets binding sub-targets for **Renewable Fuels of Non-Biological Origin** (RFNBOs) in industry (only hydrogen) and in transport (including e-methane):

- Binding target of 14.5% reduction of GHG intensity in transport from the use of renewables by 2030;
- Binding target of at least 29% share of renewables within the final consumption of energy in the transport sector by 2030.

It allows for double counting of RFNBOs in quota obligations and for use in maritime sector.

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4.2.2.2. Access to markets

The Renewable Energy Directive (RED III)

A. For e-methane as a synthetic fuel of biological origin, RED III establishes **key sustainability and greenhouse gas (GHG) reduction criteria**, which determine eligibility for renewable energy targets and financial incentives. Compliance with these criteria allows e-methane to:

- Be counted towards national renewable energy obligations.
- Access subsidies and financial support.
- Avoid penalties under schemes like the EU Emissions Trading System (ETS).

B. To be recognised as such, RFNBOs must meet the criterion of **at least 70% GHG emissions reduction compared to a fossil fuel comparator** (Article 29a, RED III).

The fossil fuel comparator is set at 94 grams of CO_2. The 94 gCO_2eq/MJ represents the life-cycle emissions intensity of standard fossil fuels used in transport, serving as a baseline for evaluating the environmental performance of alternative fuels. In the case of hydrogen produced as an RFNBO, this translates to a carbon intensity threshold of approximately 3.38 kg CO_2eq per kilogram of hydrogen.

Rules for calculating GHG emission reductions from RFNBOs[24] [25] are the following:

The total GHG emissions (E) from production and use of a RFNBO is calculated as the sum of emissions from:

- supply of inputs (e_i)
- emissions from processing (e_p)
- emissions from transport and distribution (e_{td})
- emissions from the combustion of the fuel in its end-use (e_u) to which are subtracted emissions savings from carbon capture and geological storage (e_{ccs}).

The formula is expressed as follows:

$$\boldsymbol{E = e_i + e_p + e_{td} + e_u - e_{ccs}}$$

Specifically, to the e_{ccs} factor, these subtracted emissions factor also plays a role in the formula to calculate GHG emission from the production and use of biomass fuels, including biomethane. However, for this calculation specifically, the application of the emissions factor e_{ccs}, directly related to the production of biomass fuels, is set to end by 31 December 2035 and not applicable anymore as of 2036 onwards.
This decision comes as a result to use CO_2 only from air and biogenic sources for the production of RFNBOs after the 2035-2040 period.
In fact, from 2036 onwards, RNFBO producers will be the only ones able to claim the GHG intensity reduction credit from direct air capture or biogenic CO_2 capture.

The quantity of **CO_2 used as input for RFNBO** production and that would otherwise have been emitted into the atmosphere is included in the calculation of emissions savings. Several requirements are specified for this purpose (Annex, Part A, point (10)):

- The CO_2 used must not have received credits for emissions savings from other CO_2 capture and replacement.

[24] Commission Delegated Regulation (EU) 2023/1185 supplementing Directive (EU) 2018/2001 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.
[25] Scheme principles for the production of RFNBO and RCF-(2025) REDcert GmbH

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- The CO_2 must come from an eligible source including biogenic CO_2 from biogas upgrading or biogases combustion as detailed in the Table 4 2.
- Electricity and heat used in the CO_2 capture process shall be included in the calculation of emissions attributed to inputs.

Table 4 2 List of eligible sources of CO_2 for RFNBO production

Source of CO_2	Eligibility end date
CO_2 captured from the combustion of fuels for electricity generation under the EU ETS	31/12/2035
CO_2 captured from other activities under the EU ETS	31/12/2040
CO_2 from direct air capture	No end date
CO_2 from the production or the combustion of biofuels, bioliquids or biomass fuels complying with the sustainability and GHG saving criteria	No end date

EU legislation set **specific rules for the sourcing of electricity**, related to the production of RFNBO intended for transport.[26] To be considered renewable, the installation producing hydrogen should either be directly connected to the installation producing renewable electricity (Article 3 of the Delegated Regulation (EU) 2023/1184) or use electricity sourced from the grid under certain conditions (Article 4(2) and (4)):

- It should comply with a criterion of **additionality** (Article 5) ensuring that only newly generated renewable electricity is utilized so that the renewable hydrogen production does not divert renewable electricity away from other uses. In particular, the installation producing electricity must not have been in operation for more than 36 months before the installation producing hydrogen.
- It should comply with a criterion for **temporal and geographic correlation** (Article 6 and 7) to guarantee a direct physical flow of renewable electricity to the electrolyser, thereby avoiding the need to activate fossil fuel power plants to meet the electrolysis electricity demand.

According to RED, producers must be certified under a national or a voluntary scheme approved by the European Commission.[27]

C. The RED III also defines **traceability rules**.

a. A crucial mechanism introduced by RED II and RED III is the **Union Database** (UDB): this is a central IT platform which will ensure *traceability of the environmental attributes of renewable fuels*, including e-methane, and mitigate fraud risks.
b. Additionally, RED mandates the deployment of **Guarantees of Origin** (GO) registries for renewable gases. Gas GO are the regulated tool to *prove to consumers the renewable origin* of the commodity and to make public claims in that regard.

[26] Commission Delegated Regulation (EU) 2023/1184 supplementing Directive (EU) 2018/2001 by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin.
[27] See full list of the approved Schemes online. https://energy.ec.europa.eu/topics/renewable-energy/bioenergy/voluntary-schemes_en

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The Gas Directive and Gas Regulation

The EU Gas Directive (2024/1788) and the Gas Regulation (2024/1789) set out the legal framework for gas market liberalisation and infrastructure access. These rules are essential for e-methane investors as they influence market entry and grid integration.

Key requirements include:

- **Right to grid access**: E-methane producers entitled to request a gas grid connection.
- **Gas Guarantees of Origin**: Obligation for gas suppliers from 2026[28] to prove sales of renewable and low-carbon gases by cancelling GOs. The Gas Directive builds on certification mechanisms regulated by the RED and extends it to "low carbon" gases. E-methane can also directly be recognised as "renewable" under the RED III and therefore receives a GO proving its renewable origin. Gas suppliers delivering renewable and/or low-carbon gas as part of their contract with consumers will have to prove this through the purchase of the corresponding Gas Guarantees of Origin and their cancellation in the gas GO Registry. Cancellation statements can then be requested, by competent authorities.

Successful implementation of these provisions at the Member State level in the coming few years will be a determining factor in investment attractiveness. Member States must transpose the Gas Directive officially by July 2026.

4.2.2.3. Competitiveness

Energy Taxation Directive (ETD)

Under the ETD currently in force, reduced tax for biofuels (but not e-fuels) is allowed but is considered state aid and therefore subject to state aid control. Currently under revision, ETD establishes minimum tax rates for energy products based on environmental consideration. It proposes lower tax rates for renewable fuels, including RFNBOs such as e-methane. If implemented, the revised ETD would allow for much lower tax rates on sustainable biomethane and e-methane than fossil fuels without it to be considered state aid.

Key investment factors:

- **Lower tax burden**: E-methane that meets sustainability criteria could benefit from preferential tax treatment, improving its competitiveness against fossil natural gas.
- **Tax certainty**: Harmonisation of energy taxation across the EU provides long-term stability for investors.
- **Potential national variability**: The ETD allows Member States to implement additional tax incentives, meaning investment conditions could still vary across EU countries.

The EU Emissions Trading Scheme (ETS)

The EU Emissions Trading Scheme (EU ETS) is a major climate policy for reducing GHG emissions in energy-intensive sectors. It operates on a "cap-and-trade" principle: a cap is set on the total emissions allowed from covered sectors, and a corresponding number of emission allowances is issued. Each allowance permits the emission of one tonne of CO_2 equivalent. Over time, the cap is gradually reduced, tightening the supply of allowances and driving emissions down.

[28] Contingent to effective national transposition of the Gas Directive into national legal frameworks.

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From an economic perspective, this creates a **market price for carbon**. Companies must either reduce their emissions or buy allowances to cover them, progressively introducing a financial incentive to switch to low-carbon or zero-carbon alternatives.
If e-methane meets EU sustainability and GHG reduction criteria, it can be considered zero-rated under the EU ETS. This means they do not incur any emissions cost for the user. For companies operating in sectors covered by the EU ETS—such as power generation, chemicals, or heavy industry—replacing fossil gas with e-methane reduces their need to surrender allowances. *As the carbon price increases, the cost advantage of e-methane over natural gas becomes more significant*.
Sectors under the EU ETS include all companies with large fuel combustion units (above 20 MW thermal input). These operators can reduce compliance costs by switching to certified renewable gases, making e-methane an economically attractive choice in a tightening carbon market.
Additionally, from 2027, the EU ETS 2 [29] will become fully operational, introducing a carbon price on emissions from the buildings and road transport sectors, with the objective of stimulating investments in energy efficiency. The ETS 2 will cover emissions upstream, meaning the obligation to surrender allowances will fall on the fuel suppliers rather than end-consumers. During the first three years the ETS 2 is operational, if the price of allowances exceeds EUR 45 (in 2020 prices, i.e., adjusted for inflation), additional allowances may be released from a dedicated Market Stability Reserve to address excessive price increases. Regulated entities must pay an excess emissions penalty of EUR 100 (USD 108.24), adjusted for inflation, for each tCO_2 emitted for which no allowance has been surrendered, in addition to buying and surrendering the equivalent number of allowances. However, the increased cost of supplied fossil fuels is expected to be passed on to end-consumers, thereby creating a direct financial impact. A Social Climate Fund is set up reinforce the effect of EU ETS 2 in driving consumers to switch to low-carbon fuel supply and technologies.

The Net-Zero Industry Act (NZIA)

The Net-Zero Industry Act was proposed by the Commission in 2023 and adopted in 2024. Its overall purpose is scaling up the EU's manufacturing capacity of "net-zero technologies" that are commercially available. The NZIA has the following objectives:

- Scale up manufacturing capacity of strategic net-zero technologies through faster permitting procedures
- Facilitate carbon removal with clear CO_2 injection capacity.
- Support the demand for net-zero technologies and address regulatory sandboxes
- Set up a Net-Zero Academy to foster skills and workforce training.

Sustainable and renewable fuels of RFNBO origin and hydrogen technologies are included in the list of net-zero and strategic net-zero technologies, thereby benefitting from dedicated funding programmes and faster implementation and permitting procedures.

The regulation is beneficial to the biomethane sector as it sets the overall target for net-zero manufacturing capacity to meet at least 40% of the EU's annual deployment needs by 2030, providing predictability, certainty and long-term signals to manufacturers and investors.[30]

[29] https://climate.ec.europa.eu/eu-action/carbon-markets/ets2-buildings-road-transport-and-additional-sectors_en
[30] https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en

4.2.2.4. Regulatory demand drivers

Renewable Energy Directive

Under the 2023 revision of the Renewable Energy Directive (RED III), the EU has introduced a **specific sub target for renewable fuels of non-biological origin** (RFNBOs), such as green hydrogen and its derivatives, in the transport sector.

- By 2030, at least 5.5% of all transport fuels in each Member State must come from advanced biofuels and RFNBOs, with a *minimum of 1% specifically from RFNBOs.*
- Importantly, *RFNBOs can be double counted towards this target and the overall renewable energy target in transport*. This increases their economic value for fuel suppliers. This regulatory measure aims to make capital-intensive RFNBO projects more attractive for fuel suppliers.

FuelEU Maritime Regulation

The FuelEU Maritime Regulation, adopted in June 2023, sets mandatory GHG intensity reduction targets for fuels used in the maritime sector. The regulation mandates:

- A gradual **GHG intensity reduction of marine fuels**, starting with a 2% reduction by 2025, increasing to 80% by 2050:
  - 2025: 2%
  - 2030: 6%
  - 2035: 14.5%
  - 2040: 31%
  - 2045: 62%
  - 2050: 80%
- Incentives for using **RFNBOs (double counting until end of 2033)** to meet these targets.
- A penalty system for non-compliance, reinforcing demand for compliant fuels.

Scope of the obligation: all ships in the EU with a gross tonnage above 5,000 in commercial passenger transport or cargo. Concerning its geographic scope, the regulation covers 100% of the energy consumed on board when the ship is in an EU port, 100% of the energy consumed when traveling between EU ports, and 50% of the energy consumed when leaving or entering an EU port.

The Regulation allows for flexibility in applying the target if there is evidence of insufficient production capacity and availability in the maritime sector, uneven geographical distribution, or excessively high prices. For investors, the regulation creates a predictable and growing market for e-methane in shipping.

Road transport legislation: CO_2 emission performance standards for cars and vans & for heavy-duty vehicles

- The CO_2 emission performance standards for passenger cars and light commercial vehicles sets the target to reduce emissions by 2030 by 55% for new cars and by 50% for new vans. By 2035, both new cars and vans have the obligation of reducing their emissions by 100%.
- The CO_2 emission performance standards for heavy-duty vehicles sets the target for new HDVs:

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- 45% emissions reductions from 2030;
- 65% emission reductions from 2035;
- 90% emissions reduction from 2040.

In the Impact Assessment for the CO_2 emission standards for HDVs, the economic analysis on the crediting system is limited to biodiesel and RFNBO. Biomethane was not taken into consideration, even if it provides for higher GHG reductions and lower local emissions.

Both regulations allow for some flexibility in complying with the GHG reduction targets and are expected to be reviewed in 2026 (LDVs) and 2027 (HDVs).

4.2.3. Policy and regulatory checklist

This subsection provides a structured checklist of indicators that investors and project developers can use to evaluate whether the policy and regulatory conditions are favourable for project development.
The checklist is organised by five policy categories introduced earlier in the chapter: Political Signals, Regulatory Stability, Access to Market, Competitiveness, and Regulatory Demand Drivers. For each category, it outlines specific items to verify at EU and national levels.
The aim is to support a systematic due diligence process. By using this checklist early in the planning phase, project teams can identify opportunities, potential risks, and better understand the institutional and policy frameworks within which they are operating.

4.2.3.1. A. Political Signals

EU-level

#	Item	What to Check	Assessment ✕✓?
1	Political commitment	Are there clear targets for renewable energy set in EU legislation, the level of ambition? • For 2030 • Beyond 2030	
2	Political commitment	Are there other political ambitions or commitment for renewable energy set by the EU institutions? *(e.g., strategies published by the European Commission, statements by the European Council)*	

National level

#	Item	What to Check	Assessment ✕✓?
	Political commitment	Are there clear and high target for renewable energy set in national legislation?	
3	National Energy Strategy	Is biomethane/e-methane explicitly prioritised in national long-term energy or climate plans such as NECPs?	
4	Dedicated National Targets	Has your country set specific biomethane or RFNBO production or consumption targets?	

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5	National Implementation of REPowerEU	Are there funding programmes or public calls under REPowerEU for RFNBO technologies?	

4.2.3.2. B. Regulatory Stability

EU-level

#	Indicator	What to Check	Assessment ✕✓?
6	2030 Energy Policy Framework	Is the EU energy policy framework set to remain stable by 2030?	
7	2040 Energy Policy Framework	Is the EU energy policy framework for the 2030 decade clear and set to remain stable?	
8	Future policy changes	Are there any expected policy changes likely to impact the business environment for renewables before 2030?	

National level

#	Indicator	What to Check	Assessment ✕✓?
9	Forecasted Policy Revisions	Are any relevant national legislation revisions announced within 1–3 years with impact on support schemes, sustainability rules or innovation policy?	
10	Policy Implementation	Is the national transposition of RED III complete and coherent with your project?	
11	Long-term Support Commitments	Are support mechanisms (e.g. FiTs, tax incentives) guaranteed for 10-15 years?	
12	Stability of Permitting Framework	Is the permitting process for biomethane or hydrogen-based projects predictable and consistent?	

4.2.3.3. C. Access to Markets and Export Opportunities

EU-level

#	Indicator	What to Check	Assessment ✕✓?
13	RED III Compliance	Can your project meet GHG reduction & sustainability criteria for RFNBOs or for biomethane?	
14	Eligible CO_2 Source	Is the CO_2 expected to be used from a compliant source?	
15	Union Database	Will you be able to comply with mass balance rules of the RED III EU and the chosen certification scheme?	

National level

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#	Item	What to Check	Assessment ✕✓?
16	RED III Compliance	Is the national transposition of RED III complete and coherent with your project?	
17	Access to grids	Is there a right for grid connection actionable for the area where your project is located? (i.e. in a gas-served area or not)	
18	Access to grids	Does the national regulation allow biomethane/e-methane injection into the gas grid?	
19	National Injection Standards	Are there clear and feasible national specifications for biomethane/e-methane injection?	
20	GO issuance	Is a national registry of gas GO operational?	
21	GO issuance	Does the national registry issue GO for e-methane where renewable attributes are fully recognized?	
22	GO export	Is the gas GO registry connected to other GO registries of other EU countries? Do the other registries recognize e-methane GO?	
21	Tradability	If the country operates a compulsory database for sustainable fuels, has the Member State connected it to the Union Database (UDB)?	

4.2.3.4. D. Competitiveness

EU-level

#	Indicator	What to Check	Assessment ✕✓?
22	EU ETS	• Can your product be zero-rated based on EU ETS rules? • How much price advantage would that give to EU ETS suppliers compared to natural gas consumption?	

National level

#	Item	What to Check	Assessment ✕✓?
23	Support Mechanisms	• Is there a support scheme for production? • How much aid per MWh can you get? • What are the criteria for eligibility? • If based on auctions, when are the next tenders and what are their criteria?	
24	Support Mechanisms	• Is there a support scheme for investment? • How much capital grant can you get? • What are the criteria for eligibility?	
25	Renewable value	Can you claim the GO even when the project is subsidized? In case of subsidies, is the value of the GO included in the level of support or consumption?	
26	Taxation	Is your e-methane eligible for reduced taxation in the country of the project?	

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27	Carbon price	Is the carbon price of the national ETS market high enough to be competitive with fossil alternatives?	
28	Permitting	Is the permitting process streamlined or lengthy in your country?	

4.2.3.5. E. Regulatory Demand Drivers

EU-level

#	Indicator	What to Check	Assessment ✕✓?
29	FuelEU Maritime Regulation	• Is your e-methane targeted at maritime markets? Is it RFNBO-compliant?	
30	CO_2 emissions performance standards for cars, vans and HDVs	• Is your e-methane targeted compliant with GHG reduction targets? Does it respect the carbon neutrality life cycle?	

National level

#	Item	What to Check	Assessment ✕✓?
31	RED III National Targets	Has your Member State transposed RED III and set general or sectoral targets for RFNBOs?	
32	RED III Transport Targets	Has your Member State transposed RED III and set specific sub-targets for biomethane or RFNBOs in transport?	
33	National Mandates	Are there national blending mandates or incorporation quotas imposed on gas suppliers or fuel suppliers?	
34	Consumption Subsidies	Are there subsidies or tax breaks for end-users of renewable gas?	
35	Public Procurement Mandates	Are public authorities or fleets under renewable energy procurement requirements? If so, are e-methane and gas vehicles eligible?	

4.3. Commercial Considerations

As a general consideration, the various stages involved in e-methane production—such as renewable electricity generation, green hydrogen production, CO_2 recovery, methanation, and subsequent steps to ensure the gas quality are highly interconnected. Consequently, the overall efficiency and economic viability of e-methane production depend on the cumulative performance and energy losses of each stage.
Therefore, a holistic approach to optimize the whole process and the overall system architecture it is important including logistical arrangement
Depending on the local circumstances such as access to feedstock and supporting infrastructure there is also a choice between large, centralized e-methane plants benefiting

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from economies of scale or smaller, decentralized facilities optimized for specific local resources and demand.
The following sections provide simplified information on financial mechanisms.

4.3.1. Energy related revenues (support schemes, biofuel/RNFBO quota, GOs)

There are several energy related revenues that have an impact on a business case, but these are to a large extent country specific.

- In **France**, for renewable methane there is a national support scheme (FiT), a GO system natural gas distributors and bioCNG quota for transport. The current incentive scheme (MD 15/09/2022)
- In **Greece** a recently developed national policy framework for the installation of biomethane plants has been established. Although investment and operational support schemes are planned to be implemented, currently no dedicated pricing mechanisms or clear financial support for biomethane have yet been defined. Nevertheless, an active GO system has been employed for biomethane units with valid operating licenses. EU market dynamics still exert a significant influence on business cases
- **Italy** provides a FiT for biomethane offers a fixed revenue stream for 15 years, making the recipient less dependent on external factors like GOs or gas prices. Plants under previous scheme (MD 02/03/2018) receive a 10-year incentive in addition to revenue from gas sales, potentially exposing them to more market fluctuations.
- In **Sweden**, like in all EU countries there is a national biomethane production support and tax exemption for biomethane use in transport and as a heating fuel and from 2026 a gas GO system. It is currently unclear whether e-methane is eligible for production support and tax exemption like biomethane.
- **Ukraine** does not have national biomethane or e-methane support scheme or biofuel quota. Therefore, the EU market has the biggest impact on business cases. The system of GOs for biomethane is planned to be implemented. Large investment projects — especially those exceeding €12 million — may be eligible for targeted state support. This includes tax incentives, customs duty exemptions, and access to land or infrastructure for qualifying projects. Biomethane facilities that meet specified criteria can apply for such support.

4.3.2. Revenues from flexible operations

In general, market conditions for flexible operation market are yet not well developed but have large potential realized. From a technical point of view, it is possible to have an option of switching between biomethane and electricity production to meet the demand better. However, it is a viable option mostly for large scale plants.
Technologies based on gasification installation are already considered to be more flexible with variability in load or feedstock. Nevertheless, after any change in operation conditions, production must be run continuously for a while. An easier switch can happen between e-methane/e-LNG production for flexible operation although more CAPEX is required with high storage.

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4.3.3. Economic cost estimates

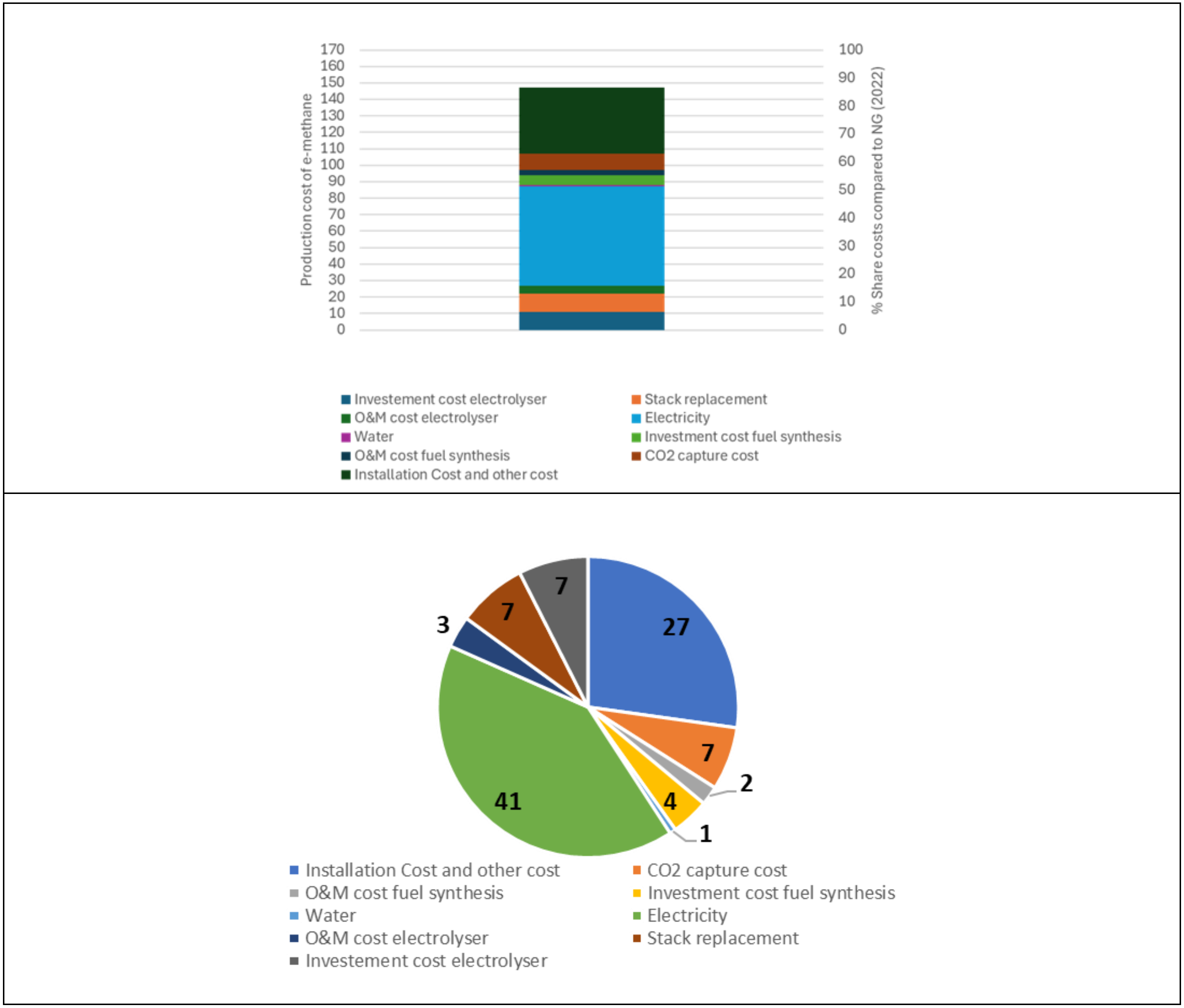

Figure 4 1 Production cost e-methane (147 EUR/MWh), compared to fossil NG (From Grahn et al., 2018) [31]

4.3.3.1. Investment costs (CAPEX)

Methanation project investment costs can vary widely based on plant size, technology choices, and storage needs. Reported capital costs range from as low as €36,000/GJ/hr SNG to as high as €415,000/GJ/hr SNG. For a smaller plant outputting 70,000GJ per year, this translates to total capital costs between €3.36million and €29million (€48/GJ to €414/GJ).

The STORE&GO project provides detailed insights into these costs, highlighting system components such as high-pressure steel tanks for hydrogen and methane storage, with base

[31] Grahn M., Brynolf S., Taljegård M. Electro-methane – production cost estimates and integration aspects https://regatec.org/Resources/REGATEC_2022_conf_proc_web.pdf

case assumptions around €33.33/kWh (LHV). According to STORE&GO, the methanation unit itself typically accounts for 15–30% of the overall system cost. [32] [33]

These findings emphasize the need for strategic planning in technology and storage solutions to optimize investment and ensure business viability.

For the different BIOMETHAVERSE demonstration pathways, - primarily the biogas reactors, the upgrading process and the methanation reactors – the relevant considerations are examined. The requirements for reactors differ between the demonstrated methanation pathways.

- In the **EMG** for both 1c-ADBES and 2c-ADBES the major capital expenditures are associated to the electrodes and reactor's interior surface of the reactor and membranes, as they these components are critical for enabling microbial community activity. Additional investment is required in a feed port must allow precise and adjustable flow control, ensuring long-term stability by limiting any increases in pH within the reactor.
- In the **EBM** the main capital investment lies in the reactor design which must be engineered to optimize transfer yields. Significant expenditures are also linked to integrating the 4 pilots systems, where evaluation synergy is essential to ensure that aggregated impacts justify the upfront investment.
- In the **ETM** the catalytic methanation reactor represents a major capital investment, primarily due to the cost of the catalyst itself and the financial impact of its expected replacement frequency.
- **ESB**: In a trickle bed reactor (TBR), the main capital expenditures are determined by the bed volume and the choice of packing material, as these directly influence gas–liquid mass transfer and biofilm formation. Additional investment is required for efficient heating and cooling systems to ensure stable operation without disrupting microbial activity. Further CAPEX is associated with ensuring a gastight reactor top, which demands high-quality gaskets and lids to prevent gas leakages and safeguard process integrity.
- For the **IBM** a key capital cost factor in reactor design is the choice of material for the mixing system. Since gas recirculation rates and the mixing of H_2 to raw gas mixing ratio can accelerate corrosion, material selection directly impacts investment costs and reactor lifetime.; Using polyethylene component is recommended as a cost-effective solution, offering improved corrosion resistance and reducing the need for premature replacement.

For major installations, investment costs are driven by strategic choices such as on-site hydrogen production, compression or injection systems, potential liquefaction, and the type of gas storage selected.
Other factors impacting the investment cost to consider are lengthy environmental permitting, lack of clarity in grid access costs, and absence of dedicated investment support mechanisms can make project financing less attractive.

[32] https://www.storeandgo.info/fileadmin/downloads/deliverables_2020/Update/20180424_STOREandGO_D8.3_RUG_accepted.pdf
[33] www.storeandgo.info/fileadmin/downloads/deliverables_2020/Update/20181031_STOREandGO_D7.5_EIL_accepted.pdf

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4.3.3.2. Operational expenses (OPEX)

Among operational expenses specific to the demonstrated technologies the most important is the electricity for the electrolyzer (hydrogen production). From several previous reports electricity stands about 60% of the operational cost in a methanation plant There are some minor costs for electricity needed to run the methanation process and the reactor as well as additional electricity for gas compression or liquefaction (syngas, hydrogen, methane) related to the increased gas production due to the e-methane technology.

Most of the demonstrated technologies do not incur additional operational costs for specific maintenance that would be different from regular AD or gasification plant. However, most technologies do require extra chemicals to run the process, like catalyst, granular sludge for nutrient source, salt for anodic chamber and acid/base for pH control. Additionally, external labs may be set up for necessary biotechnology services.
In general, the plant's operational hours per year may lead to lower costs by distributing fixed costs over greater output.

According to techno-economic studies [32] [33] [34] [35], the operational costs account for about 3.5%-of capital costs. When factoring in energy input, like electricity and CO_2 feedstock prices, operational costs represent approximately 13% of the total methane production cost. These estimates reflect year-round continuous operation of a PtG plant producing e-methane and is supported by data from demonstration plants and pilot projects.

Among non-technical factors, are public acceptance, land market availability, uncertainty in feedstock availability, bureaucratic barriers (e.g., permitting procedures) and complicated conditions for establishing electricity and gas grid connections.

4.3.4. Supply Chain Dependences

Another important aspect is to consider what is the share of domestic versus imported components. Imports of parts such as tanks, compressors, mixers, and reactors are bare minimal, both due to the maturity of European manufacturing capabilities, as well as European leadership in knowhow of these technologies. Therefore, all material for manufacturing the necessary components of the demonstrated technologies can be sourced within EU, but manufacturing capacity and supply chains for all electrolyzer types must be significantly scaled up.
There are obviously other considerations on critical material and supply chain, regarding hydrogen production but this is out of scope in this report, but are described in the recent EBA publication *Decarbonising Europe's hydrogen production with biohydrogen* [36]*:*

- **EMG** system relies on the use of very similar materials as for anaerobic digestion systems. Reactors are made of steel at the pilot level and could be made out of concrete for industrial size as for classical anaerobic digestion units. Electrodes used on electromethanogenesis reactor consist of brush type graphitic carbon which can easily be sourced and produced in Europe. Other items such as membranes, sensors pumps, and general BoP systems are widely available on the European market.

[34] Radosits et al., (2024) Costs and Perspectives of Synthetic Methane and Methanol Production Using Carbon Dioxide from Biomass-based Processes
[35]Technology pathways in decarbonisation scenarios- https://op.europa.eu/en/publication-detail/-/publication/599a1d8e-509a-11eb-b59f-01aa75ed71a1/language-en

[36] Decarbonising Europe's hydrogen production with biohydrogen

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- **ETM**: All equipment required for the implementation of the ETM system can be reliably sourced within the European market. Key components including pre-heaters, condensers, cooling fans, and the membrane-based upgrading unit are readily available from EU suppliers, as is the green hydrogen utilized in the thermochemical methanation process. Furthermore, extensive research on the nickel- and iron-based catalysts employed in the catalytic conversion stage, has been conducted at a European level, ensuring both technological maturity and secure supply chains within the EU.
- **EMB**: the entire array of components for the EBM plant can be sourced with ease within the European market. This is primarily because the core elements consist of stainless-steel reactors, diffusers and membranes, electrolyzer, and process control instrumentation, all of which are widely employed across European industrial sectors.
- **ESB** technology is not dependent on any material out of the ordinary .To build an TBR plant, the required components include stainless steel for reactor vessels and tubes, plastic carrier bodies, an electrolyzer, standard process equipment such as pumps, valves, fans, heat exchangers, chillers, water heaters, compressors, sensors, and electrical and control systems, as well as possibly gas purification technology that uses chemicals or membranes; during operation, consumables include a nutrient solution (e.g., a residual product found locally), additive chemicals such as sulfur and phosphate, acid/base for pH control and for the electrolyser, and obviously syngas, all of which can be purchased from EU suppliers.
- **IBM** technology uses standard materials and equipment, including a biogas digester with an integrated gas recirculation system made of corrosion-resistant materials like polyethylene, mixers, and sensors for monitoring critical parameters (e.g., pH, temperature, pressure). Essential process equipment includes electrolyzer, valves, pumps, fans, and gas analyzers. Unlike other pathways, IBM does not require separate methanation reactors, reducing complexity and costs. Consumables include locally sourced green hydrogen. All components for the IBM pathway can be procured from EU suppliers, ensuring supply chain resilience. The use of local feedstock and integration with existing AD systems further enhances sustainability and cost-effectiveness.

4.3.5. Assess the market potential: How and to whom e-methane will be sold/off take?

Renewable methane is flexible energy carrier and represent a versatile alternative to fossil fuel with growing market opportunities across key multiple sectors and its usage depend mainly on infrastructure availability and the national regulatory environments beside the market demand.
In the power sector renewable methane is primarily utilized in cogeneration systems that simultaneously produce electricity and heat, offering industries and buildings reducing reliance on non-renewablesThe importance of power production from renewable methane is expected to grow for increased stability and flexibility for the electricity system via gas turbines and locally for increased capacity.
In industry, renewable methane serves as fuel for high-temperature processes that are hard to decarbonize (e.g., steel, ceramic, glass and basic materials manufacturing).
Leveraging renewable methane as carbon feedstock for chemical synthesis and fertilizer production is increasingly recognised as a strategic pathway to accelerate corporate net zero commitments and create new value chains.

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Renewable methane is a key option for decarbonizing heavy-duty transport through cost-effective compressed and liquified forms (bioCNG and bioLNG) and it is also a growing interest for bioLNG in the maritime sector with a potentially large market ahead as many new ships the last couple of years are LNG/LNG-ready ships) making it a critical component in strategies targeting sustainable fleet operations and logistics.

In terms of the geographical variations in renewable methane end use in Europe, the majority is used in the transport sector in countries such as Italy, Sweden and Norway. In countries such as Germany, on the other hand, a greater portion of the renewable methane produced is used to heat buildings or converted into electricity. The decision to switch to renewable methane is influenced by several factors, beside its availability, including its cost, which is typically higher than NG if not accounting for carbon cost. On the other hand, compared to other levers (e.g., electrification) and climate neutral alternatives, renewable methane can be more competitive not having infrastructure constraints and its adoption will not require more resources than what is currently being used.

Previous results indicate that significant renewable methane utilization across various end-use sectors is expected within a timeframe of 3-5 years although a bigger scale up will occur from 2040 onwards.

As discussed in the previous sections of chapter 4.2, to scale up the use of renewable methane several conditions must be met including:

- a clear and stable legislative framework setting level of playing field in Europe with no internal market barriers;
- effective support schemes or demand pull (such as a blending mandate).

Setting steep GHG emissions reduction target at sectoral level drives accelerated emission reduction and advances sustainability objectives.[37] The widespread acceptance of market-based approaches by leading voluntary GHG reporting frameworks is critical factor enabling the expanded use of renewable methane in climate mitigation strategy.
Additionally, consistency and transparency in the treatment of renewable methane within the EU ETS system and GHG protocol are also important. On a more general level, increased EU climate and renewable ambitions can drive the uptake of biomethane while streamlined permit processes are necessary to guarantee timely capacity scale-up. Finally, it should be tracked and traded consistently across different areas, recognizing the amount of biomethane produced and used (mass balance) and allowing it to be bought and sold easily between countries (cross-border trade) with e-methane that should be recognized in support schemes.

The table below shows main drivers and barriers including EU measures regulating the different end use sectors.

[37] www.biomethaverse.eu/wp-content/uploads/2024/07/BIOMETHAVERSE_D.4.1.pdf

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Table 4 3 Summary of barriers and drivers necessary to scale up the use of renewable methane

	Main Drivers	Main Barriers
Heat /Power	• CO_2 and energy tax exemption • EU ETS • Energy Efficiency Directive	• weak price and policy signals supporting services (balancing etc.) • low electricity prices • weak acknowledgement of the importance for plannable, flexible, and local heat and power production from renewable methane • lack of simplified procedures for connecting facility to gas distribution and electricity networks. • Incentives for full electrification of industrial heat • No dedicated funding programmes for sustainable methane in EU Innovation Fund (exclusion from eligibility criteria to receive funding).
Buildings	• Available distribution • RED III: Indicative renewable energy share national target, heating and cooling incremental sub-target, district heating and cooling incremental sub-target • EPBD: zero emissions buildings (ZEB) target, RE in total annual primary energy use in ZEBs • CO_2 and energy tax exemption • Energy Efficiency Directive • Ecodesign and Energy Labelling Regulations	• Competition with electrification of the sector • Incentives to electricity • Regulations impacting the installation of new gas boilers • Gradual phase out of fossil fuel boilers in all buildings with a potential risk of disregarding existing boilers for the use of renewable methane. • Low financial incentives • Low incentives to greening the gas grid due to prioritisation of full electrification. • Delays in Securing Technical Connection Approvals from Gas Distribution Operators • Limited capacity of the GDS to accept biomethane in certain periods • Lack of market driven instruments to pull the demand for renewable methane (green gas contracts, blending obligations)
Industry	• RED III: annual indicative renewable energy target Art22 and 22b • 42% of RNFBO in industry in 2030 • REDIII Art 29 and 30 POS • Implemented Registries of GO • EU ETS Directive and Monitoring and Reporting Regulation (zero emission rating) • Energy Taxation Directive Art 17 and Annex I (reduction in excise duty of fuels and electricity for energy intensive businesses • high CO_2 and energy tax on fossil fuels • EU ETS – increased carbon price and extension • CO_2 and energy tax exemption • Available distribution • Revocation of export duty in non EU countries	• Competition with electrification of the sector • Cost of biomethane compared to natural gas • Tax-Exempt Revocation • lacks a modern accredited laboratory for renewable methane analysis. • Delays in Securing Technical Connection Approvals from Gas Distribution Operators • lack clarity on how to account for renewable gases in emissions reporting • The proposed minimum taxation levels under the ETD for fuels and electricity do not reflect their actual environmental impact, creating unfair market conditions (similar tax for fossil fuels and renewable fuels).
Transport	• RED III: Art 25 Renewable energy share target or GHG intensity reduction target • Sub-target of 5.5% by 2030 for RNFBOs	• Energy Taxation Directive Art 7, 8, 10, 15, 16, high minimum taxes • Competition with electrification of the sector • Vehicle offer on the market • ICE ban 2035

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	• FuelEU Maritime: GHG intensity limits on Life Cycle Approach basis Fuel EU Maritime emission intensity quotas • Energy Taxation Directive Art 7, 8, 10, 15, 16, Possibility of tax exemption or reduction • Available distribution and transport network • Deployment of refuelling stations • AFI Regulation Art 8-9 Appropriate number of filling stations • Trans-European Transport Network (TEN-T) initiative development of multimodal network • Incentives for low carbon vehicle fleets • Investment support/ capital grants for filling stations • ETS2 for road transport • ETS1 extension to maritime • CO_2 emission performance standards for cars and vans • CO_2 emission performance standards for heavy duty vehicles	• EU CO_2 Standards and Combustion Engine Phase-Out on Biomethane Development in Road Transport • infrastructure to support renewable methane use in transport • reduced emission reduction quota for diesel and gasoline. • End of Low-Emission Vehicle Purchase Bonus in European Bonus-Malus Taxation Systems • Lack of refueling points on road and ports • No recognition and inclusion of carbon neutral fuels • No inclusion of carbon correction factor • Focus on Tank to Wheel accounting system instead of a full life cycle Well to Wheel accounting system of GHG emissions. • Come up with a Union wide methodology to account for vehicles exclusively running on CO_2 NF and assess the life cycle of emissions from production to end use.

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End uses- industry-

For industrial processes biomethane and e-methane serves both as a sustainable fuel and as a feedstock used as a building block for chemical synthesis production of basic materials in the so called 'gas to chemicals'. For instance, renewable methane can be used to produce pharmaceuticals, fertilizers, and plastic, as well as to produce chemicals (e.g., ethanol, hydrogen, and ammonia). Nevertheless, exact volumes currently being used are difficult to assess, as the available statistics focuses on energetic uses thus underestimating the role of renewable methane. Gas is also particularly well suited for high-temperature industrial process, where options for decarbonisation are limited. The glass industry is consuming around 70 TWh natural gas per year renewable methane is explored as one of the most viable decarbonisation substitute options for natural gas in furnaces for glass melting. It can be also used to produce pharmaceuticals, fertilizers and plastic, as well as to produce chemicals (e.g., ethanol, hydrogen, and ammonia). According to scientific community and experts in the chemical industry, utilizing C from CH_4 in the fertilizer value chain and converting into chemicals could significantly advance net zero objectives.

The ceramic industry for example has adopted a decarbonization roadmap in 2012 and a new one in 2021 with a view to meet the net-zero target by 2050. The latter takes into account energy sources such as hydrogen. Decarbonization pathways include biogas, hydrogen and electricity, each of which has the same share in the final target: 33% biogas, 33% hydrogen, 33% electricity. These targets are not binding but represent a commitment taken by sectors where in some cases the decarbonization strategy aims at reaching climate neutrality by 2025. Other industry targets, like Science-Based Targets Initiative (SBTis), are under development. For instance, several companies in the chemical sector set specific target under SBT.[38] The submission of SBTi implies a reduction of 42% of energy need (Scope 1 and 2) for 2030 and Net Zero Emission target for 2040. In the building sector there are companies bound by internal target (-12% under scope 1 and 2). The chemical sector has expressed support for the EU's objective of climate-neutrality by 2050, which it currently substantiates with a dedicated Transition Pathway. While the target is to be fully decarbonized by 2050, the aim is to reduce emissions by 70% by 2040 compared to 2020. To achieve this companies in the fertilizer sector will define their decarbonization roadmap to meet the 2040 target by 2026.

Renewable use in industrial energy applications is anticipated to increase considerably and its share in industrial energy use could approach 100% by 2035. This highlights the industry's commitment to sustainable energy solutions, and the growing feasibility of this energy carrier as a primary source. Additionally for raw material use, there is readiness to transition high level of interest from the industry in adopting this solution.

End uses -buildings

Renewable methane can be used to generate heat and electricity through cogeneration systems, which produce both electricity and heat simultaneously. This is particularly useful for industries or buildings that require both electricity and heat, such as hospitals or industrial processes. the heat can either be generated directly on-site or produced off-site and distributed through a district heating grid for residential and tertiary buildings. As biomethane is compatible with existing gas-based space heating systems, it can decarbonise household heating in a non-invasive manner. Replacing natural gas with biomethane requires minimal additional investment, making it an attractive solution for decarbonizing buildings. This approach is particularly well-suited when other alternatives are not feasible

[38] SBTi-criteria.pdf (sciencebasedtargets.org)

due to technical, regulatory, or financial constraints. Biomethane can complement the electrification of household heating, for example by using hybrid heat pumps.
Several examples of the use of renewable methane in urban heating networks can be found in Europe.
In this sector countries, for example, Germany, Germany's Building Energy Act (GEG), mandating 65% renewable heating in new buildings by 2024, is likely to drive up biomethane demand in the sector.

End uses -transport-

In Europe, renewable methane usage in the transport sector reached 8.63 TWh in 2022, serving as significant fuel source. Biomethane can be used as a transport fuel either in compressed form (bio-CNG) or in liquefied form (bio-LNG). It is one of the few readily available fossil fuel alternatives for long distance and energy intensive transport segments (heavy-duty vehicle (HDV). The bio-LNG market is growing in Europe with 27 active bio-LNG-producing plants by the end of 2022. This number is expected to rise to 109 plants by 2025 with a projected production capacity 15.4 TWh per year. Norway and Sweden pioneered Bio-LNG production, with Europe's first plants starting in 2011 and 2012.

In the transport sector, the use of renewable methane is expected to evolve significantly over the next decade. While its adoption in light vehicles is declining, the heavy-duty vehicle (HDV) segment is experiencing rapid growth. This trend is likely to continue, and it is projected that biomethane could account for 100% of the fuel share in HDVs before 2030. The maritime sector is expected to growth in biomethane use. Most new ships being built are LNG-ready, facilitating the integration of biomethane as a low-blend fuel option. Therefore, biomethane could constitute 10-20% of the maritime fuel mix by 2030 and could play a crucial role in reducing maritime emissions.

End uses- electricity

In power plants for electricity generation thanks to its high efficiency with a lower heating value (LHV) of around 36 MJ/m³ (compared to 16-28 MJ/m³ for biogas). The transition to a power system dominated by renewables, including variable sources providing fluctuating levels of electricity lead to an increasing need for energy system flexibility. In this context, reinforce the electricity grid and the P2G is a solution to a problem that is inevitable if we want to continue to develop renewables in EU as this contributes to greening Europe's electricity not only by producing baseload volumes of green electricity, but also can be used to generate electricity as needed thus by providing flexibility and storage options for the energy system as a whole. In 2022, 6.8 TWh of biomethane was used in Europe for power generation, resulting in an estimated 2.6 TWh of electricity.

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5. Social considerations

Generally social impacts of biomethane/e-methane plants are mainly linked to the biogas value chain, and only to limited extent related to the demonstrated methanation technologies per se.
The costs and benefits associated with health, safety, environmental, and societal impacts are challenging to quantify and connect to economic profitability. While these factors can be incorporated as constraints, an additional challenge in formulating the objective function is the quantification of uncertainty. Compounds with significant health, safety, or environmental risks, such as highly toxic or explosive substances, known carcinogens, or hazardous air pollutants, must be carefully monitored. It is essential to track these compounds to ensure they do not reach unsafe levels in any stream and to identify potential environmental release points.
The plant must be accepted by the local community and located safely to avoid adding significant risks to the population.
It should generally be sited downwind of residential areas.
For a new site, the community should provide necessary services for plant workers. The community must also be consulted about the plant's water use, discharge, and impact on local traffic.
Some communities may welcome the plant for job opportunities and economic benefits.
The following sections address various aspects valid for all demonstrated technologies related to social considerations.

All these aspects are integrated alongside technological and market factors—such as social trends that shape business demand—because, despite their indirect nature, they play a crucial role as drivers influencing market needs, industry acceptance, and long-term viability. Although their impact is complex to assess, social factors significantly contribute to shaping and aligning market dynamics. Furthermore, there is a growing need to actively involve communities in the decision-making process to ensure that they not only have a voice but also directly benefit from the resulting innovations and developments.

5.1. Job Creation

Published in February 2023[39], EBA study "B*eyond energy: monetising biomethane's whole-system benefits"*, quantified the value of the biogas and biomethane positive externality. A future biomethane industry has the potential to support the creation of stable jobs across the value chain, and particularly in the rural economy. Biomethane production can contribute to the creation of between 1.1 and 1.8 million jobs across the value chain in Europe by 2050. As biomethane production through anaerobic digestion will involve a more decentralised production model based on agricultural wastes, residues and sustainable crops, its deployment is expected to bring new employment benefits especially to rural regions across Europe.
Accordingly, e-methane production can generate both direct and indirect jobs, such as jobs at the site or in companies involved in planning, construction and operation, feedstock providers, quality control specialists, biomethane suppliers and users. The development of biomethane infrastructure could boost employment in rural areas, particularly in agricultural waste management and logistics. In some cases (e.g., IBM), it can be estimated that for 1GWh of methane produced in a year approximately 0.5 direct and 1 indirect jobs are created, which is equivalent to 25,0000 new jobs by 2050.

[39] https://www.europeanbiogas.eu/wp-content/uploads/2023/02/20230213_Guidehouse_EBA_Report.pdf

5.2. Financial benefits for farmers and waste producers

The demonstrated technologies do not affect the biomass use or the digestate output in a biogas plant, but the increased methane output the potential improved business case for new biomethane plants may indirectly affect farmers and waste producers positively.
Biogas solutions based on waste as feedstock create value to organic waste streams from different parts of society (farmers, household, industries, forest owners, etc.) previously requiring cost to manage. Increased demand for organic residues and low-ILUC biomass gives additional income to farmers, forest owners and related industries. Additionally, this solution provides said farmers with low cost biofertilizer and soil improvers.

5.3. Odour and Air Emissions

Odours from biogas plants is a common concern but can be minimized with proper filtration, air treatment, and good operational management. Anaerobic digestion of slurry reduces odours compared to untreated livestock manure. At modern biomethane plants, which use mature technology, odours and air emissions are minimal. Odours mainly come from transporting and storing materials, but closed reception halls with air treatment units help prevent their spread. Additional solutions like closed storage tanks, silos, manure cellars, and air scrubbing further minimize odours. The biological process in biogas plants reduces unpleasant odours, sanitizes feedstock, and lowers weed seed germination. However, permitting may be delayed due to social concerns over odours and emissions.

5.4. Water demand and possible contamination

Of the demonstrated technologies it is mainly the hydrogen production that impacts water demand. Hydrogen production via electrolysis requires significant amounts of pure water. To produce 1 kg of hydrogen from electrolysis, 9 kg of water is required.

In the biogas value chain, AD plants typically have adopted technologies that help to reduce water consumption and water recirculation, such as connection to water treatment plants, safety measures to prevent surface run and general compliance with environmental protection norms.
Offsite investments often involve interactions with utility companies such as water suppliers. They may be subject to scrutiny because of their impact on the local community through water consumption, discharge and traffic.
Obviously, water resource availability is a concern, particularly in regions with seasonal droughts. Future biomethane projects must ensure efficient water management and recirculation systems to avoid negative environmental impacts.

5.5. Noise pollution and traffic

Noise pollution and traffic are not relevant to the technologies demonstrated except in cases where high methane output may require additional transportation by truck.

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In the biogas value chain plants operators can take measures to do an appropriate layout of the 'noise sources' on the plant and soundproof those.
The delivery of biomass to the biogas plant will cause more locally concentrated transport, depending on the size of the biogas plant. However, the traffic plan, usually part of the environmental license application, imposes strict routes to transporters. Moreover, biomass transport is only allowed during working days.

5.6. Risk of pathogens and heavy metals

There is no increased risk of pathogens and heavy metals of the technologies demonstrated. In the biogas value chain, the risk of pathogen contamination is most commonly linked to the stage when digestate, the nutrient rich residue left after the biogas production, is applied to agricultural land. The application of digestate to agricultural soils is recognized as a sustainable soil management practice in the EC proposal for Soil Monitoring Law. The stable organic fraction of digestate sustainably enriches the humus content of the soil. Humus formation is critically important for soils due to nutrient retention, soil structure improvement, water retention, pH buffering, microbial habitat and carbon sequestration. Animal and plant pathogens that may be present in the original feedstock are either vastly diminished or wholly eradicated during the technical and thermal pre-treatment of the feedstock and due to the microbial conditions inside the digester (in particular the combined factors of temperature, microbial competition and ammonia production). Digestate quality control usually falls under specific country legislation and is ensured by certification systems. In Greece, there is currently no national standard for digestate quality certification, making it difficult for digestate to be widely accepted as a fertilizer. Establishing a clear regulatory framework for digestate use could enhance market uptake.

5.7. Land use competition

Land use competition is not relevant to the technologies demonstrated per se, as they are established at existing biogas or gasification plants and in general do not require more land. E-methane production does not require more biomass since it is produced from the access CO_2, which does not affect land competition.
For establishment of a biogas or gasification plant obviously, an adequate sufficient suitable land must be available for the plant and potential and for future expansion as explained in section 4.1.2.
The land should be flat, well-drained, and have suitable load-bearing capacity. A site evaluation is necessary to assess the need for special foundations.
Biomethane production can coexist with food production without significant negative impacts on food prices or security, as long as appropriate measures are in place to manage potential conflicts and ensure sustainability.
Biomethane will be largely produced from waste and residues which do not have an impact on land competition.
By using smart cropping system and intermediate crops and low-ILUC certified biomass in combination with increased use of biofertilizer, biogas from agricultural biomass can be produced without negative impact on land competition but with positive impact on soil health and biodiversity.

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5.8. Risk assessment-main considerations

There are no major construction or operational risks associated with the demonstrated technologies. The only operational risk to consider regarding personnel safety is the risk of exposure to potentially toxic/flammable/explosive gases due to leakage or incorrect operation. The risk of staff exposure remains constant over time. However, the risk of process issues most likely would decrease as technologies mature. Similarly, the risks related to unexperienced operators should decrease as experience is built up within the team. All of the above risks can lead to fines and damage of industry's reputation, affecting profit directly and indirectly. The risks can be minimized with gas alarms safe installations and preventative safety work, such as continuous leak detection and training of staff.

Profits are highly sensitive operational risks such as electricity price volatility and availability and cost of biogas feedstock. Mitigation strategies include securing long-term supply contracts (e.g. for electricity and feedstock), considering investing in a hydrogen and e-methane system that allows for flexible operation to reduce exposure to peak electricity prices. Other mitigation measures are investing in advanced monitoring and safety systems to minimize equipment downtime and adopt an in-house solution for green hydrogen production system.

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6. Annex I

6.1. Overview of main regulatory factors in the 5 target countries

This Annex presents a **policy and regulatory snapshot** for five countries—**France, Italy, Greece, Ukraine, and Sweden**—based on the preliminary information provided by Project Partners. It is designed to help project developers and investors **assess the enabling environment** for e-methane production across the following **five Policy Factors**, as outlined in Chapter 4.2:

1. **Regulatory Stability** – predictability and consistency of legal frameworks and support schemes.
2. **Access to Market** – infrastructure access, grid injection rights, Guarantees of Origin.
3. **Export Opportunities** – cross-border trading of e-methane and compatibility of national GO systems.
4. **Competitiveness** – production and investment support, taxation policies, and carbon pricing frameworks.
5. **Regulatory Demand Drivers** – demand-side signals such as blending mandates, quotas, and end-user incentives.

Each country-specific table provides an **initial categorisation** of available information according to these five factors.

Disclaimer: The information presented in this document is **not exhaustive** and should be considered a **preliminary mapping**. National and European regulations evolve rapidly, and implementation timelines may vary. Therefore, project stakeholders are strongly encouraged to verify the current status of national laws, support schemes, and infrastructure access with relevant national authorities or legal experts before making investment decisions.

France

Policy Factor	Indicator	Assessment	Information
Regulatory Stability	Incentives for energy diversification	Positive	France supports biomethane with a feed-in tariff (FiT) system for 15 years, reducing investor uncertainty.
Access to Market	Operational GO registry	Positive	GO system in place; GOs can be used by gas suppliers for compliance.
Export Opportunities	GO export and recognition	Negative	Gas GOs from France are not tradable beyond national borders.
Competitiveness	EU ETS	Positive	Biomethane can be zero-rated

Italy

Policy Factor / Category	Indicator	Assessment	Information
Regulatory Stability	Support mechanisms and timeline	Neutral	The current incentive scheme offers a FiT for 15 years but strict implementation timelines discourage some investors.
Access to Market	Bio-waste and digestate policy	Mixed	Compost from bio-waste has End-of-Waste status; digestate does not.
Export opportunities			
Competitiveness	CAPEX and FiT support scheme	Positive	Combined production and investment support exists under MD 15/09/2022.

Greece

Policy Factor / Category	Indicator	Assessment	Information
Regulatory Stability	Policy maturity	Neutral	There is currently a lack of effective pricing mechanisms, such as FiTs or production subsidies, which slows down the scaling of biomethane. While energy authorities and relevant associations systematically issue policy recommendations aimed at streamlining and shortening approval procedures, the employment of stable pricing mechanisms is essential to accelerate biomethane adoption.
Access to Market	Grid access and GO	Neutral/Positive	While a national framework on biomethane production has been established, the technical and regulatory provisions for establishing grid injection points remain undefined. In parallel, a GO scheme has already been deployed for operational plants, ensuring methane traceability.
Export Opportunities	Bio-CNG and bio-LNG	Neutral	Although the policy framework explicitly addresses the potential export of bio-CNG and bio-LNG to fueling stations and individual end-users, detailed technical guidelines for efficient distribution are still under development.
Regulatory Demand Drivers	CapEx / OpEx support scheme and consumption-side mandates	Neutral/Negative	Legislation clearly defines capital and operational investment grants for the full or partial conversion of biogas units into biomethane units. However, no binding blending quotas for biomethane have yet been established, nor are there complementary mechanisms to guarantee long-term market demand, ultimately limiting competitiveness.

Sweden

Policy Factor / Category	Indicator	Assessment	Information
Regulatory Stability	Policy reliability	Neutral	Production and investment support schemes in place, but long-term security is lacking. National energy climate policies are unstable and changing -e.g. increasing competitiveness for fossil fuelsin transport.
Access to markets		Neutral/positive	Few restrictions, but a limited gas grid means need for liquefaction to e-LNG to access wider markets
Export Opportunities	Infrastructure and bioLNG	Neutral	Export options exist, but gas grid is limited; bioLNG development is growing.
Competitiveness	Tax incentives	Positive/negative	Biomethane benefits from tax exemptions. However, e-methane cannot be exempted with the current Energy Tax Directive (ETD)

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Ukraine

Policy Factor / Category	Indicator	Assessment	Information
Regulatory Stability	Stability and infrastructure development	Positive	Support for decentralised biomethane production with infrastructure investment and tax exemptions.
Access to markets	Infrastructure access and grid injection rights	Neutral	Ukrainian biomethane producers have access to grid injection points, but further regulatory development is needed for broader market integration. Delays in signing technical agreements with GDS operators are possible. Strict requirements for a higher calorific value of biomethane under Ukrainian legislation.
Export Opportunities	GO registry and market access	Neutral	The Ukrainian registry is not in operation yet, but it is planned to be synchronised with EU database; export possible via GTS and bioLNG.
Competitiveness	Pricing model	Positive	Biomethane pricing includes natural gas benchmark plus premium.

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7. Annex II: Survey-Questionnaire Results

7.1. PartA (technical factors)

- The results indicate that organizations primarily focus on Market demand fulfillment (33.3%) and Cost Efficiency (31.6%). These two goals are significantly prioritized over Environmental Sustainability (20.2%) and Technological Innovation (14.9%) when respondents ranked their organizational goals.
- Interest in e-methane investments is predominantly driven by Environment and sustainability concerns (33.6%). Following closely is the market growth potential (29.4%) of these investments and the prospects for financial return (25.2%). "Other" unspecified motivations accounted for a smaller portion (11.8%).
- The overwhelming primary concern for investing in e-methane technology is Regulatory policy instability, cited by 71% of respondents. Market volatility of energy is a concern for the remaining 29%, while tech risk and competition from others were not identified as primary concerns by any respondents in this particular question.
- The adoption of e-methane technologies is most strongly believed to be driven by Sustainability commitment incentives and policy (40%). General Energy demand (25.2%) is also a significant factor, followed by benefits related to Waste management (19.2%) and improvements in Tech efficiency (15.6%).
- When analyzing project viability, social factors received the highest importance rating (26.4% share of perceived importance). Economic factors (e.g., costs, returns) and the type and quality of information available were rated almost equally important (both 25%), with technical feasibility (e.g., technology readiness) following closely (23.6%). This suggests balanced consideration of these aspects, all perceived as relatively important.
- Input materials are considered highly important for e-methane investments. A majority of 56% rated them as "Extremely Important" , and another 31% rated them as "Very Important". Only 12% rated them as moderately important, with no respondents considering them irrelevant.
- There is no consensus on a specific plant size being more attractive for investment. The responses were varied: the most common type of answer indicated uncertainty ("Don't know," "depends," "no threshold"). For those who did provide specific figures, the sizes ranged widely between 35 GWh/y (or >210 Nm3/hr) to 150 GWh/yr (or >1,000 Nm3/hr), indicating diverse views or context-dependent preferences.
- A strong majority of respondents (79%) find it more attractive for investment if energy supply is managed externally. Only 21% prefer in-house management, with no respondents indicating this choice has no influence.
- Among the projects presented, ex situ biological methanation was selected by the highest percentage of respondents (73%) as one of the top 2 most attractive for investment, bio-electrochemical assisted AD was the second most frequently chosen (47%), followed by catalytic methanation (27%), and then in situ biological methanation as well biological methanation of syngas (both 20%).
- When evaluating biomethane or e-methane technologies, the ROI range of 5–10% is considered the most important by a majority (62.5%) of respondents. An ROI greater than 10% is important to the remaining 37.5%, while an ROI below 5% was not selected by any respondent.
- The most important investment size range is 1–10 million EUR, favored by 45% of respondents. This is followed by investments of more than 10 million EUR (36%). Smaller investments of less than 1 million EUR were considered most important by 18% of respondents.
- When asked to rank general concerns, Market volatility of energy (31.7% weighted importance) and Regulatory policy instability (31.0%) emerged as the top two concerns, with nearly equal perceived importance. Tech risk (19.3%) was ranked as a moderate concern, followed by Competition from others (12.4%), This differs slightly from the previous question on primary concern, suggesting that while regulatory instability might be the single biggest hurdle, market volatility is an almost equally significant ongoing concern.

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7.2. Part B (market-commercial policy factors)

- The survey indicates a near-unanimous agreement on the critical importance of national recognition for the use of national guarantees of origin as proof of the share of biomethane in the purchased and used gas by the ETS operator. 86% of participants rated this as "Extremely Important". This resulted in an exceptionally high average importance score, stressing a strong demand for official validation in this area.
- When asked if at national level there is recognition of GO from other countries for renewable methane as zero-rated emissions under the EU ETS, a clear majority of respondents (69%) indicated that this recognition does not exist (e.g. in Italy, Poland, Switzerland, France, the Netherlands and Greece). This suggests that further harmonisation of compliance documentation must be achieved.
- There is a strong consensus that the production of e-methane is not currently profitable without governmental support. A significant 38% "Strongly disagree" with the idea of profitability without aid, and another 31% "Disagree". Interestingly, 31% remained neutral but critically, no respondents believed it was profitable, highlighting a dependence on external support mechanisms.
- The survey reveals that "Capital Grants" are the most common form of support, identified by 77% of respondents. Other notable schemes include "Feed-in-premium (FiP)" and "Feed-in-tariff (FiT)", both available according to 23% of participants. "Mandates Quotas," "Tax exemption," and "Tax reduction" were each mentioned by 15%. The category of "Financial Incentives" was not reported as available by any respondent.
- Regarding specific types of incentives, "Credits for emission savings" are widely available, with 86% of respondents confirming their existence. "Subsidies for producing renewables and hydrogen" were reported by 29% of participants, while incentives for "CO_2 recovery" are less common, noted by 14%.
- Participants ranked "Road transport" as the most crucial potential market for the commercialisation of these innovative technologies, achieving a weighted score of 5.21 (representing 27% of the weighted importance). The "Maritime" sector followed closely with a score of 4.93 (25%). "Energy-intensive industries" (such as chemicals and steel) were ranked third with a score of 3.57 (18%). "Power generation" and "Buildings" were seen as comparatively less significant markets, each garnering 13% of the weighted importance.
- Permitting procedures/delay - bureaucracy with public admin" was identified as the most significant non-technical factor impacting investment costs, with a high importance score (25% of weighted influence). The second most critical factor was "Procedures/conditions for establishing electricity and gas grid connections,"(20%). "Procurements" were ranked third (16%), followed by "Public opinion" (14%), "Costs for acquisition of the site/land allocation" (13%), and "Safety requirements" (12%).
- There is a strong preference for extended long-term visibility from EU and national frameworks. A combined 76% of respondents advocate for 15 years or more, with 38% specifically calling for "15 years" and another 38% requesting "20 years or more." A further 25% suggested "10 years" would be appropriate. No respondents felt that a short-term view of 5 years was adequate, emphasizing the need for stable, long-range planning.
- To make e-methane competitive in the EU, a substantial carbon price is deemed necessary. The majority of respondents (71%) believe a carbon price in the range of "€200-250 EUR/ton " is required. An additional 29% indicated a price between "€150-200 EUR/ton" would be sufficient. No participants felt that a carbon price below €150 EUR/ton would achieve the necessary competitiveness.
- The survey asked about specific incentives that would significantly improve the business case for building and establishing e-methane facilities with a blending mandate being preferred over a fixed consumption target. Another important aspect highlighted is that biogas conversion should be facilitated and biomethane subsidized, especially as other renewables are used simultaneously, while developing and implementing such innovations as well injection capacity and grid flexibility.

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8. Annex III Workshop (script) on Biomethane Planning Decision Guide[40]

Time	Description	Material
9.30 – 10.00	Arrival of participants and registration	Participant list for registration Name tags, Programme Welcome coffee Communication Officer (EBA)
10.00 – 10.10	Short presentation of Biomethaverse project and explanation of objective focus	PowerPoint presentation Project Coordinator-Senior Researcher (ISINNOVA)
10.10 – 10.40	Presentation of the draft structure of Biomethane and e-methane decision guide including technical and policy dimensions	PowerPoint presentation Technical Project Officer (EBA) and Policy Director (EBA)
10.40 – 11.00	Replicability analysis	Project Coordinator - Senior Researcher, ISINNOVA
11.00 – 12.00	Innovations in bio-methanation technologies Presentation of the 5 innovative pathways Highlights for Implementation Challenges and Impacts	Presentation from the 5 demo leaders (ENGIE, CERTH, CAP Holding, RISE, MHP) Exploring the demo sites from the Biomethaverse project Director PtG & Renewable Hydrogen, (Kanadevia Inova) Research Engineer CEA LITEN (METHAREN[41])
12.00-13.00 Lunch break and group photo		
13.00 – 13.45	Feedback session on technical considerations for e-methane production Technical Director (EBA) is the Moderator and reads each question one at the time. Participants are invited to use their smartphones to scan the QR code provided and answer the session’s questions online. Once the QR code is displayed, each participant visualizes the question with their mobile phone, enabling them to access and complete the digital survey or form (Slido platform). This approach streamlines data collection and encourages real-time engagement throughout the workshop. Moderator gives participants time to answer and take notes (paper or laptop), the discussion is recorded on TM.	
	<u>Guiding questions</u>: 1)What does your organisation prioritise as a goal? Please rank them from most important to least important. • Cost Efficiency • Environmental Sustainability	

[40] https://www.biomethaverse.eu/event/biomethane-planning-decision-guide-workshop-2025/
[41] https://metharen.eu/

- Technological Innovation
- Market demand fulfillment

2)What motivates interest in biomethane/e-methane investments?

- Environment and sustainability
- Market growth potential
- Financial return
- Other

3)What is the primary concern in investing in biomethane/e-methane?

- Market volatility of energy
- Regulatory policy instability
- Tech risk
- Competition from others

4)What factors do you believe will drive the adoption of biomethane and e-methane?

- Energy demand
- Sustainability commitment incentives and policy
- Tech efficiency
- Waste management

5) Rank the importance of the following factors in analysing a project's viability for investment or R&D initiatives (1 = Slightly Important, 5 = Very Important)

- Economic factors (e.g., costs, returns, cash flow)
- Social factors (e.g., community impact, acceptance)
- Technical feasibility (e.g., technology readiness, infrastructure needs)
- Type and quality of information available (e.g., data reliability, transparency)

6) On a scale of 1 to 5 (1 = Not Important at All, 5 = Extremely Important), how important are input materials (e.g., raw materials, CO_2 gas, renewable electricity, nutrients) in influencing logistics, site suitability, and production potential?

7)Is there a specific plant size that is more attractive for investment? If so, which one?

8)Is it more attractive for investment to manage energy supply in-house or externally (e.g., using a CHP unit to generate electricity during periods of high energy prices)?

- in house
- externally
- does not influence

9)Can you pick the top 2 most attractive for investment projects from those presented?

- In-situ and Ex-situ Electro Methanogenesis (EMG)
- Ex-situ Thermochemical/catalytic Methanation (ETM)
- Ex-Situ Biological Methanation (EBM)
- Ex-Situ Syngas Biological methanation (ESB)
- In-situ Biological Methanation (IBM)

10)True or false: Price and demand volatility of the offtake product, and the technology readiness level (TRL), are the two most important factors in investment decisions.

11)True or false: Price and demand volatility affect revenues only in the short term, while efficient energy balance is more important for long-term cost savings and stability, making it a more reliable factor in decision-making.

12)What is a reasonable yet attractive payback period (in years) for investment?

13)Among the following ROI ranges when evaluating biomethane or e-methane technologies, which one is the most important?

ROI Ranges:

- ROI < 5%/ ROI 5–10% / ROI > 10%

14)Among following investment size ranges when evaluating biomethane or e-methane technologies, which one is the most important?

Investment Size:

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	• < 1 million EUR • 1–10 million EUR • 10 million EUR 15) What are the concerns in implementing e-biomethane technologies? Please rank them from most important to least important. • Market volatiliy of energy • Regulatory policy instability • Tech risk • Competition from others • Other (specify orally)
13.45 -- 14.30	Feedback session on market and commercial considerations for e-methane production Policy Director (EBA) is the Moderator and read each question one at the time. Participants are invited to use their smartphones to scan the QR code provided and answer the session's questions online. Once the QR code is displayed, each participant visualizes the question with their mobile phone, enabling them to access and complete the digital survey or form (Slido platform). This approach streamlines data collection and encourages real-time engagement throughout the workshop. Moderator gives participants time to answer and take notes (paper or laptop), the discussion is recorded on TM.
	Guiding questions: 1.On a scale of 1 to 5 (1 = Not Important at All; 5 = Extremely Important), how important is it that the country recognise the use of national guarantees of origin as proof of the biomethane share in the gas purchased and used by the ETS operator? 2.Does your country also recognise the use of GO from other countries for the recognition of biomethane as zero-rated emissions under the EU ETS? YES or NO 3.The production of e-methane is profitable without governmental support. • Strongly disagree/ Disagree/Neither agree nor disagree/Agree/Strongly Agree 4.Are there subsides and available support schemes in your country? • Capital Grants • Feed-in-premium (FiP) • Feed-in-tariff (FiT) • Financial Incentives • Mandates Quotas • Tax exemption • Tax reduction 5.Are there incentive for: • CO_2 recovery • Credits for emission saving • Subsides for producing renewables and hydrogen 6.Please rank the following end-use sectors in order of their importance as potential markets for the commercialisation of these innovative technologies. From most important to least important. • Road transport • Maritime • Buildings • Power generation • Energy-intensive industries (chemicals, steel, pulp and paper, plastics, cement, non-ferrous metals, glass, and ceramics) 7.Which non-technical factors influence mostly the investments costs. Please rank them from most important to least important. • Permitting procedures/delay - bureaucracy with public admin

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	• Costs for acquisition of the site/land allocation • Safety requirements • Procurements • Public opinion • Procedures/ conditions for establishing electricity and gas grid connections 8.How much long-term visibility should EU and national frameworks provide to support the success of your project? (e.g., targets, support schemes, tax incentives, etc.) • 5 years • 10 years • 15 years • 20 years or more 9.What is the level of carbon price that would make the e-methane competitive enough against natural gas in the EU ETS? • 50-100 • 100-150 • 150-200 • 200-250 10.What types of tax incentives for the building & establishment of the e-methane facility would improve significantly your business case? For instance, would a investment tax credit help? 11.Based on the technologies presented in the previous session, and guided by the moderators, participants develop recommendations for policy measures that stimulate, enhance, strengthen the market uptake of e-methane technologies	
14.30 – 15.00	Coffee break	
15.00 – 15.20	Social acceptability and environmental considerations	Researcher (ENEA)
15.20 – 15.30	Conclusion and wrap up	Project Coordinator (ISINNOVA) Final words and conclusion

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