D3.3 Preliminary sustainability assessment and eco-design modelling

Deliverable:	Preliminary sustainability assessment and eco-design modelling
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CONTENTS

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Table of figures

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Executive Summary

BIOMETHAVERSE aims to unlock a new generation of biomethane technologies capable of increasing production, lowering costs, and strengthening the integration between electricity and gas grids in support of Europe's energy transition. While the project's core objectives are technological and economic, the innovations developed are expected to have significant environmental and social implications—ranging from greenhouse gas (GHG) reductions and circularity improvements to job creation and regional energy resilience.

Five innovative methanation technologies are being demonstrated across Europe at pilot scale, covering a variety of catalytic, biological, and electrochemical approaches. These include:

- **ElectroMethanoGenesis (EMG)** in France
- **Ex-Situ Thermochemical Methanation (ETM)** in Greece
- **Ex-Situ Biological Methanation (EBM)** in Italy
- **Ex-Situ Syngas Biomethanation (ESB)** in Sweden
- **In-Situ Biological Methanation (IBM)** in Ukraine

This deliverable (D3.3) builds upon prior work in WP3, particularly the methodology (D3.1) and the process flowsheeting and performance modeling of the technologies (D3.2). The current report is based on the the same methodology and tools used in Deliverable 3.2 and on the preliminary flowsheeting reported. However, processes and results have been updated due the availability of new operational data from the pilot plants, recent literature, and refined process modelling.

Therefore, the results of the **updated flowsheeting** are reported together with a **preliminary sustainability assessment**, with a dual focus:

1. **Environmental performance**, through Life Cycle Assessment (LCA), and
2. **Social performance**, through Social LCA and stakeholder engagement tools.

Given that pilot plants are not yet fully operational, this assessment remains preliminary. The modelling structure developed remains consistent with that used in Deliverable 3.2, but is designed to integrate real operational data as it becomes available, allowing for refinement in the upcoming deliverables (D3.6–D3.8) focused on upscaling, optimization, and comprehensive sustainability assessments. To contextualize the technological evaluation within the broader biomethane value chain, each pilot is analysed not only at the level of its core innovation but also with integration of upstream processes (e.g., anaerobic digestion, gasification, electrolysis). This allows for a more holistic analysis of energy use, environmental impacts, and social implications.

The environmental evaluation, based on attributional LCA, focuses on two key mid-point indicators:

- **Climate change (GHG emissions, measured as the global warming potential over 100 years - GWP100)**
- **Primary energy demand from fossil sources**

These impact categories were assessed for both current electricity mixes and a projected renewable-dominated scenario, using the *LCA for Experts* software (developed by Sphera, previously known as GaBi) and impact characterization according to the EF 3.1 method. Despite current limitations in data availability, the analysis clearly indicates that most technologies—especially when powered by renewables—offer substantial environmental benefits compared to fossil natural gas.

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On the social side, the assessment includes:

- A **literature review** mapping key social opportunities and risks across six dimensions: employment, territorial development, circular economy, community well-being, social acceptability, and resource use;
- A **Social Life Cycle Assessment (S-LCA)** using the PSILCA database to identify social risks and performance hotspots across the value chain;
- A **stakeholder survey**, targeting workshop participants and the wider e-biomethane community through EBA mailing lists, to assess local perceptions of social acceptability and impact factors;
- An **expert focus group** to qualitatively validate findings and enrich the interpretation of results.

Together, these components establish a robust preliminary framework for sustainability evaluation, setting the stage for future iterations that will integrate experimental data and enable techno-economic optimization across the five demo cases.

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1. BIOMETHAVERSE in a nutshell

BIOMETHAVERSE aims to diversify the technology basis for biomethane production in Europe, increase its cost-effectiveness, contribute to the uptake of biomethane technologies, and support the priorities of the SET Plan Action 8.

To meet these goals, **five innovative biomethane production pathways** will be demonstrated in five European countries: France, Greece, Italy, Sweden, and Ukraine.

The five selected demonstrators go beyond the state of the art and thus beyond technologies already implemented at commercial scale and rely on:

- In-situ and Ex-Situ ElectroMethanoGenesis (EMG): Electricity enhanced biomethane production (by ENGIE, France);
- Ex-situ Thermochemical/catalytic Methanation (ETM): Thermochemical/catalytic upgrading of biogas using hydrogen (by BLAG, Greece);
- Ex-Situ Biological Methanation (EBM): Biological upgrading of biogas using hydrogen, including feed-stock pre-treatment via ozonolysis (by CAP, Italy);
- Ex-Situ Syngas Biological methanation (ESB): Biological methanation of syngas from thermal gasification (by RISE, Sweden);
- In-situ Biological Methanation (IBM): Hydrogen integration in the AD reactor (by MHP, Ukraine).

The project's objectives will be achieved through the implementation and consolidation of the following founding pillars:

- Demonstration of Innovative Biomethane Pathways;
- Assessment and Optimisation of Innovative Biomethane Pathways;
- Replicability, Planning Decisions, Market Penetration, and Policy Dimension;
- Dissemination, Exploitation & Communication.

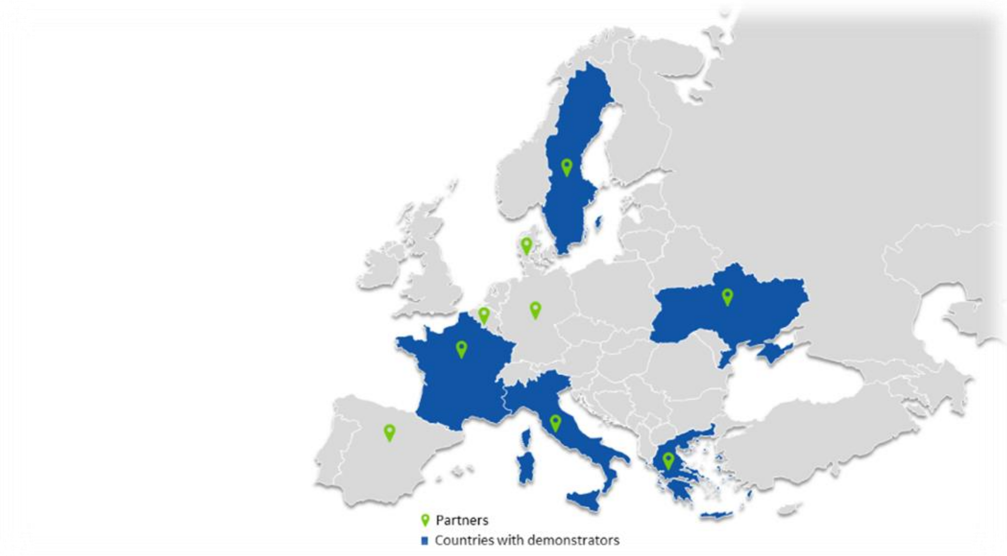

Figure 1 - BIOMETHAVERSE Countries and Partners

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1.1. Deliverable content

This document focuses on a preliminary sustainability assessment of the innovative pathways developed in Biomethaverse. The analysis builds upon, and updates, the outcomes of Deliverable D3.2, which provided the initial energy and process analysis of each pilot, including key aspects such as significant streams and outcomes in terms of composition, volumetric flow rates, and expected biomethane yield. In this deliverable, these results have been revised and expanded: for each pilot, the upstream processes (feedstock appropriation, anaerobic digestion, gasification) have been integrated and analysed anew, providing a more comprehensive and up-to-date overview of the biomethane production pathway and the impact of adopting Biomethaverse technologies.

The structure of the document is organized into chapters.

Chapter 2 illustrates the methods and tools for the environmental sustainability.

Chapters 3 to 7 are dedicated to the five demos. Each chapter provides a brief introduction of the technology under consideration and the preliminary flowsheet of the process, analyzing the entire biomethane production pathway: from the initial feedstock to the biomethane suitable for injection into the gas grid. For each section, the results of the flowsheeting performed using AspenPlus®, with a focus on the core elements of the process and key assumptions regarding stream composition, flow rates, and operating conditions is reported. Then, for each pilot, based on the energy and mass balances of the processes, the results of the environmental analysis, performed with the software LCA for Experts (former Gabi, from SPHERA) are presented.

Chapter 8 compares the energy and environmental performances of the Biomethaverse technologies.

Finally, in the last section (Chapter 9), the methodological approach and preliminary results of the analysis of the social impacts of the technologies developed are presented. The social aspects are assessed with a triangulation of methodologies encompassing Social LCA, a survey, and an experts focus group.

1.2. Abbreviations and acronyms

AD: anaerobic digestion

ADP: Abiotic Depletion Potential

EBM: Ex-Situ Biological Methanation

EF 3.1: Environmental Footprint Impact Assessment Method version 3

EMG: Electro Methanogenesis

ESB: Ex-Situ Syngas Biomethanation

ETM: Ex-Situ Thermochemical Methanation

GHG: greenhouse gas/gases

GWP: global warming potential

KPI: key performance indicatos

IBM: In-Situ Biological Methanation

LCA: Environmental performance, through Life Cycle Assessment

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NG: natura gas

NIMBY: Not In My Back Yard

NIMTO: Not In My Term of Office

PED: primary energy demand S-LCA: Social Life Cycle Assessment

1c-AD-BES: single-chamber bio-electrochemical system for anaerobic digestion

2c-AD-BES: double-chamber bio-electrochemical system for anaerobic digestion

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2. Methods and tools for the environmental sustainability

The mass and energy balances of the demonstration plants have been estimated by means of the ASPEN Plus software. This tool is the leading process simulation software in the chemical industry and presents an extensive database for the chemical and physical properties of compounds and several pre-build processes blocks useful for the simulations of the typical units of chemical systems (such as pumps, compressors, reactors, heat exchangers). The different systems were thus modeled as a combination of Aspen Plus blocks, using kinetic reactors, Gibbs reactors, or RSTOCK blocks to simulate the different reactions occurring during the methanation process. As well, upstream processes are modelled by means of specific data obtained from literature, regarding Anaerobic Digestion, Gasification, and PEM Electrolysis (Agostini et al., 2015; Giuntoli et al., 2017).

The elaborated mass and energy balances were fed to the software for LCA, LCA for Experts, which is a specialized tool used by experts and organizations to evaluate the environmental impacts of products, processes, or services throughout their entire lifecycle—from raw material extraction to disposal or recycling. This includes: quantifying environmental impacts such as greenhouse gas emissions, resource and land use consumption, pollution of air, water and ecosystems; supporting sustainable product design and development; identifying hotspots or stages with the highest environmental burdens; informing corporate sustainability strategies and decision-making.

In this preliminary study, LCA for Experts has been applied to evaluate the carbon footprint of the modeled pilots and the primary energy demand from fossils. The analysis was limited to these two impact categories because of the preliminary nature of the report, which is based mostly on literature data, as the pilot plants have not yet delivered the complete results needed for a comprehensive analysis. The aim of the work is rather to set up a modelling architecture capable of accommodating the results of the demonstrators once available.

For consistency, a unique location of the plants was chosen, to enable comparability. For example, the power consumption was modelled with the Italian Electricity mix, and an Italian mix of renewables (50% solar and 50% wind). In addition, for comparison, the reference scenario is modelled as a biomethane plant without the Biomethaverse technology.

The main assumptions used during the process modeling were gathered from deliverable D2.2, or taken from recent literature (Chauvy et al., 2020; Dionisi, 2017a; Geppert et al., 2016; Paniagua et al., 2022).

Finally, a set of Key Performance Indicators (KPIs) were identified to evaluate and compare the energy performances of the different systems.

2.1. Energy performance indicators

Hereby the main KPIs for each demonstration plant are defined. These KPIs serve as critical benchmarks, providing a foundation for meaningful comparisons among the different technologies implemented at the demonstration scale. To be noted that, even if the entire pathway has been modelled, the energy performance indicators are related only to the innovative technologies, core of the Biomethaverse project.

- Specific electric consumption – en_{el} [$kWh_{el}/kWh_{HHV,BM}$]: Total electric consumption of the system (including the auxiliaries such as pumps and compressors) per MWh of biomethane produced.

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Eq.1
$$en_{el} = \frac{P_{el}}{G_{BM} * HHV_{BM}}$$

Where P_{el} [kWh] represents the total electric power consumption of the system, G_{BM} [kg/h] the mass flow rate of the produced biomethane and HHV_{BM} [MJ/kg] the high heating value of biomethane.

- Hydrogen consumption – $cons_{H2}$ [kg_{H2}/$kWh_{HHV,BM}$]: hydrogen consumption per kWh of biomethane produced.

Eq.2
$$cons_{H2} = \frac{G_{H2}}{G_{BM} * HHV_{BM}}$$

- Carbon Conversion Rate – CR [%]: Ratio between the carbon contained in the produced biomass, $C_{biomethane}$ [mol_c/h], and the carbon contained in the feedstock entering the system, $C_{feedstock}$ [mol_c/h].

Eq.3
$$CR = \frac{C_{biomethane}}{C_{feedstock}}$$

- Energy efficiency of plant – η [%]: Total energy efficiency of plant, calculated as the ratio between energy output (biomethane high heating value, HHV [MJ/kg], multiplied by the mass flow G_{BM} [kg/h]) and the energy input, comprehensive of the chemical energy of the feedstock (high heating value of the feedstock, HHV [MJ/kg], multiplied by mass flow $G_{feedstock}$ of the biomass [kg/h]) and the electrical consumption of the system.

Eq.4
$$\eta = \frac{G_{BM} * HHV_{BM}}{G_{feedstock} * HHV_{feedstock} + P_{el}}$$

2.2. Environmental Performance Indicators

An attributional LCA was performed in order to provide a comprehensive assessment of the potential environmental impacts and benefits associated with the modeled plants/processes, used to improve the cost effectiveness of technologies for biomethane production.

The adopted functional unit is 1 MJ of biomethane produced. The environmental midpoint indicators preliminarily selected for this study include climate change and primary energy demand from fossils.

The evaluation was conducted at the mid-point (i.e., the emissions into the environment were quantitatively estimated, not the impact at the endpoint). Two Environmental impact categories were evaluated, the primary energy demand (PED) from fossil resources and the total GHG emissions. In order to account for the expected decarbonization of the power sector, the GHG emissions and PED were also evaluated by considering (i) the current Italian electricity production mix, and (ii) a hypothetical future scenario dominated by RES and characterized by a 50% share of wind and 50% of photovoltaics

The applied impact assessment methods were chosen in accordance with the recommendations of the International Life Cycle Data System for the Environmental Footprint Programme. The evaluation

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of environmental impacts was thus conducted using the Environmental Footprint Impact Assessment Method version 3 (EF 3.1) ("European Platform on LCA | EPLCA," n.d.):

- Climate change: radiative forcing as Global Warming Potential – GWP100 (indicator); kg CO_2 eq (unit); source of characterization factors: method EF 3.1;
- Resource use, energy carriers: Abiotic Depletion Potential, fossil fuels - ADP fossils (indicator); MJ (unit); source of characterization factors: method EF 3.1.

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3. FRENCH INNOVATIVE BIOMETHANE DEMONSTRATOR

DEMONSTRATION: In-Situ and Ex-Situ Electro-methanogenesis (EMG): an electrochemical/biochemical route to produce biomethane from CO_2 and renewable electricity

- Production pathway: electrochemical in combination with biochemical
- Inputs: CO_2 + electricity + water

3.1. Brief description of the site

The anaerobic digestion plant of ENGIE is located at Evron, in **Mayenne** region, it produces around 2,300,000 m^3 of CH_4 per year (21 GWh, gas consumption of 5,000 persons). Around 220 $Nm^3\ h^{-1}$ are injected into the natural gas grid. Biogas is produced from 30,000 tons per year of agro-industrial and agricultural residues. The plant has a 9,000 m^3 digestion volume with a hydraulic retention time higher than 50 days. The digestate is valorized through land-spreading (3,000 ha, 21 farms).

3.2. Technology description

Electro-methanogenesis (EMG) is known as a fast-developing process that can **produce biomethane directly from CO_2 and renewable electricity**. The basic principle of this technology is to **boost the anaerobic digestion (AD) microorganism metabolism by applying a voltage on two electrodes**, integrated either directly in the digestate (*in-situ*), or in a system using biogas as an input (*ex-situ*). In both cases**, the electrodes are covered by electroactive biofilms**, capable of exchanging electrons with solid material.

Within the reactor, CO_2 reduction into CH_4 occurs thanks to the microbial biofilm's ability to act as a catalyst for these reduction reactions. Protons (H^+) and CO_2 are thus combined to yield CH_4 and water. In an optimally operating plant, no surplus H_2 is generated, so the theoretical reaction efficiency is higher than that of electrolysis followed by biomethanation.

Two configurations are evaluated:

The first configuration has the **electrodes in the digester (single chamber),** which is then called **a bio-electrochemically-improved anaerobic digester** (**1c-AD-BES**). The electrodes increase the overall biogas production of the AD plant by fostering both oxidative and reductive processes in AD. A 1c-AD-BES is implemented to produce biogas with a biomethane content up to 70-80%.

The second configuration, the classic EMG reactor, has two compartments (**double chamber**) separated by a proton exchange membrane (**2c-AD-BES**). Here, water is split on the anode, and CO_2 is reduced to CH_4 on the microbial cathode under the applied voltage. A 2c-AD-BES can be used for the **biogas upgrading to high-purity biomethane** (>95%) and power-to-gas applications, **by bio electrocatalytically converting the remaining biogas CO_2 share**.

In Figure 2 it is represented a simplified scheme of the modeled process, where it is possible to identify the main component, as pump for digestate and water movement, reactors, compressor and water and hydrogen separator for cleaning and compression of biomethane.

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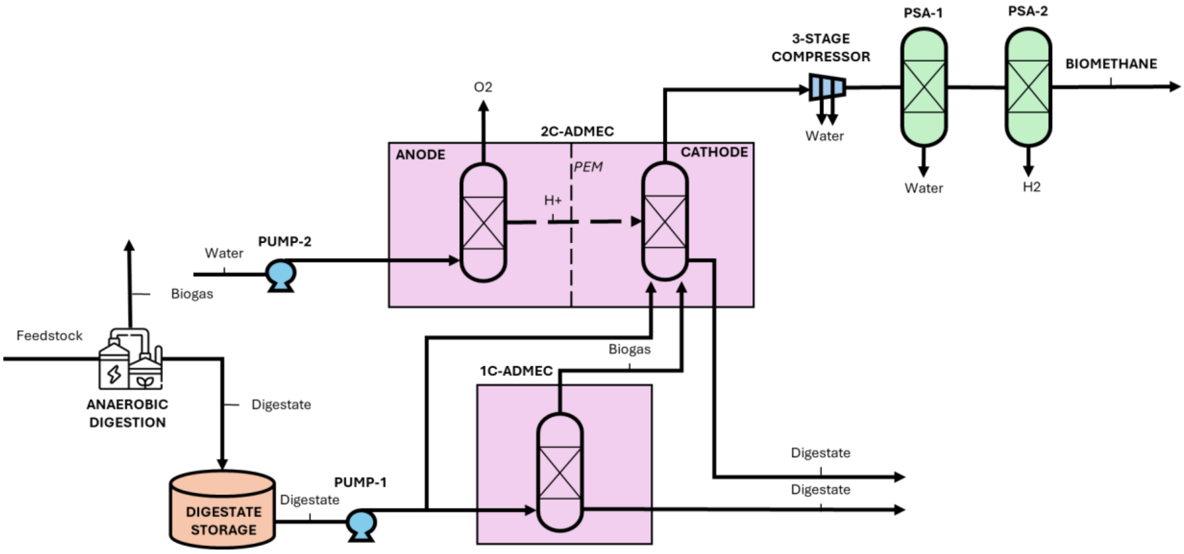

Figure 2 - Process flowchart of EMG technology

3.3. Preliminary flowsheet and assumptions

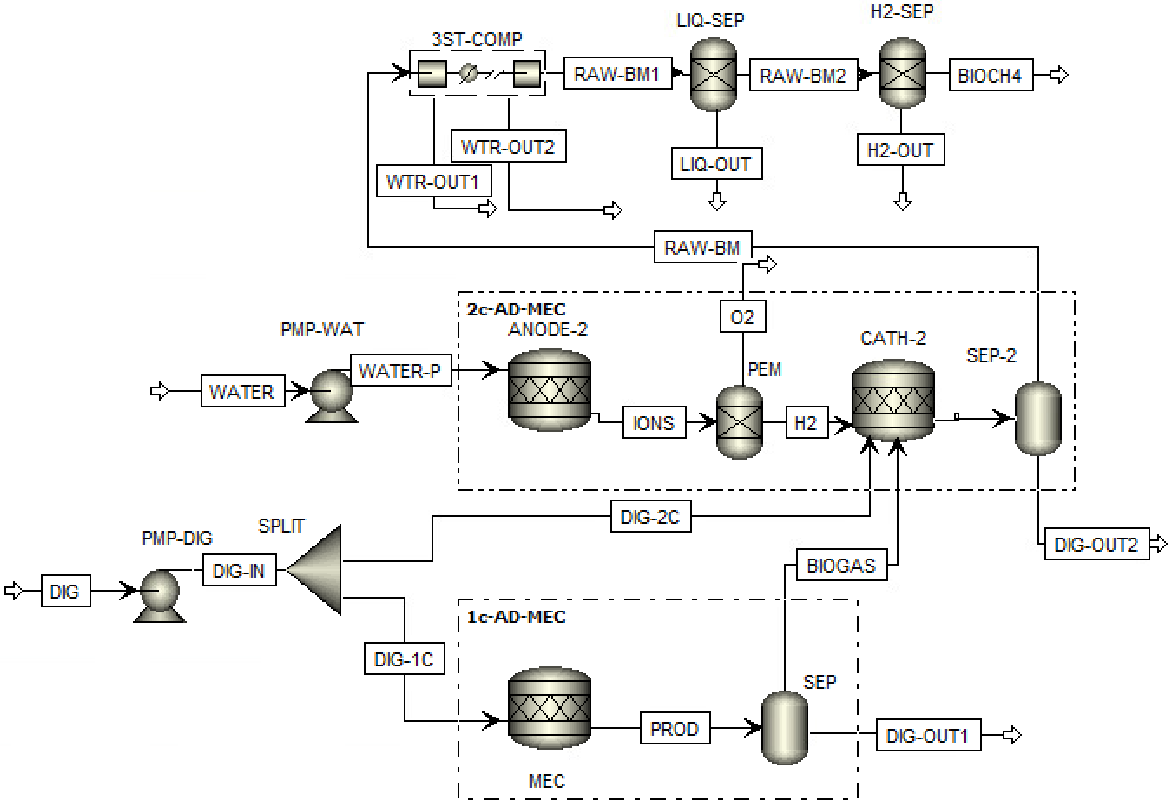

Figure 3 – Preliminary AspenPlus flowsheet of EMG technology

Figure 3 reports the Preliminary flowsheet of EMG pilot plant developed in the AspenPlus®. In this case, the main inlet stream is a digestate (300 l/d, produced by the upstream anaerobic digestor) that is partially (100 l/d) sent to the first electrochemical digester (1c-AD-BES), while the remaining is sent to the second electrochemical digester (2c-AD-BES). The system water consumption has been evaluated considering a stoichiometric ratio with respect to CO_2 content in the biogas stream at the outlet of the first reactor. In the first reactor, the volumetric flow of digestate can produce around

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213 l/d of biogas, enhancing the decomposition of the remaining organic matter contained in the digestate.

As described by the recent literature available (Horváth-Gönczi et al., 2023; "Microbial electrolysis cells for electromethanogenesis: Materials, configurations and operations," n.d.; Nagendranatha Reddy et al., 2022; Zhang et al., 2019), the main reactions occurring in the first reactor are reported in Eq. 5 and Eq. 6. At the anode (Eq. 5) side we have the decomposition of organic matter (acetic acid), and then at the cathode (Eq. 6) the formation of methane (Ao et al., 2024).

Eq. 5 $$CH_3COOH + 2H_2O \rightarrow 4H_2 + 2CO_2$$

Eq. 6 $$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

The biogas is then sent to the cathode (Eq. 7) side of the second reactor, in which CO_2 reacts with H+ produced at the anode (Eq. 8) side through water electrolysis.

Eq. 7 $$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

Eq. 8 $$2H_2O \rightarrow 2H_2 + O_2$$

At the end of the process a cleaning and compression stage for gas grid injection are added. In the next Table 1 and Table 2, the main assumptions are represented.

Table 1 - Composition of digestate

Molecule	Value	Unit
H_2O	98	vol.%
CH_3COOH	2	vol.%

Table 2 - Main assumptions of EMG technology

Parameter	Value	Unit
Temperature of reactors (Del. 3.2)	35	°C
Pressure of reactors (Del. 3.2)	1	bar
Pressure at the outlet of the process (Bai et al., 2009a)	5	bar
Pressure drop at each reactor (Bai et al., 2009a)	2000	Pa
Pump Efficiency (Ferrario et al., 2024a)	0.75	-
Pump mechanical/electrical efficiency (Ferrario et al., 2024a)	0.94	-
Conversion ratio of CH_3COOH in the first reactor	80	%
Conversion ratio of H_2 in the second reactor	90	%

3.4. Mass and energy balance

As results, given the assumptions and the flowsheet described in the previous paragraph, the following mass and energy balance of the main streams are shown in Table 3 and Table 4.

Table 5 reports the main KPIs estimated for the EMG technology.

Table 3 - Mass balance of EMG technology

STREAM	VALUE	UNIT
DIG-1C - Digestate at the inlet of the first reactor	100.0	l/d
H_2O	*98*	*vol.%*

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CH_3COOH	*2*	*vol.%*
WATER - Water at the inlet of the second reactor	0.2	l/d
BIOGAS - Biogas production from the first reactor	213.8	l/d
CH_4	*67*	*vol.%*
CO_2	*33*	*vol.%*
DIG-2C – Digestate at the inlet of the second reactor	200.0	l/d
H_2O	*98*	*vol.%*
CH_3COOH	*2*	*vol.%*
RAW-BM - Biomethane at the outlet of the second reactor	231	l/d
CH_4	*90*	*vol.%*
CO_2	*3*	*vol.%*
H2	*6*	*vol.%*
H2O	*1*	*vol.%*
BIOCH4 - Biomethane after cleaning and compression stage	8.28	l/d
CH_4	*97*	*vol.%*
CO_2	*3*	*vol.%*

Table 4 - Energy balance for EMG technology

Parameter	Value	Unit
Biomethane production	84	kWh
Electricity consumption	230	kWh
Cooling duty	0	kWh
Heat duty	0	kWh

Table 5 - KPIs of EMG technology

Parameter	Value	Unit
Specific electric consumption - en_{el}	2.78	kWh_{el}/kWh_{bm}
Specific consumption of hydrogen - $cons_{H2}$	0	kg_{H2}/ kWh_{bm}
Carbon conversion rate - CR	12	%
Efficiency of plant - η	29	%

As results the EMG technology is characterized by a low plant efficiency and a high specific electric consumption, due to its objective of valorise digestate that otherwise would be wasted. A more comprehensive analysis, including so upstream processes, will be crucial for this technology to evaluate the overall efficiency and profitability.

3.5. Upstream process – AD

As mentioned before, a holistic analysis of the entire biomethane production pathway is crucial to better evaluate pilot performances, and to have an overview about the role this technology may have at industrial scale.

To do so, anaerobic digestion process has been modelled by means of literature data (Giuntoli et al., 2017). In the next table the main assumption utilized are resumed:

Table 6 - Anaerobic Digestion parameter assumption, EMG process

Parameter	Value	Unit
Biogas Yield	15.7	MJ/kg_{VS}
Volatile solids	0.217	kg_{VS}/kg_{total}
Biogas Yield	3.4069	MJ/kg_{total}
Total Solids	0.237	kg_{dry}/kg_{total}
$LHV_{Biowaste}$	20.7	MJ/kg_{dry}
Electricity	0.029	MJ/MJ_{biogas}

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For the upgrading process, instead, the total consumption has been assumed being 3% of the biomethane energy content (Giuntoli et al., 2017).

In the next image, the Sankey diagram of the process:

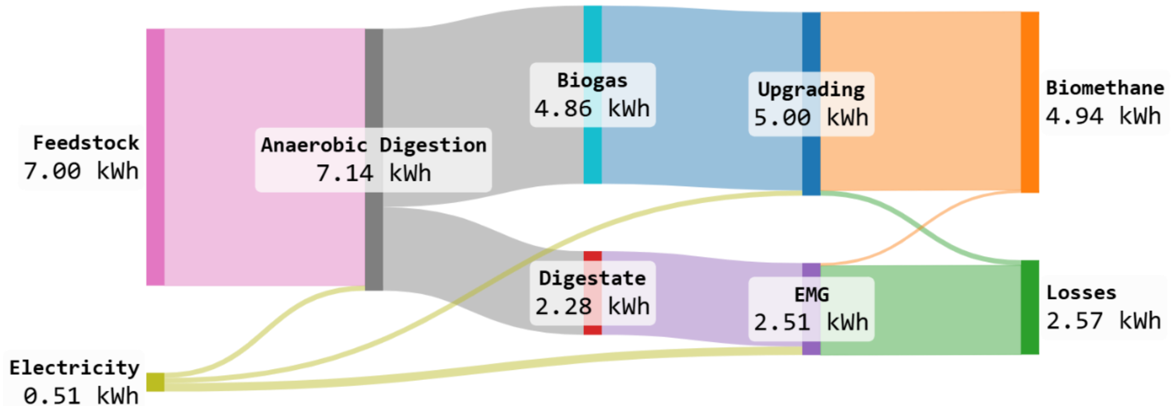

Figure 4 - Sankey diagram of Energy flows, EMG process

It is possible to notice how the losses stream of the entire process accounted in the EMG technology are significant. However, this is due to the feed they are using, digestate, a stream that otherwise would not be valorised for its energy content. While with EMG it is possible to produce an additional amount of biomethane.

3.6. Preliminary environmental impacts

In the next figure, the PED from fossils for the EMG process shows that the impact of biomethane production through this pathway is very low compared to the reference case (fossil NG production). In the case of the current electricity mix, most of the impact is associated with power supply, and this is reduced by more than 90% by shifting to renewable energy resources. On the contrary, impact due to biogas production does not change. In the end, such pathway shows a significant reduction in terms of fossil resource use compared to natural gas.

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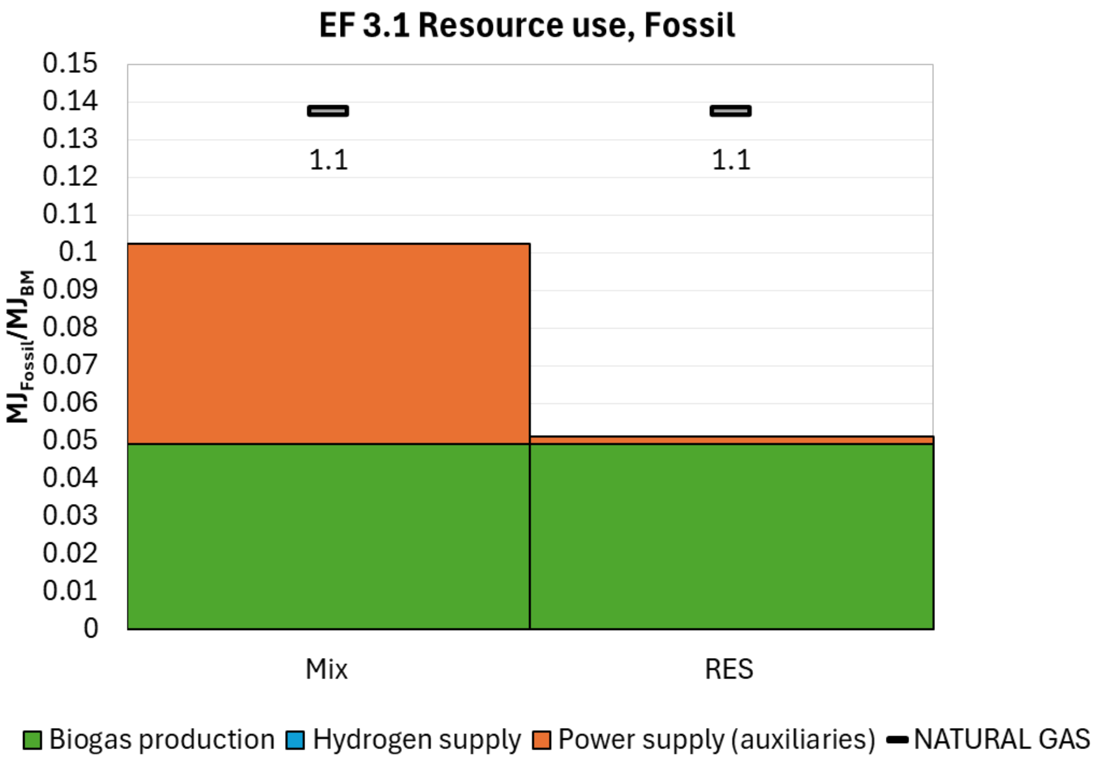

Figure 5 - Primary energy demand, EMG process (current energy mix – Mix, RES energy mix – RES)

Impacts on GHG emissions exhibit a similar pattern to that of the PED from fossils, indicating that power supply strongly affects the results. This pathway shows stronger reduction in terms of GHG emissions with respect to fossil natural gas.

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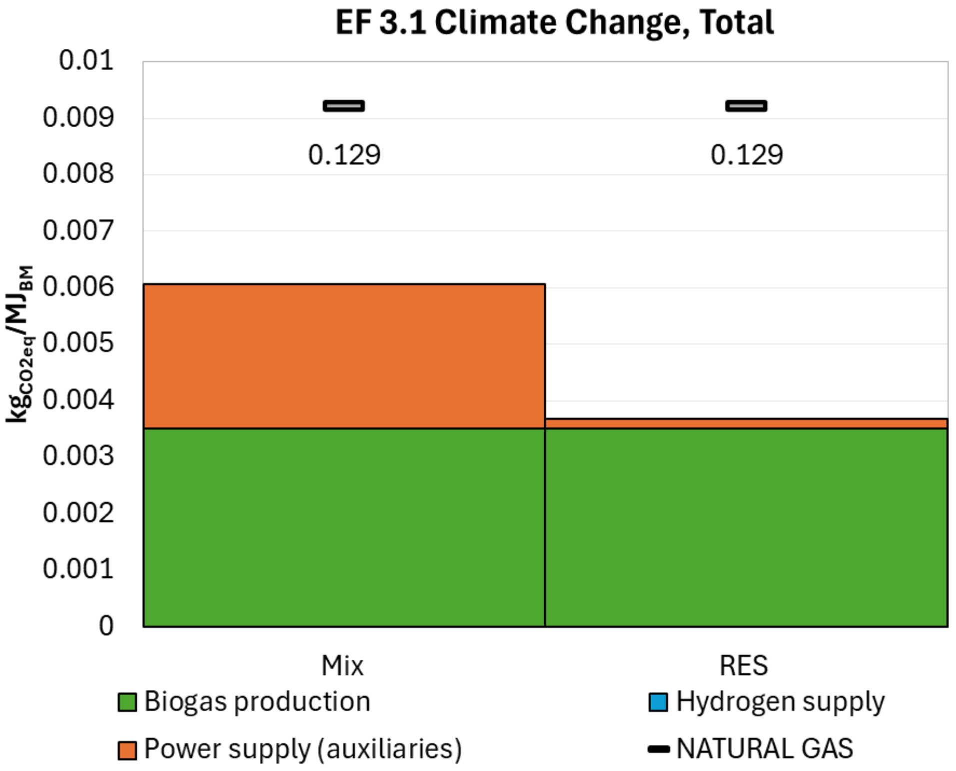

Figure 6 - GHG emissions, EMG process (current energy mix – Mix, RES energy mix – RES)

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4. GREEK INNOVATIVE BIOMETHANE DEMONSTRATOR

DEMONSTRATION: Ex-Situ - Thermochemical/catalytic Methanation (ETM)

- Production pathways: thermochemical
- Inputs: Biogas + hydrogen

4.1. Brief description of the site

The Biogas Lagadas S.A. (BLAG) plant is located in **Kolchiko – Lagadas,** in **Central Macedonia Region**. The BLAG plant exploits around 70,000 tonnes of livestock and agro-industrial waste per year, yielding 8,400 MWh of electricity and 70,000 tonnes of organic soil improver suitable for fertilizing 2,000 ha of agricultural land. The plant has a capacity of 290 Nm^3 CH_4/h^{-1}. The BLAG's biogas plant has 2 fermenters with 4,500 m^3 active volume for biomass (each one) and 10,000 m^3 of biogas buffer capacity. The total flow is 500 Nm^3h^{-1} at 100 mbar. The CHP generator produces 1MW_e.

4.2. Technology description

The technology concerns the conversion of CO_2 contained in the biogas to biomethane, through its reaction with renewable hydrogen in a catalytic reactor.

$$CO_2 + 4H_2 \xrightarrow{catalyic\ reaction} CH_4 + 2H_2O$$

The catalytic reactor can handle a mixture of methane and carbon dioxide (raw biogas); thus, **no separation of the biogas is required before conversion**. The reaction takes place at high pressure and temperature.

The individual stages of the whole process include:

- A cleaning and compressing step of the biogas,
- catalytic methanation reaction,
- processing of the final biomethane stream.

The final product is biomethane that already meets pipeline quality gas standards (e.g., 96-98 vol.% CH_4).

In Figure 7 it is represented a simplified scheme of the modeled process, where it is possible to identify the main component, as compressor for biogas movement, thermochemical reactors, condenser and heat exchanger for start-up of the plant, as well water and hydrogen separator for cleaning and compression of biomethane.

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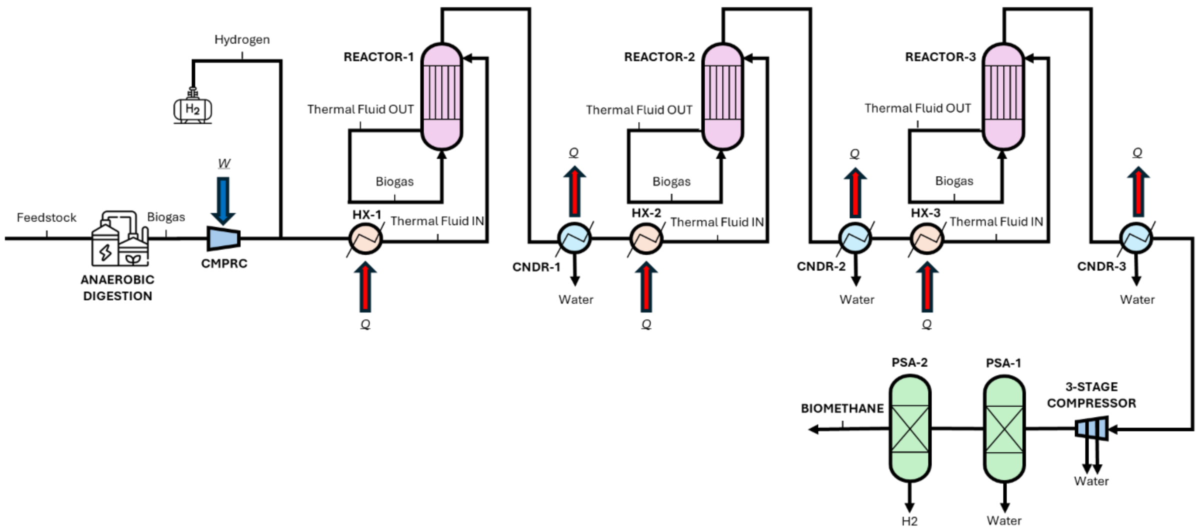

Figure 7 - Process flowchart of Ex-situ Thermochemical/catalytic Methanation (ETM) technology

4.3. Preliminary flowsheet and assumptions

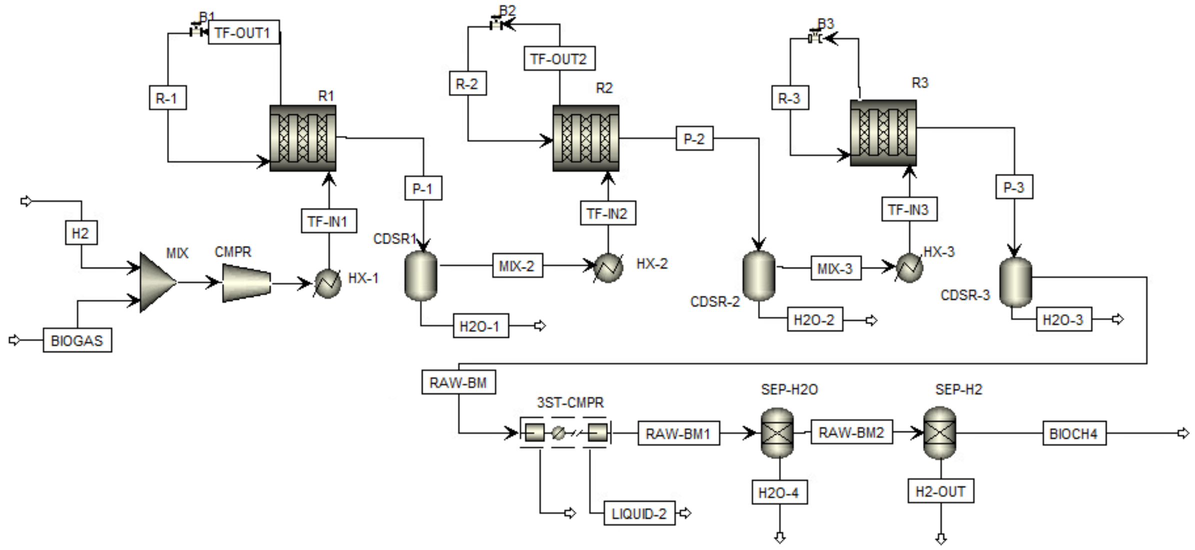

Figure 8 - Preliminary AspenPlus flowsheeting of Ex-situ Thermochemical/catalytic Methanation (ETM) technology

Preliminary flowsheet of Ex-situ Thermochemical Methanation (ETM) technology has been simulated in AspenPlus software starting from the biogas stream and hydrogen input in stoichiometric ratio with respect to CO_2 content in the biogas stream. Three reactors are modeled following the input from demo leader described in Deliverable D2.2 concerning dimension and catalyst loading. At the end of the process a cleaning and compression stage are added for gas grid injection. In the next Table 7 and Table 8, the main assumptions are listed.

Table 7 - Biogas composition

Molecule	Value	Unit
CH_4	60	vol.%
CO_2	40	vol.%

Table 8 - Main assumptions of ETM technology

Parameter	Value	Unit
Temperature at the inlet of reactor 3 (Del 3.2)	250	°C
Pressure at the outlet of the process(Bai et al., 2009a)	5	bar

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Operative pressure (Del 3.2)	10	bar
Pressure at the outlet of the process (Bai et al., 2009a)	10	bar
Pressure drop at each reactor (Bai et al., 2009a)	2000	Pa
Compressor Efficiency (Ferrario et al., 2024a)	0.75	-
Compressor mechanical/electrical efficiency (Ferrario et al., 2024a)	0.94	-

4.3.1. Reactor modelling

The methanation process occurring in the three catalytic reactors follows the well-known Sabatier reaction (Eq. 9).

Eq.9 $$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

The three reactors have been modeled with an RPLUG Aspen block, implementing a suitable kinetic that is able to fit experimental data obtained from a lab-scale experimental campaign reported in Deliverable D2.2. Different kinetics are proposed for CO_2 methanation in the literature. In this report, the formulation proposed by Falbo et al. (Falbo et al., 2018) was considered. Falbo et al. report a comparison of the CO_2 conversion rate (X_{CO2}) obtained experimentally in a lab-scale reactor (with a length of 2.49 cm and a diameter of 10mm) with methanation of a pure CO_2 stream and the ones obtained through modeling in Aspen Plus.

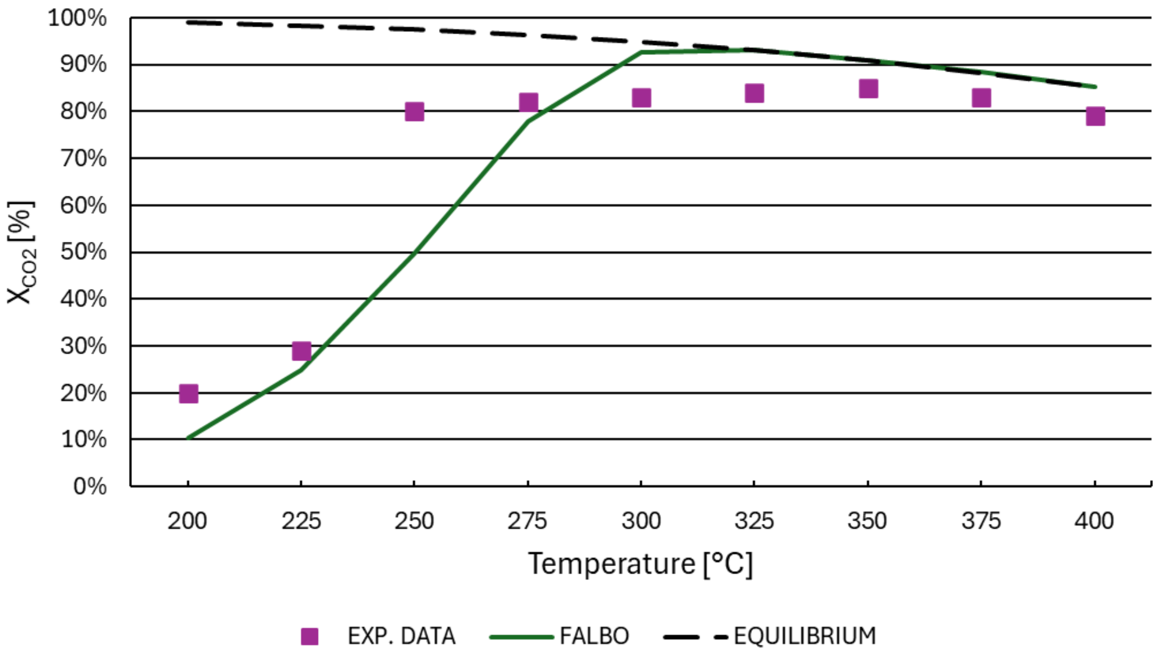

Figure 9- Kinetic comparison with experimental data

In this way it is possible to obtain a temperature profile inside the reactor (Figure 10 - Temperature profile of the biogas stream inside the three reactors, Figure 10), allowing further discussion strategies for reactor cooling.

As it is possible to notice the first reactor is the most critical one in terms of temperature peak, as it reaches almost 650 °C. A proper cooling strategy would be fundamental to reduce such temperature. The second and third reactors have smaller temperature peaks, since part of the reaction has already taken place in the first reactor.

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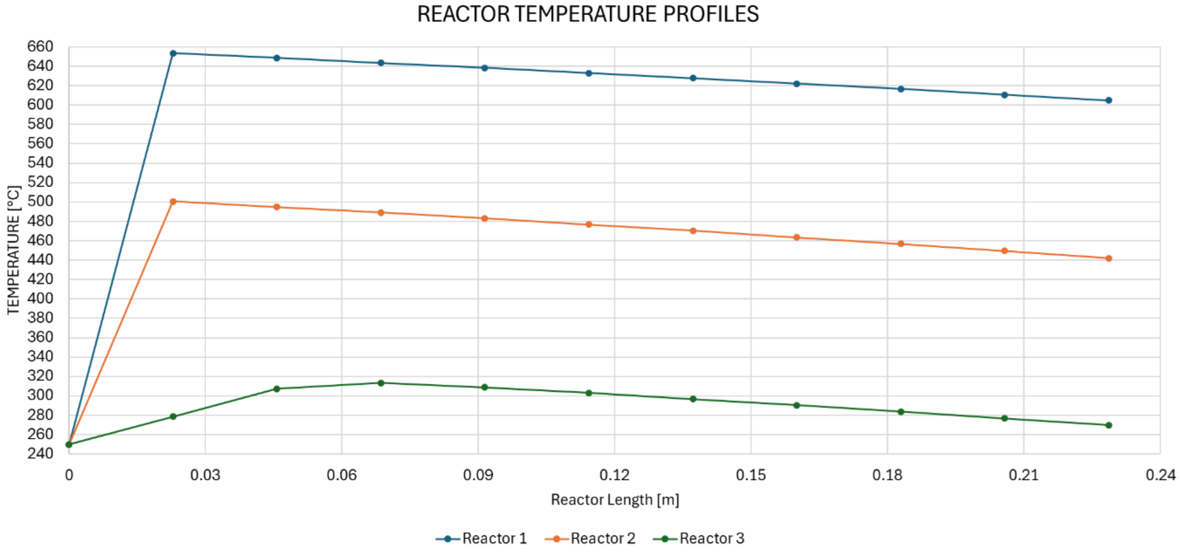

Figure 10 - Temperature profile of the biogas stream inside the three reactors,

Table 9 - Thermal fluid temperature at the inlet and outlet of each reactor

STREAM	VALUE	UNIT
Reactor – 1		
Thermal Fluid IN	40.69	°C
Thermal Fluid Out	182.45	°C
MAX-T	653.6	°C
Reactor – 2		
Thermal Fluid IN	40.0	°C
Thermal Fluid Out	169.35	°C
MAX-T	500.75	°C
Reactor – 3		
Thermal Fluid IN	40	°C
Thermal Fluid Out	123.61	°C
MAX-T	313.24	°C

4.4. Mass and energy balance

As results, given the assumptions and the flowsheet described in the previous paragraph, the following mass and energy balance of the main stream are expressed in the next Table 10 and Table 11.

Then, the visualization of the main KPIs for the ETM technology follows in Table 12.

Table 10 - Mass balance for ETM technology

STREAM	VALUE	UNIT
BIOGAS – Biogas flowrate at the inlet of the process	6.0	m^3/h
CH_4	*60.0*	*vol.%*
CO_2	*40.0*	*vol.%*
H2 – Hydrogen flowrate at the inlet of the process	9.6	m^3/h
BIOCH4 – Biomethane flowrate after compression and cleaning	*0.4*	m^3/h

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CH_4	98.2	vol.%
CO_2	1.8	vol.%

Table 11 - Energy balance for ETM technology

Parameter	Value	Unit
Biomethane production	59.96	kWh
Electricity consumption	0.7	kWh
Heat duty	1.3	kWh
Cooling duty	9.5	kWh

Table 12 - KPIs of ETM technology

Parameter	Value	Unit
Specific electric consumption - en_{el}	0.010	kWh_{el}/kWh_{bm}
Specific consumption of hydrogen - $cons_{H2}$	0.013	kg_{H2}/ kWh_{bm}
Carbon conversion rate - CR	99.0	%
Efficiency of plant - η	92.5	%

As results the ETM technology is characterized by a plant efficiency of about 92.5% and a hydrogen consumption of 0.013 kg_{H2}/ kWh_{bm}.

4.5. Upstream process – AD and Electrolysis

As mentioned before, a holistic analysis of the entire biomethane production pathway is crucial to better evaluate pilot performances, and to have an overview about the role this technology may have on an industrial scale.

To do so, anaerobic digestion process and electrolysis have been modelled by means of literature data (Giuntoli et al., 2017). In the next table the main assumption utilized are resumed:

Table 13 - Anaerobic Digestion and Electrolyzer parameter assumptions, ETM process

PARAMETER	VALUE	UNIT OF MEASURE
ANAEROBIC DIGESTION		
Biogas Yield	15.7	MJ/kg_{VS}
Volatile solids	0.217	kg_{VS}/kg_{total}
Biogas Yield	3.4069	MJ/kg_{total}
Total Solids	0.237	kg_{dry}/kg_{total}
$LHV_{Biowaste}$	20.7	MJ/kg_{dry}
Electricity	0.029	MJ/MJ_{biogas}
PEM ELECTROLYZER		
Faraday Efficiency	96	%
Voltage Efficiency	73	%
Current Density	1.8	A/cm^2

In the next image, the Sankey diagram of the process:

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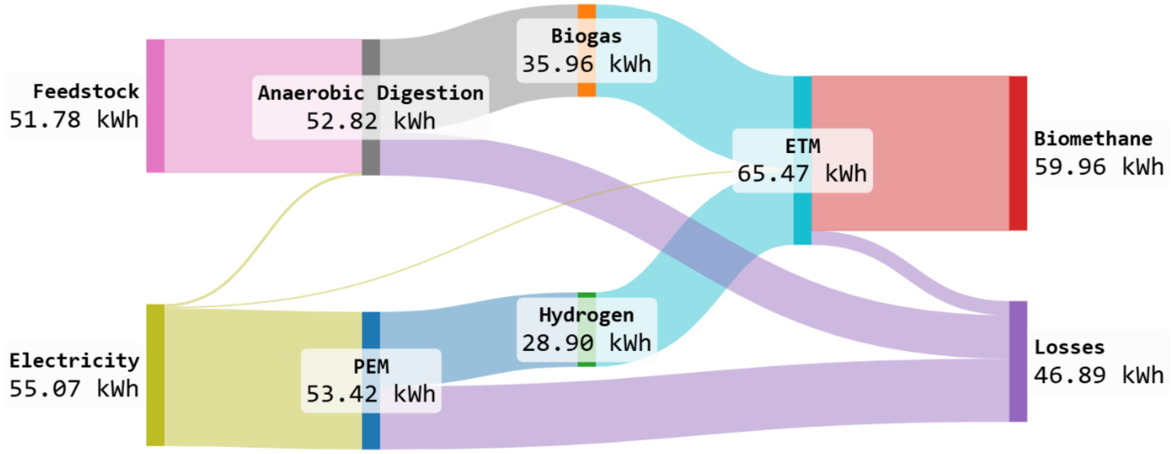

Figure 11 - Sankey diagram of energy flows, ETM process

In the biomethane production pathway of the ETM process, most of the losses are due to the electrolysis for hydrogen production, while the single ETM process has high efficiency.

4.6. Preliminary environmental impacts

Regarding fossil resource use in the ETM pathway, the high electricity consumption of the electrolyzer makes the process more impactful than the use of natural gas. Conversely, shifting toward renewable energy sources results in a significant reduction in impacts, bringing them closer to those associated with natural gas. However, electrolysis continues to account for the majority of energy consumption in the process.

Concerning climate change impacts, GHG emissions are very low whether an electricity mix or renewable energies are used. Clearly, utilizing renewable energy sources can reduce GHG emissions by an order of magnitude.

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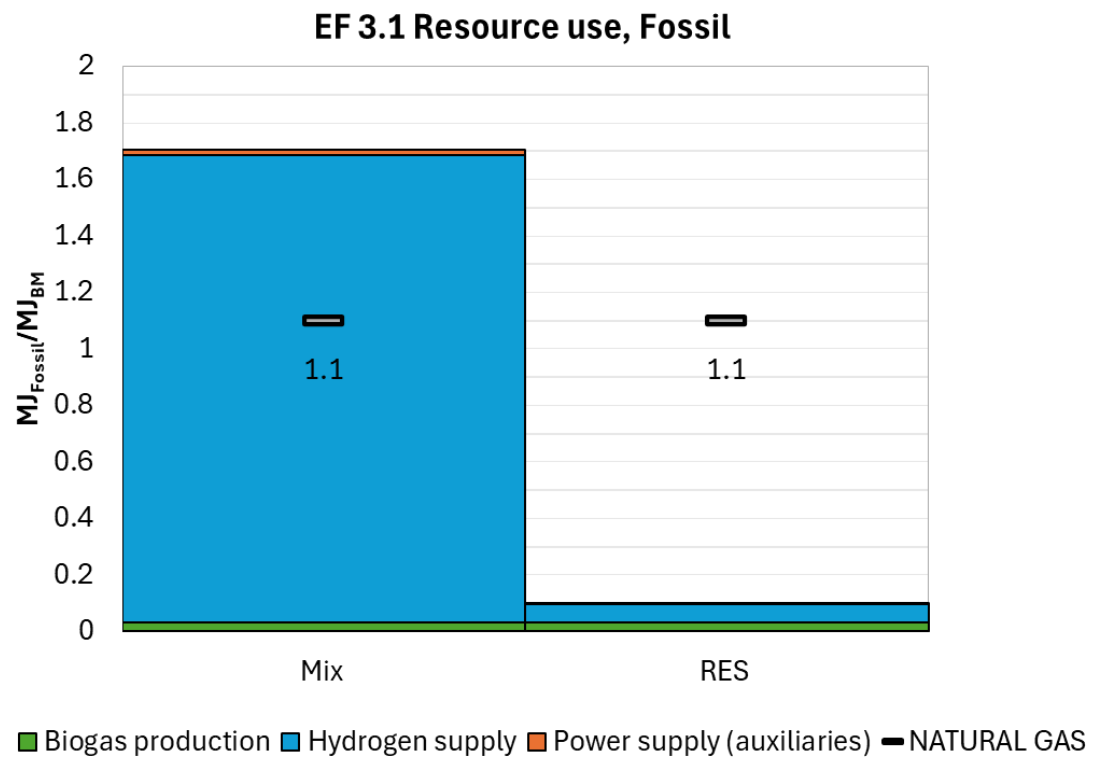

Figure 12 - Primary energy demand, ETM process

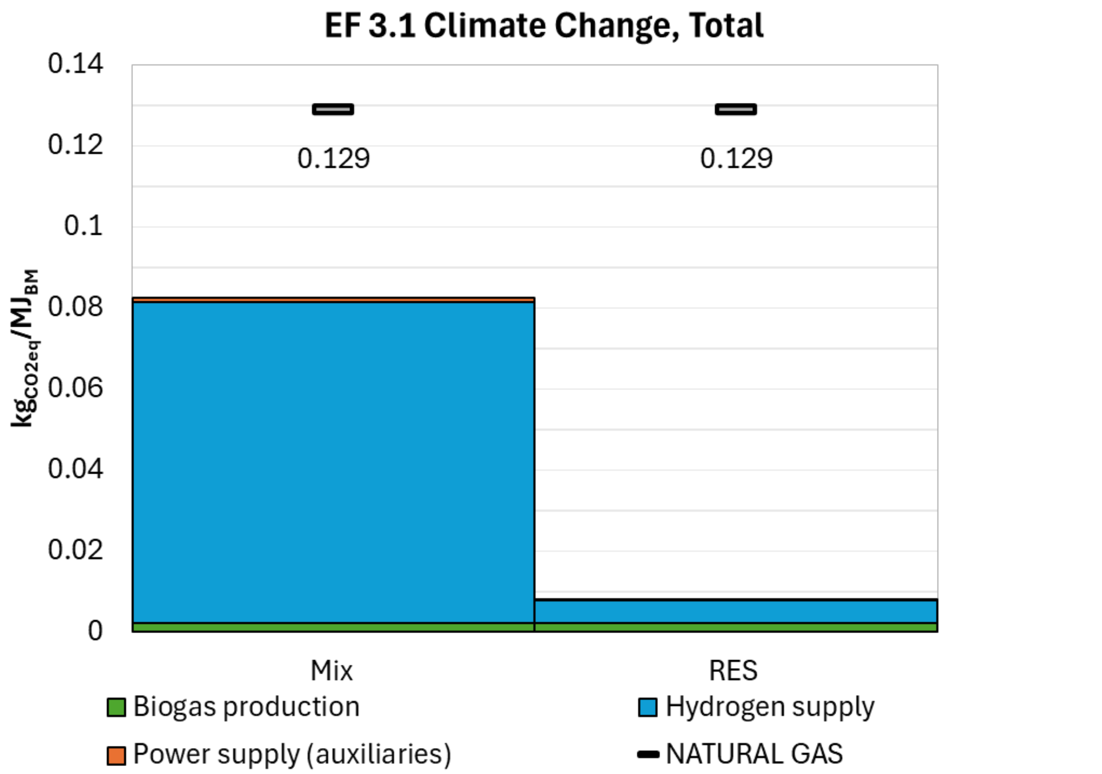

Figure 13 - GHG emissions, ETM process

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5. ITALIAN INNOVATIVE BIOMETHANE DEMONSTRATOR

DEMONSTRATION: Ex Situ Biological Methanation (EBM)

- Production pathway: biological
- Input: CO_2 +hydrogen

5.1. Brief description of the site

Gruppo CAP, as integrated water service manager for the Metropolitan City of Milan area **(Lombardy Region)** operates 40 wastewater treatment plants of different sizes and capacities over a 1,500 km^2 area. Among those, anaerobic digestion is already widely implemented as a technology to reduce sewage sludge and produce biogas for local energy production. The demo site is situated at one specific WWTP (Bresso-Niguarda), located within the **Municipality of Milan** in the neighborhood of Niguarda. Biogas produced via sewage sludge AD is already converted into biomethane via physical upgrading and sent to the natural gas distribution grid. Considering that Bresso-Niguarda WWTP has a treatment capacity of about 300,000 people equivalent, corresponding to 2,200 m^3/h of inflow from sewer, it currently produces about 90 m^3/h of biomethane.

5.2. Technology description

CAP, in collaboration with partners Politecnico di Milano, SIAD and CIC, will implement an **integrated demo plant, to achieve a more sustainable biomethane production, in a holistic approach that includes biogas upgrade side by side with several approaches to increase biogas production**.

The demonstration plant will be implemented to one of the 2 parallel AD lines, the second one will be kept as such to have a direct comparison of the overall biomethane yield improvement and production cost reduction achievable by applying the integrated technologies. It will be **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 carbon dioxide in methane and boost the 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 **reducing the digestate to be disposed of**. In the scientific literature, several experiences are reporting the application of this technology on a laboratory and pilot scale. These experiences generally describe significantly positive effects on anaerobic digestion. However, pilot-scale experiments are extremely rare. **Biological ex-situ upgrade operates at mild conditions and represents a promising and rapidly evolving technology**, in terms of reactor configurations and process volumetric intensity. Key aspects are the **gas transfer efficiency** and the **dynamic response to variable and even null H_2 load**. The *ex-situ* upgrade prototype will run biological hydrogenotrophic conversion of biogas to biomethane by Archaea present as suspended biomass and as biofilm, the latter attached on hollow fibers tubular gas transfer membranes.

In this innovative configuration, H_2 and biogas are supplied by two devices: to the biofilm by diffusion through the lumen of the membrane and, to the suspended biomass, by gas sparging. This configuration combines the scheme of a previously tested *ex-situ* reactor (V = 500 l) with the gas transfer membrane biofilm reactor, a technology already known and applied at full scale in other sectors.

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In Figure 14 and Figure 15 there are represented two simplified scheme of the modeled process, where it is possible to identify the main component, as pump for feedstock movement, reactors, compressor and water and hydrogen separator for cleaning and compression of biomethane. At this stage it is possible to identify different alternatives, indeed ozonolysis could be used as pre-treatment of the fresh sludge or as post-treatment of the digestate. As well the oxygen could be provided from external supply or as co-product of the hydrogen electrolyzer.

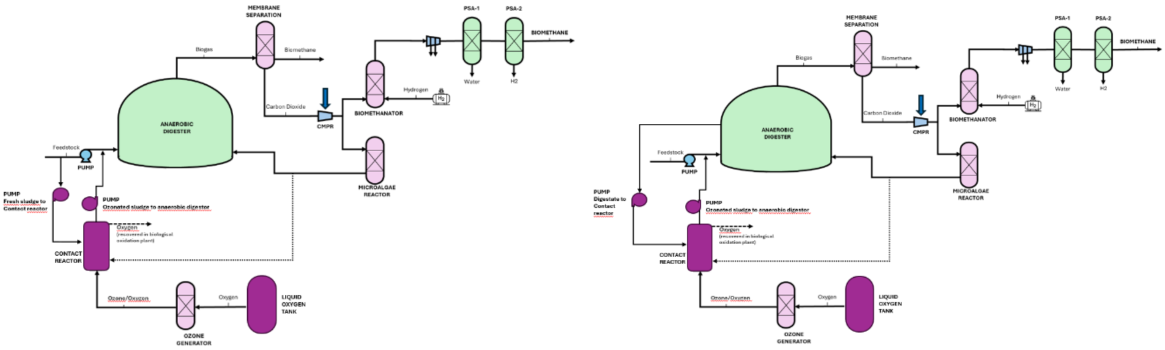

Figure 14 - Process flowchart of Ex-situ Biological Methanation (EBM) technology. Ozonolysis applied as pre-treatment of fresh sludge or as post-treatment of digestate. Co-digestion of microalgae as such or after ozonation. H_2 from electrolyzer, O_2 from external supply.

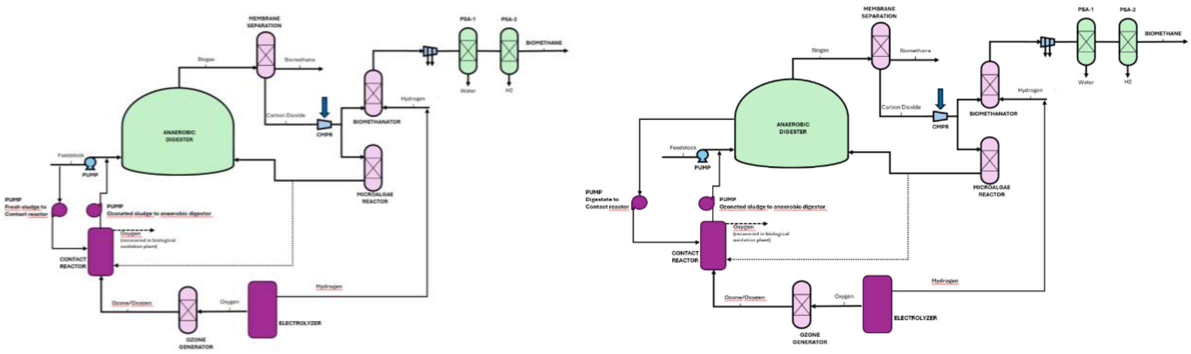

Figure 15 - Process flowchart of Ex-situ Biological Methanation (EBM) technology. Ozonolysis applied as pre-treatment of fresh sludge or as post-treatment of digestate. Co-digestion of microalgae as such or after ozonation. H_2 and O_2 from electrolyzer.

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5.3. Preliminary flowsheet and assumptions

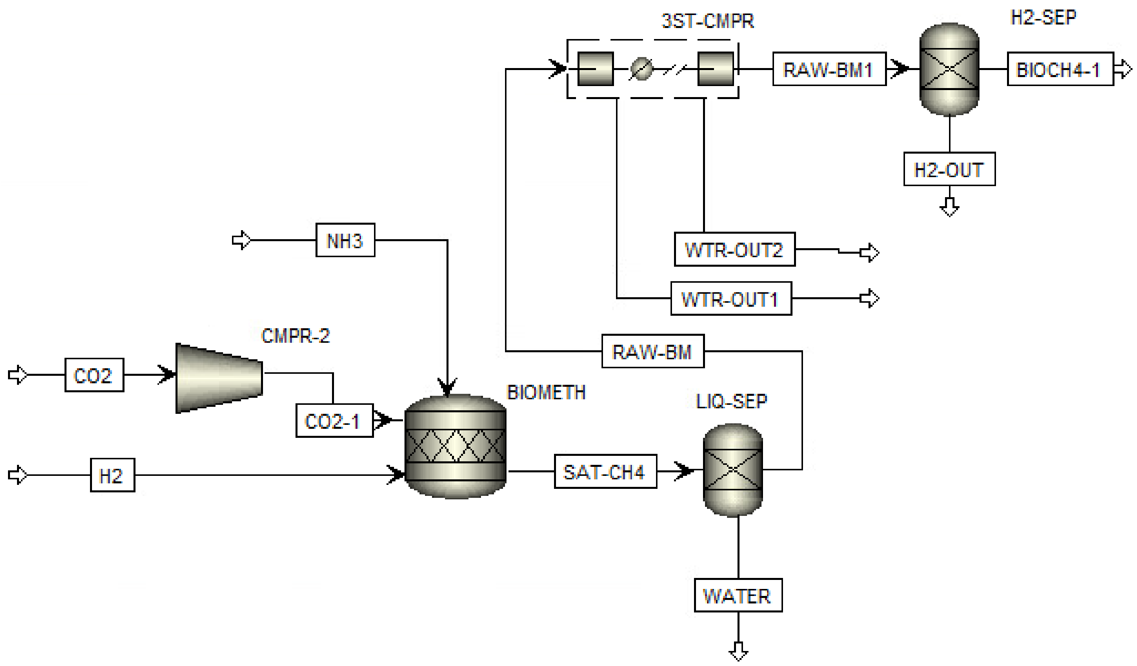

Figure 16 - Preliminary AspenPlus flowsheeting of Ex-situ Biological Methanation (EBM) technology

The preliminary flowsheet of EBM technology comprehends the biomethanator reactor modeled with a stoichiometric block in AspenPlus. The inlet flow of hydrogen and carbon dioxide is obtained from demo leader data shared in the Deliverable D2.2. The main reaction in the reactor follows the Sabatier reaction in a biological form, also called Hydrogenotrophic Methanogenesis (Eq. 10) (Dionisi, 2017a).

Eq.10 $$H_2 + aCO_2 + bNH_3 \rightarrow cC_5H_7O_2N + dCH_4 + e2H_2O$$

Where $C_5H_7O_2N$ are the microorganism produced during the process.

Further study will be conducted to obtain a more comprehensive overview of the plant, including secondary activities such as ozone generation. At the end of the process, a compression and cleaning stage is added for gas grid injection purposes. In Table 14 and Table 15, the main assumptions are reported.

Table 14 - Volumetric flowrates of reactants Del 3.2

Stream	Value	Unit
H_2	107	Nl/h
CO_2	25	Nl/h

Table 15 - Main assumptions of EBM technology

Parameter	Value	Unit
Temperature of reactors (Del 3.2)	45	°C
Pressure of reactors (del 3.2)	1	bar
Pressure at the outlet of the process (Bai et al., 2009a)	5	bar
Pressure drop at each reactor (Bai et al., 2009a)	2000	Pa
Compressor Efficiency (Ferrario et al., 2024a)	0.75	-
Compressor mechanical/electrical efficiency (Ferrario et al., 2024a)	0.94	-

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Conversion ratio of H2	95.1	%

5.4. Mass and energy balance

As results, given the assumptions and the flowsheet described in the previous paragraph, the following mass and energy balance of the main stream are expressed in Table 16 and Table 17.

Then, the visualization of the main KPIs for the EBM technology follows in Table 18.

Table 16 - Mass balance for EBM technology

STREAM	VALUE	UNIT
H_2 – Hydrogen at the inlet of the reactor	107	Nl/h
CO_2 – Carbon dioxide at the inlet of the reactor	*25*	*Nl/h*
bioCH_4 – Biomethane at the outlet of the process after cleaning and compression	*21.0*	*l/h*
CH_4	*98.5*	*vol.%*
CO_2	*1.5*	*vol.%*

Table 17 - Energy balance for EBM technology

Parameter	Value	UNIT
Biomethane production	187	kWh
Electricity consumption	2.0	kWh
Heat duty	0.0	kWh
Cooling duty	55.0	kWh

Table 18 - KPIs of EBM technology

Parameter	Value	UNIT
Specific electric consumption - en_{el}	0.010	kWh_{el}/kWh_{bm}
Specific consumption of hydrogen - $cons_{H2}$	0.033	kg_{H2}/ kWh_{bm}
Carbon conversion rate - CR	97.0	%
Efficiency of plant - η	76.0	%

As results the EBM technology is characterized by a plant efficiency of about 76% and a hydrogen consumption of 0.033 kg_{H2}/ kWh_{bm}.

5.5. Upstream process – AD, Ozonolysis and Electrolysis

As mentioned before, a holistic analysis of the entire biomethane production pathway is crucial to better evaluate pilot performances, and to have an overview about the role this technology may have at industrial scale.

To do so, anaerobic digestion process has been modelled with the ozonolysis process, part of the Biomethaverse project. Data obtained in Deliverable 2.2 is used to model the ozonolysis and Anaerobic digestion of the wastewater treatment plant. Electrolysis has been modelled by means of literature data (Hassan et al., 2022). In the next table the main assumption utilized are resumed:

Table 19 - Anaerobic digestion, ozonolysis and electrolyzer parameter assumptions, EBM process

PARAMETER	VALUE	UNIT OF MEASURE
	ANAEROBIC DIGESTION and OZONOLYSIS	
$LHV_{Feedstock}$	20.7	MJ/kg_{dry}
Electricity	0.029	MJ/MJ_{biogas}
Biogas Potential	207	NL_{BG}/kg_{VS}
VS/TS	0.59	kg/kg

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Ozone Dosage	56	g_{O3}/kg_{VS}
BMP	124	NL_{CH4}/kg_{VS}
Ozonator consumption [ref]	8	kWh/kg_{O3}
PEM ELECTROLYZER		
Faraday Efficiency	96	%
Voltage Efficiency	73	%
Current Density	1.8	A/cm^2

In the next image, the Sankey diagram of the process:

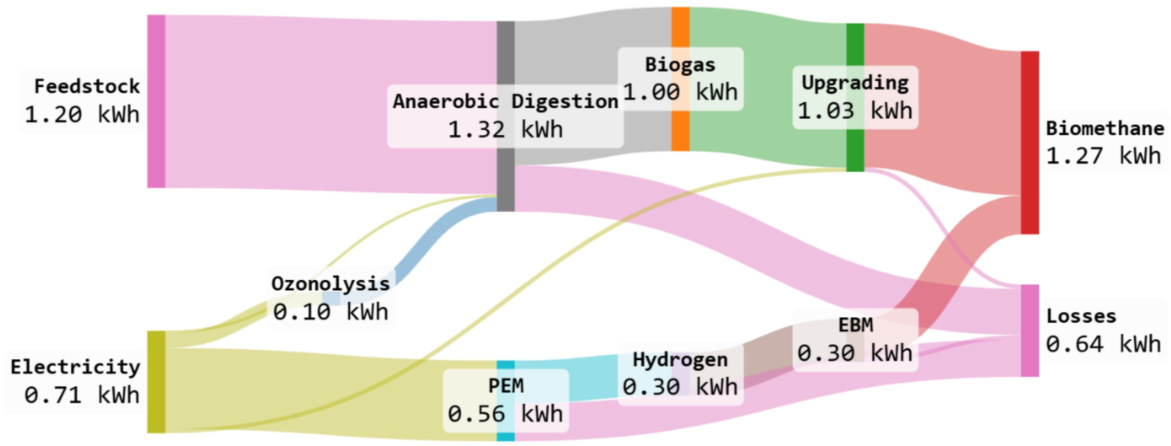

Figure 17 - Sankey diagram of energy flows, EBM process

Still, the PEM Electrolyser accounts for half of the losses of the entire production processes, however there is an increase in biogas production due to ozonolysis, and an additional 25% of biomethane produced through In-Situ Biomethanation, by valorizing CO_2 stream separated from the biogas.

5.6. Preliminary environmental impacts

Regarding the use of fossil resources in the Italian biomethane production pathway, power supply for auxiliaries (including ozonolysis) accounts for a significant portion of the resources consumed. Nonetheless, the electrolyzer remains the most impactful component. In this process, even using electricity from the grid results in slightly lower fossil resource usage compared to natural gas. A shift toward renewable energy sources markedly reduces these impacts.

In terms of climate change impact, similar patterns are observed: the electrolysis process contributes most to GHG emissions, followed by power supply. Moving to renewables greatly reduces GHG emissions associated with these two stages, while emissions from biogas production remain constant. Overall, even using grid electricity can result in lower GHG emissions than those associated with fossil natural gas.

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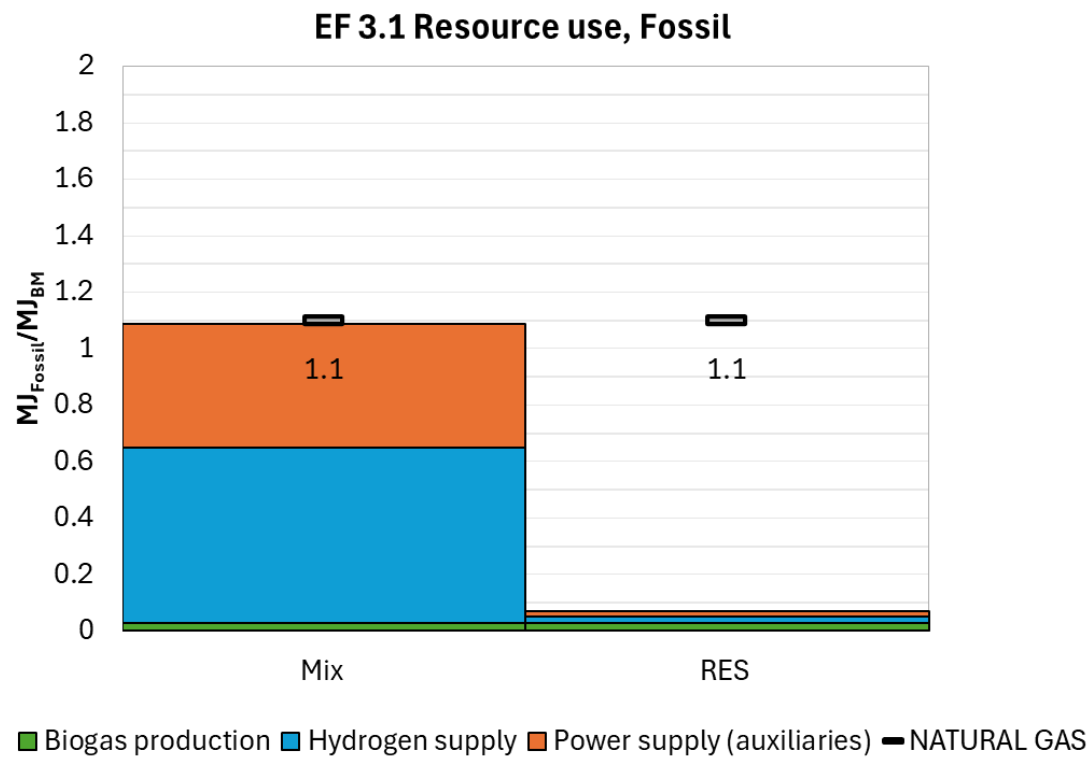

Figure 18 - Primary energy demand, EBM process

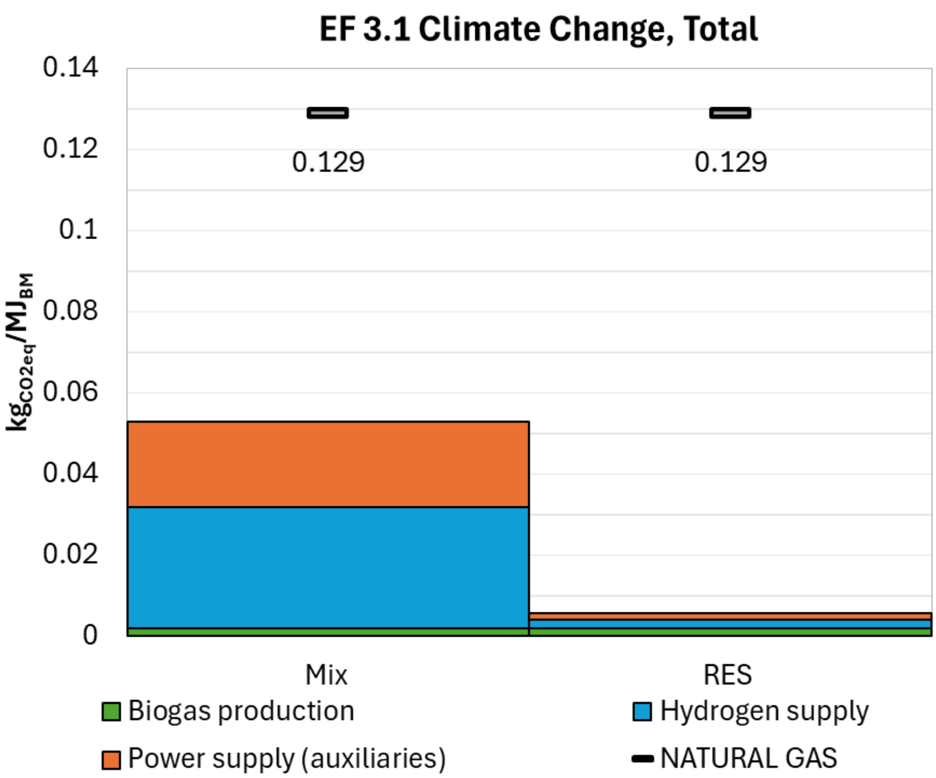

Figure 19 - GHG emissions, EBM process

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6. SWEDISH INNOVATIVE BIOMETHANE DEMONSTRATOR

DEMONSTRATION: 6.1. Ex-Situ Syngas Biological methanation (ESB)

- Production pathway: biological
- Input: syngas (+hydrogen)

6.1. Brief description of the site

The demonstration site is an existing 6 MW gasification plant owned by the company CORTUS. The plant is situated in Höganäs, Region of Götaland. The gasification technology employed is referred to as the WoodRoll® process. This involves drying, pyrolysis and gasification stages to convert raw biomass to synthesis gas (mixture of $CO + H_2$) in CO/H_2 ratio of approximately 1:2. Additionally, the gas contains CO_2 (13-14%) and some CH_4 (1-2%). Current feedstock is wood chips with 40% moisture. However, the plant could run on fuel with up to 45% moisture without pre-drying which enables conversion of woody waste products such as logging residues or municipal yard-trimmings. The produced syngas is used as a green energy input for steel powder manufacturing by an adjacent

6.2. Technology description

The specific type of biological methanation intended for demonstration in this case converts syngas (CO, H_2, CO_2 and some CH_4) from thermal gasification and/or pyrolysis via biological methanation to biomethane in a Trickle Bed Reactor (TBR). This reactor is fed by syngas and a nutrient solution which can be in the form of digestate from a co-located conventional biogas plant or reject water from municipal wastewater sludge dewatering.

The syngas meets a selectively adapted mixed culture biofilm on carriers and a continuous flow of nutrient rich solution. CO and H_2 are consequently converted to CH_4 and CO_2. The TBR design allows for a high exchange rate between the gas and liquid phase. If it is desirable to also utilize the remaining CO_2 and produce a final gas mix of very high CH_4 content, an additional source of H_2 from an electrolyser can be added to the input syngas.

This reaction between the additional H_2 and CO_2 would happen in the same TBR facilitated by the same mix culture biofilm, resulting in higher utilization of invested CAPEX and the elimination of a conventional upgrading step. The demonstration plant will be equipped with a small electrolyser able to provide external H_2 volumes from renewable electricity to achieve stochiometric balance for conversion of all CO_2 to methane.

The planned trials will demonstrate biological methanation of syngas both without and with addition of external H_2.

In Figure 20 it is represented a simplified scheme of the modeled process, where it is possible to identify the main component, as compressor for syngas movement, reactors, compressor and water and hydrogen separator for cleaning and compression of biomethane

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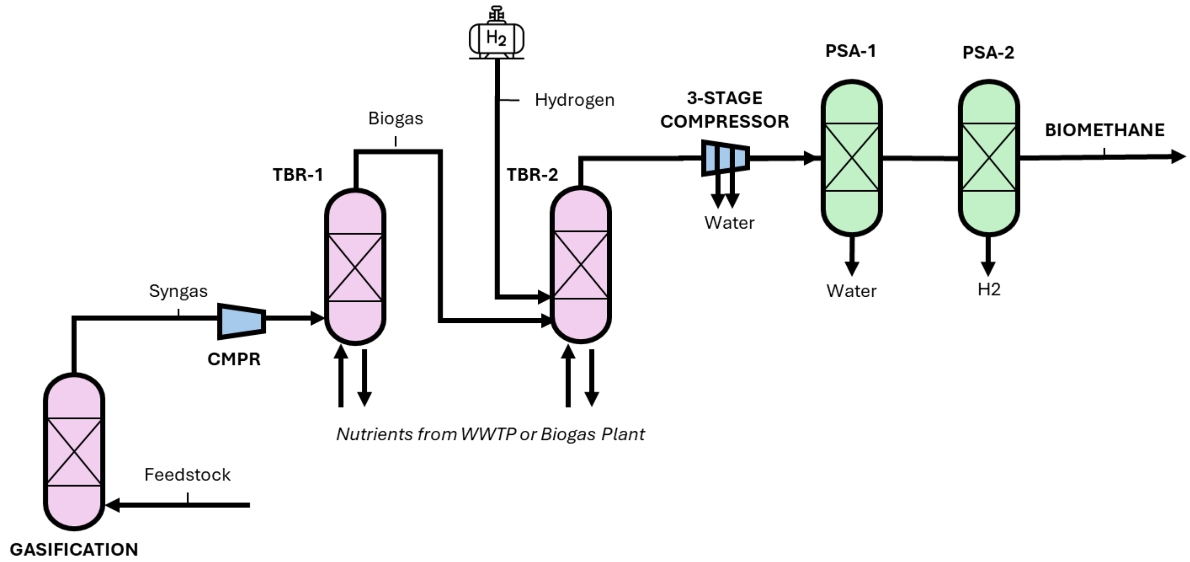

Figure 20 - Process flowchart of Ex-situ Syngas Biomethanation (ESB) technology

6.3. Preliminary flowsheet and assumptions

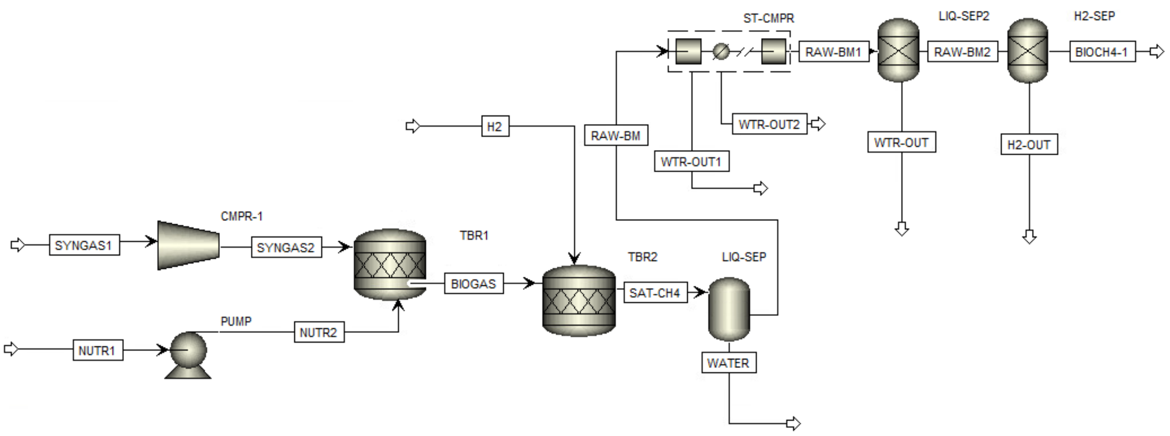

Figure 21 - Preliminary AspenPlus flowsheeting of Ex-situ Syngas Biomethanation (ESB) technology

ESB technology differentiates from the other due to the utilization of syngas in which an amount of hydrogen is already present. Composition of syngas is obtained from data shared in Deliverable D2.2 from demo leader, while hydrogen consumption is evaluated on stoichiometric ratio of CO_2 content in the stream at the outlet of the first reactor (TBR-1). To obtain biogas at the outlet of the TBR-1 the following reactions are assumed (Dionisi, 2017a; Figueras et al., 2023):

Eq.11 $$4CO + 2H_2O \rightarrow CH_3COOH + 2CO_2$$

Eq.12 $$CH_3COOH \rightarrow CO_2 + CH_4$$

Eq.12 $$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$$

While in the TBR-2 only hydrogenotrophic methanogenesis is assumed (Eq. 12).

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A compression and cleaning stage has been added at the end of the process for gas grid injection purposes. In Table 20 and Table 21 the main assumptions are represented.

Table 20 - Composition of syngas (Del 3.2)

Molecule	Value	UNIT
H_2	58	vol.%
CO_2	11	vol.%
CO	29	vol.%
CH_4	2	vol.%

Table 21 - Main assumptions of ESB technology

Parameter	Value	UNIT
Temperature of reactors (Del 3.2)	60	°C
Pressure of reactors (Del 3.2)	2	bar
Pressure at the outlet of the process (Bai et al., 2009a)	5	bar
Pressure drop at each reactor (Bai et al., 2009a)	2000	Pa
Pump Efficiency (Ferrario et al., 2024a)	0.75	-
Pump mechanical/electrical efficiency (Ferrario et al., 2024a)	0.94	-
Compressor Efficiency (Ferrario et al., 2024a)	0.75	-
Compressor mechanical/electrical efficiency (Ferrario et al., 2024a)	0.94	-
Conversion ratio of H2 at the TBR-2	95.0	%

6.4. Mass and energy balance

As results, given the assumptions and the flowsheet described in the previous paragraph, the following mass and energy balance of the main streams are expressed in Table 22 and Table 23.

Then, the visualization of the main KPIs for the ESB technology follows in Table 24.

Table 22 - Mass balance for ESB technology

STREAM	VALUE	UNIT
H_2 – Hydrogen at the inlet of the second reactor	0.2	kg/hr
SYNGAS – Syngas at the inlet of the methanation process	2.1	kg/hr
H_2	*58.0*	*vol.%*
CO_2	*11.0*	*vol.%*
CO	*29.0*	*vol.%*
CH_4	*2.0*	*vol.%*
bioGAS – Biogas at the outlet of the first reactor	2.5	kg/hr
CO_2	*25.7*	*vol.%*
H_2O	*40.8*	*vol.%*
CH_4	*33.5*	*vol.%*
bioCH4 – Biomethane after cleaning and compression	*1.1*	kg/hr
CO_2	*5.0*	*vol.%*
CH_4	*95.0*	*vol.%*

Table 23 - Energy balance for ESB technology

Parameter	Value	UNIT
Biomethane production	11.85	kWh
Electricity consumption	0.243	kWh

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Heat duty	0.00	kWh
Cooling duty	3.91	kWh

Table 24 - KPIs of ESB technology

Parameter	Value	UNIT
Specific electric consumption - en_{el}	0.02	kWh_{el}/kWh_{bm}
Specific consumption of hydrogen - $cons_{H2}$	0.012	kg_{H2}/ kWh_{bm}
Carbon conversion rate - CR	95.0	%
Efficiency of plant - η	79.0	%

As results the ETM technology is characterized by a plant efficiency of about 74% and a specific electric consumption of 0.02 kg_{H2}/ kWh_{bm}.

6.5. Upstream process – Gasification and Electrolysis

As mentioned before, a holistic analysis of the entire biomethane production pathway is crucial to better evaluate pilot performances, and to have an overview about the role this technology may have at industrial scale.

To do so, gasification process and electrolysis have been modelled by means of literature data (Ding et al., 2022). In the next table the main assumption utilized are resumed:

Table 25 - Gasification and electrolyzer parameter assumptions, ESB process

PARAMETER	VALUE	UNIT OF MEASURE
ANAEROBIC DIGESTION		
Specific Energy Consumption (% of the energy content of the Syngas)	7	$\%kWh_{Syngas}$
Gasification conversion efficiency	65	%
PEM ELECTROLYZER		
Faraday Efficiency	96	%
Voltage Efficiency	73	%
Current Density	1.8	A/cm^2

In the next image, the Sankey diagram of the process:

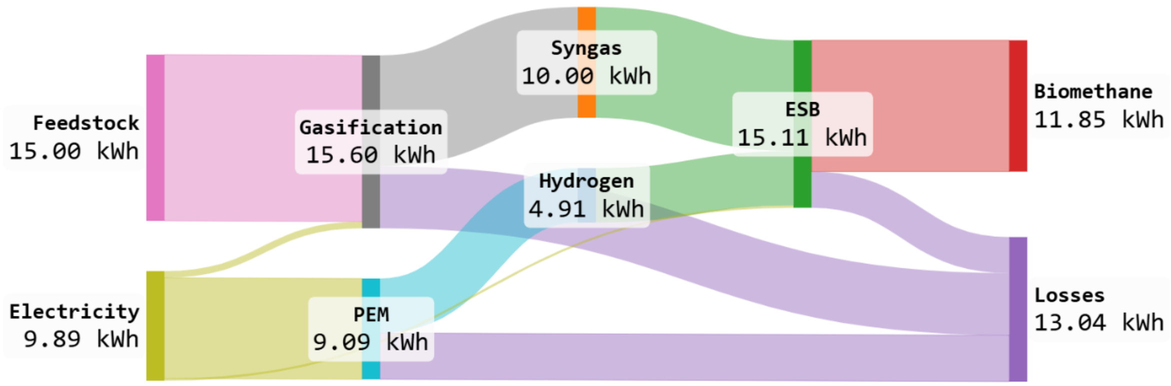

Figure 22 - Sankey diagram of energy flows, ESB process

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In the biomethane production pathway of the ETM process, most of the losses are due to the electrolysis for hydrogen production, while the single ETM process has high efficiency.

In this case, the ESB process account for high losses, mostly due to the gasification process and the Electrolyser. However, it must be noticed that due to already present hydrogen in the syngas stream, a lower amount is needed from the electrolyser.

6.6. Preliminary environmental impacts

In Ex Situ Syngas Biomethanation, hydrogen supply accounts for the largest proportion of fossil resource use. When electricity from the grid is used, this impact becomes higher than that of fossil natural gas. However, similar to other pilot processes, shifting toward renewable energy sources results in a significant reduction, with hydrogen supply being the most impactful.

Regarding fossil resource use, GHG emissions follow the same trend: emissions are higher when electricity from the grid is used compared to exclusively renewable sources. Nevertheless, using grid electricity still produces fewer GHG emissions than fossil natural gas. Additionally, transitioning to renewables markedly reduces GHG emissions associated with the biomethane production process.

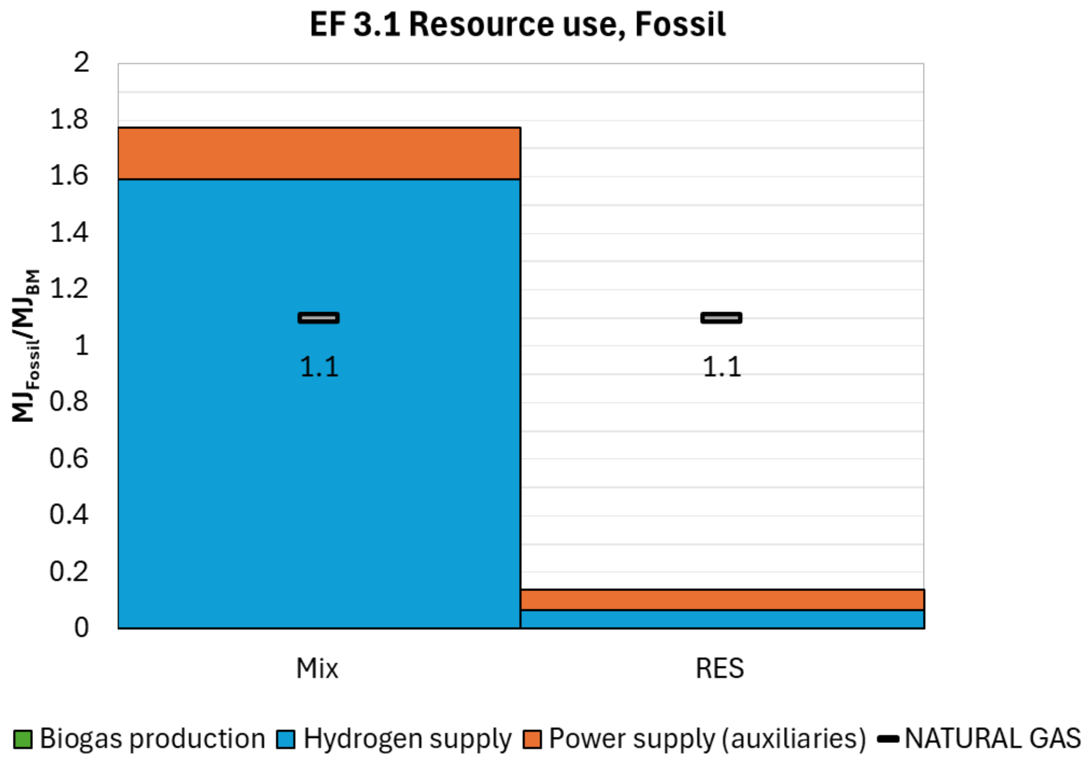

Figure 23 - Primary energy demand, ESB process

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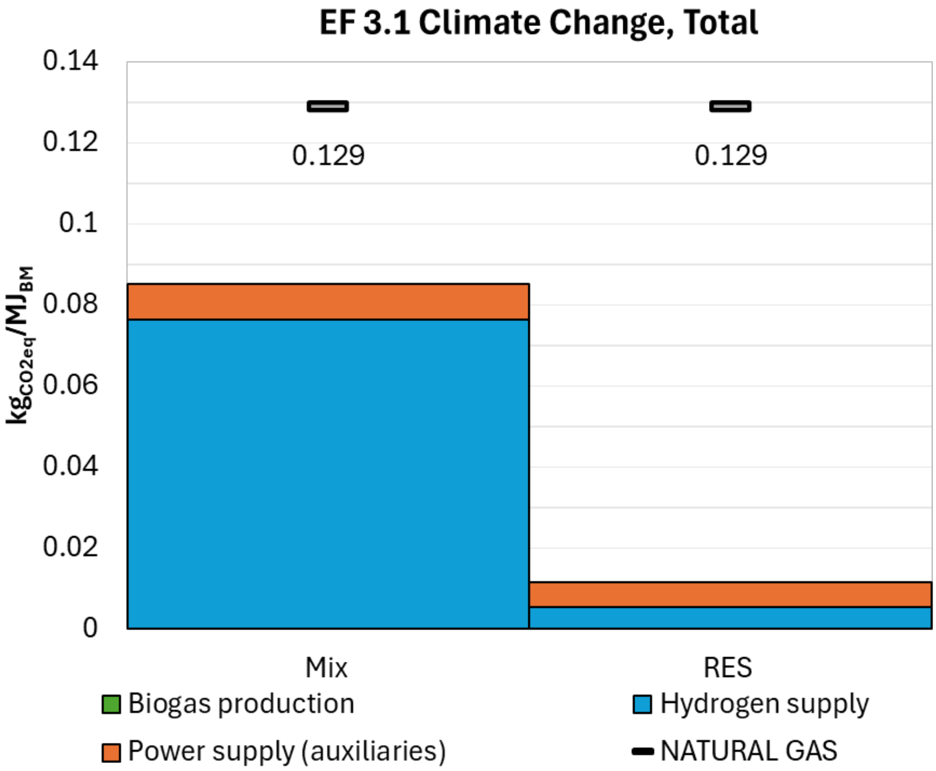

Figure 24 - GHG emissions, ESB process

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7. UKRAINE INNOVATIVE BIOMETHANE DEMONSTRATOR

DEMONSTRATION: In-Situ Biological methanation (IBM)

- Production pathway: biological
- Input: CO_2 +hydrogen

7.1. Brief description of the site

The biogas plant in **Ladyzhin**, **Vinnytsia region,** has an installed electric capacity of 12 MW, producing biogas from 330 t d^{-1} of chicken manure and other agricultural residues, producing 85,000,000 kW of electricity per year. Plant configuration consists of twelve reactors (9 main digesters and 3 post digesters) with 90,000 m^3 volume each.

Also, the complex has its own biogas pipeline that transfers biogas to the cogeneration unit located near the slaughter complex, in order to use heat to supply steam to the latter.

7.2. Technology description

During anaerobic digestion, different microorganisms convert organic residues into biogas. The process occurs in four different phases of which the last phase is methanogenesis. Two metabolic pathways of methanogenesis dominate in industrial biogas plants, i.e., acetolactic methanogenesis, where acetate is split into CO_2 and CH_4 and hydrogenotrophic methanogenesis where CO_2 is reduced with hydrogen to CH_4. Both processes run in parallel, however the first route will prevail if no interventions are made, because the naturally occurring amount of free hydrogen in the substrates is low.

By injecting hydrogen directly into an AD reactor, the second route is stimulated and the activity of the hydrogenotrophic methane formers is increased. This results both in an overall increase of the biomethane yield per given amount of feedstock, and in a higher methane concentration in the final biogas produced.

In Figure 25 it is represented a simplified scheme of the modeled process, where it is possible to identify the main component, as pump for feedstock movement, reactors, compressor and separator for cleaning and compression of biomethane.

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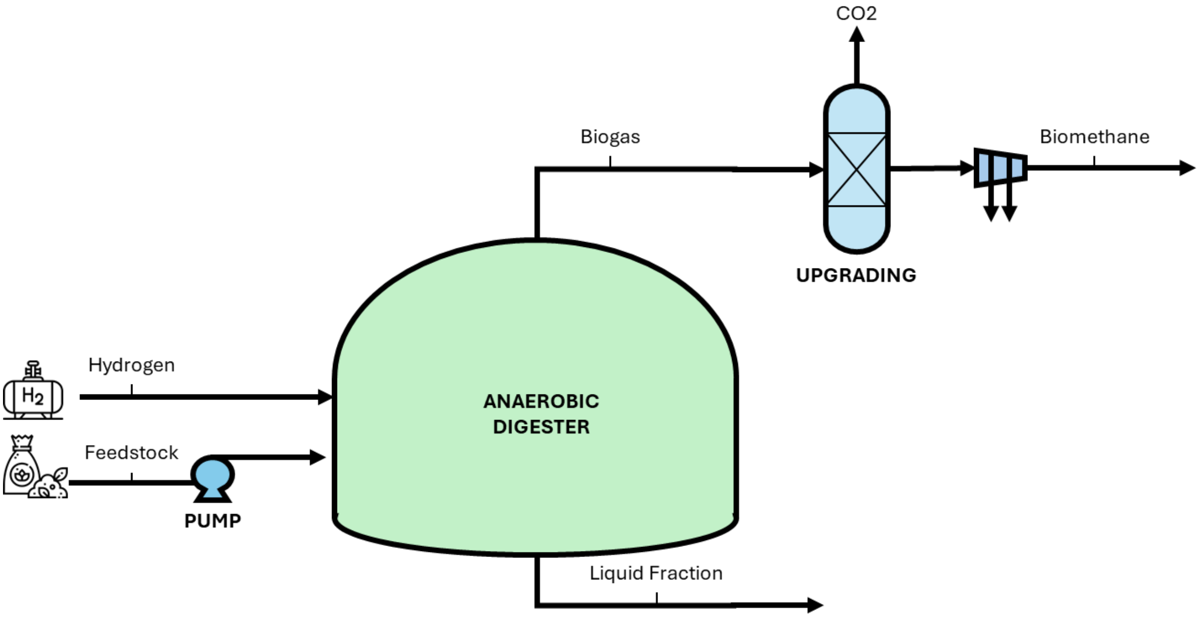

Figure 25 - Process flowchart of In-situ Biological Methanation (IBM) technology

7.3. Preliminary flowsheet and assumptions

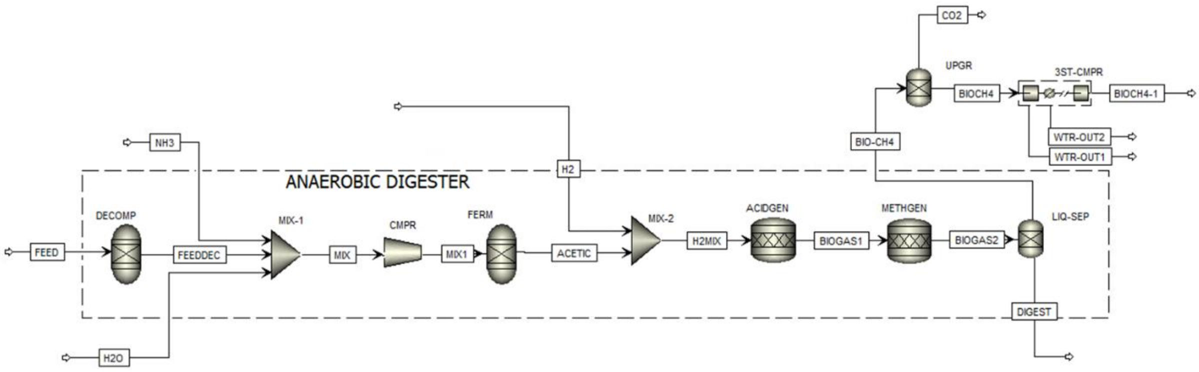

Figure 26 - Preliminary AspenPlus flowsheeting of In-situ Biological Methanation (IBM) technology

The preliminary flowsheeting of IBM represents an enhanced anaerobic digestion in which hydrogen is added to increase methane yield at the outlet. The objective is to reach an enriched biogas with a composition of about 80% CH_4 as highlighted in the Deliverable D2.2.

The AD process has been assumed following a three steps pathway, comprehending fermentation (Eq.13), Acidogenesis (Eq.14), and Methanogenesis (Eq. 15) as follows (Dionisi, 2017):

Eq.13 $$CH_aO_bN_c \rightarrow dC_5H_7O_2N + eCH_3COOH + fH_2 + gCO_2 + hH_2O + iNH_3$$

Eq.14 $$CH_3COOH + aNH_3 \rightarrow bC_5H_7O_2N + cCH_4 + dCO_2 + eH_2O$$

Eq.15 $$H_2 + aCO_2 + bNH_3 \rightarrow cC_5H_7O_2N + dCH_4 + e2H_2O$$

Where $CH_aO_bN_c$ represents the feedstock and $C_5H_7O_2N$ are the microorganisms produced during the processes. Each stoichiometric coefficient is evaluated based on the composition of the feedstock.

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At the end of the process an upgrading and compression stage is added to obtain standard quality biomethane for gas grid injection purposes. In Table 26 and Table 27 the main assumptions are represented.

Table 26 – Feedstock composition (ECN, 2019)

	Value	UNIT
Proximate Analysis		
Moisture	26.35	%
Ash	13.74	%
Volatile	70	%
Fixed Carbon	16.26	%
Ultimate Analysis		
Ash	13.7	%
C	41.9	%
H	5.5	%
O	34.4	%
N	3.83	%
S	0.65	%

Table 27 - Main assumptions of IBM technology

Parameter	Value	UNIT
Operative Temperature (Del 3.2)	40	°C
Operative Pressure (Del 3.2)	1	bar
Pressure at the outlet of the process (Bai et al., 2009a)	5	bar
Pressure drop at each reactor (Bai et al., 2009)	2000	Pa
Compressor Efficiency (Ferrario et al., 2024a)	0.75	-
Compressor mechanical/electrical efficiency (Ferrario et al., 2024a)	0.94	-

7.4. Mass and energy balance

As results, given the assumptions and the flowsheet described in the previous paragraph, the following mass and energy balance of the main stream are expressed in Table 28 and Table 29.

Then, the visualization of the main KPIs for the IBM technology follows in Table 30.

Table 28 - Mass balance of IBM technology

STREAM	VALUE	UNIT
H_2 – Hydrogen flowrate at the inlet of the digester	0.08	kg/hr
H_2O – Water flowrate at the inlet of the digester	0.23	kg/hr
FEEDSTOCK – feedstock flowrate at the inlet of the digester	1.00	kg/hr

Table 29 - Energy balance of IBM technology

Parameter	Value	UNIT
Biomethane production	5.79	kWh
Electricity consumption	0.061	kWh
Heat duty	0.12	kWh
Cooling duty	0.71	kWh

Table 30 - KPIs of IBM technology

Parameter		Value	UNIT
Specific electric consumption - en_{el}		0.01	kWh_{el}/kWh_{bm}

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Specific consumption of hydrogen - $cons_{H2}$		0.01	kg_{H2}/ kWh_{bm}
Carbon conversion rate - CR		78.0	%
Efficiency of plant - η		87.0	%

As results the IBM technology is characterized by a plant efficiency of about 877% and a specific hydrogen consumption of 0.01 kg_{H2}/ kWh_{bm}.

As for the IBM process, it happens in situ, with injection of hydrogen directly inside the digester. For this case, no upstream process has been analysed as the entire production chain has been already modelled in Aspen plus. Energy and mass balances are so already related to the biomethane production chain starting from the feedstock. In the next image the Sankey diagram of the IBM technology.

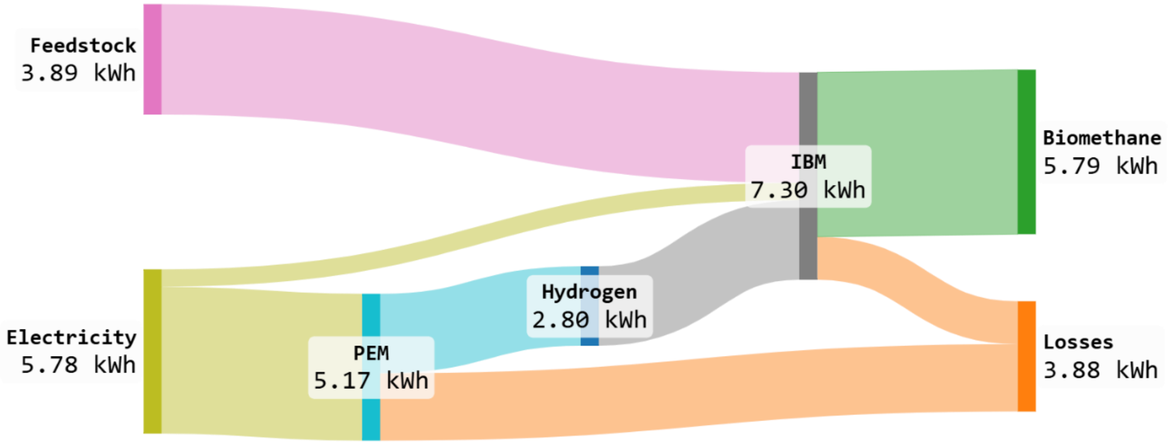

Figure 27 - Sankey diagram of energy flows, IBM process

7.5. Preliminary environmental impacts

In the In Situ Biomethanation process, hydrogen supply is the largest contributor to fossil resource use. When electricity from the grid is employed, this impact is even greater than that of fossil-based natural gas. However, as with other pilot systems, switching to renewable energy sources markedly reduces this impact, especially in the case of hydrogen supply.

Regarding GHG emissions related to fossil resource use, a similar trend is observed: emissions are higher when electricity from the grid is used compared to exclusively renewable sources. Nevertheless, grid electricity still results in lower GHG emissions than fossil natural gas. Overall, transitioning to renewable energy significantly decreases the impacts related to the biomethane production process.

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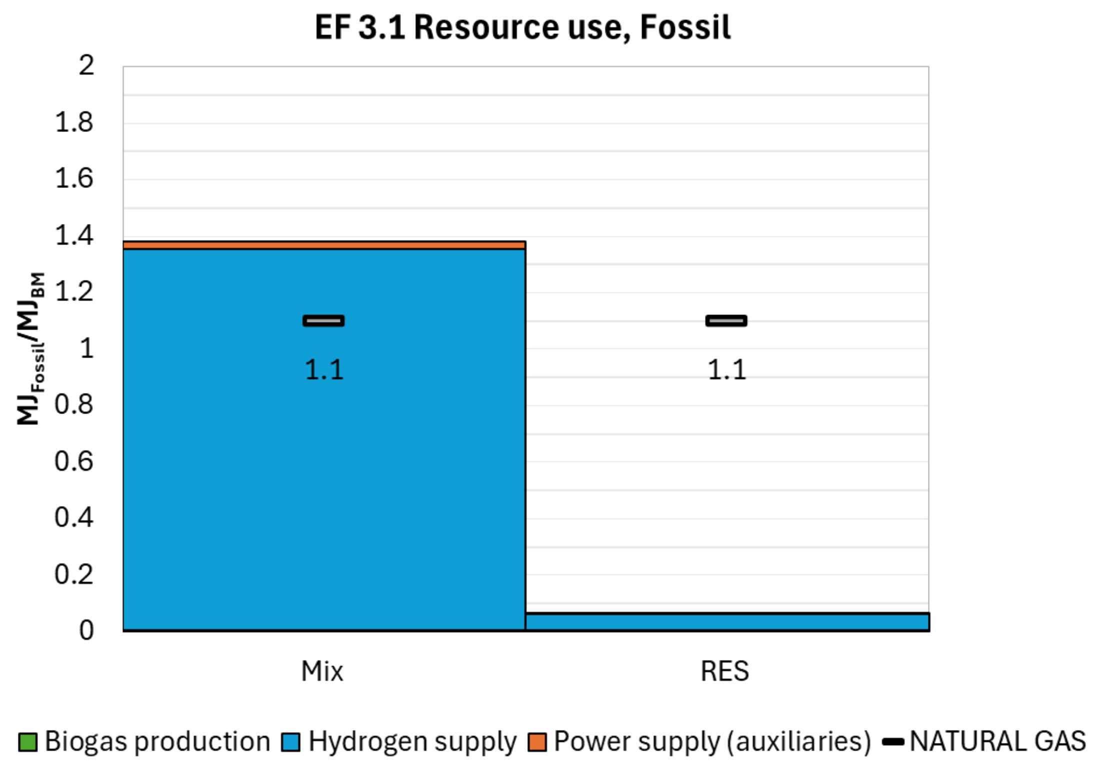

Figure 28 - - Primary energy demand, IBM process

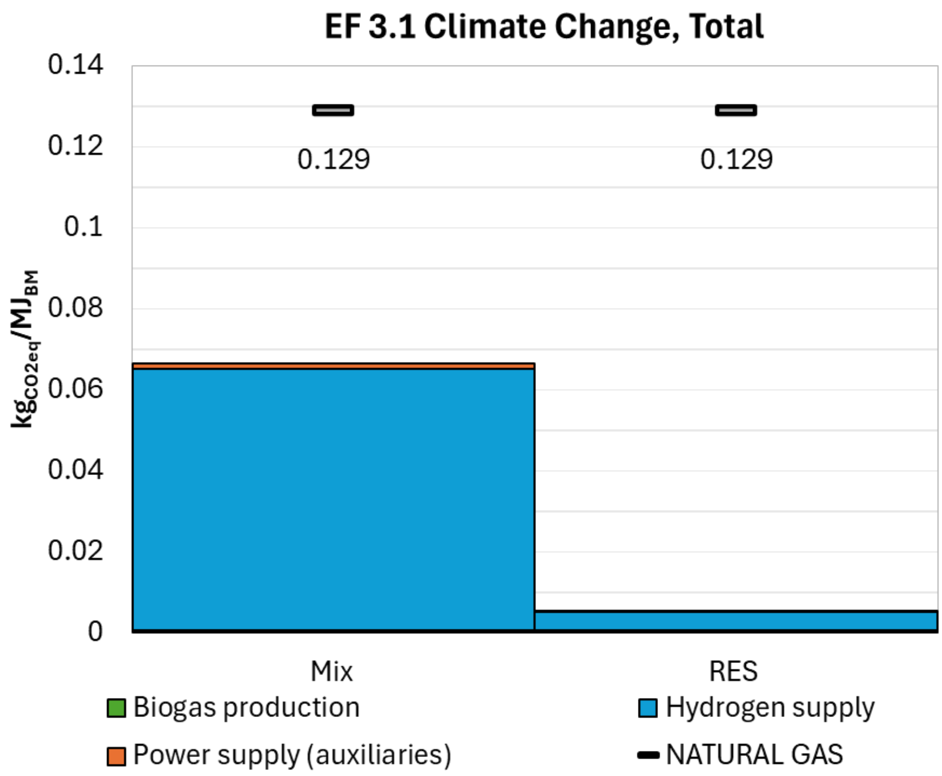

Figure 29 - GHG emissions, IBM process

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8. Energy and Environmental performances of the Biomethaverse technologies

By comparing all the technologies together, it is possible to extract more comprehensive insights. First, the next figure presents the specific energy consumption of the entire biomethane production processes. ETM and IBM are quite similar, both showing a notable increase in biomethane yield compared only to the AD process. However, their specific energy consumption per kWh of biomethane is higher than in the reference case (AD). This is because, on one hand, the feedstock amount is reduced, but on the other hand, because hydrogen production via electrolysis is energy intensive. EBM and EMG are the only pathways with lower specific energy consumption than the reference case. Notably, EMG does not require an external hydrogen supply chain, as power is directly used by bacteria. Additionally, EMG works with an already processed feedstock (digestate), so the increase in biomethane production is marginal. ESB, on the other hand, exhibits a high specific energy consumption with only a modest increase in biomethane yield.

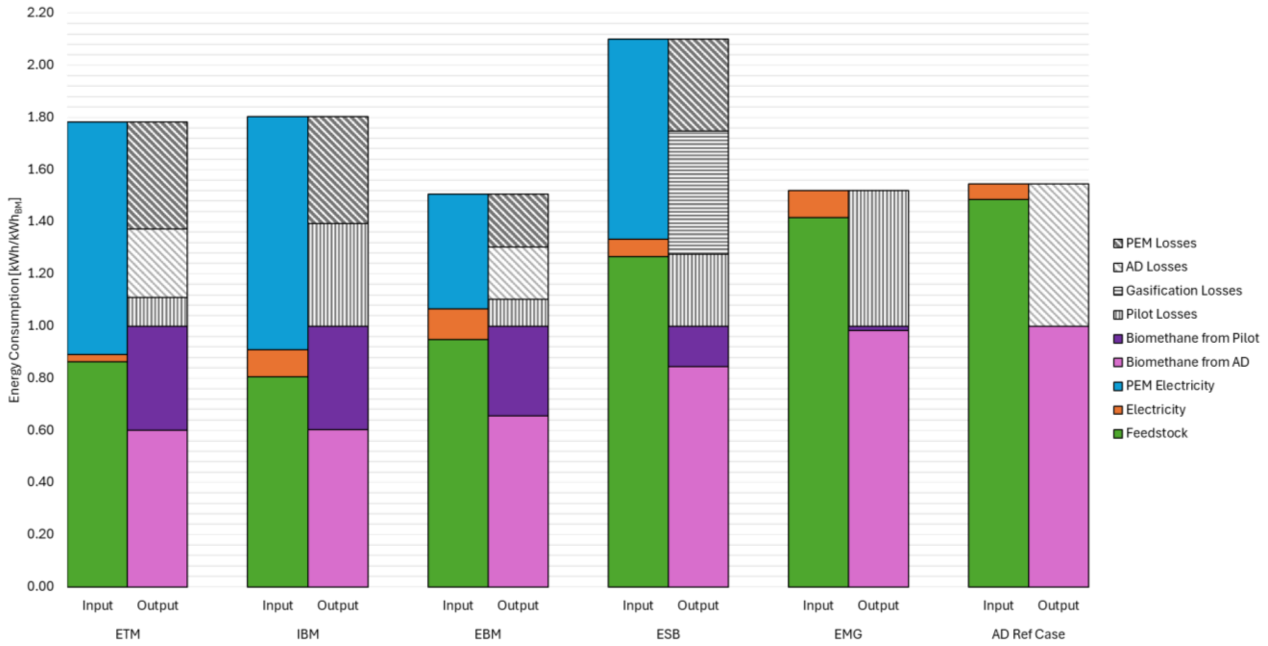

Figure 30 - Overall energy consumption, comparison of all technology and AD as reference case

Regarding environmental impacts, in the next two figures the main environmental impact categories are reported for all the pilots.

In the category of PED from fossils, hydrogen supply is the most impactful component across all pilots. The only technology that can achieve lower impacts than natural gas, when using the electricity mix, is EMG, which does not depend on external hydrogen production due to its internal production within the second reactor. When renewable energy sources are used, all pilots perform significantly better than the fossil natural gas.

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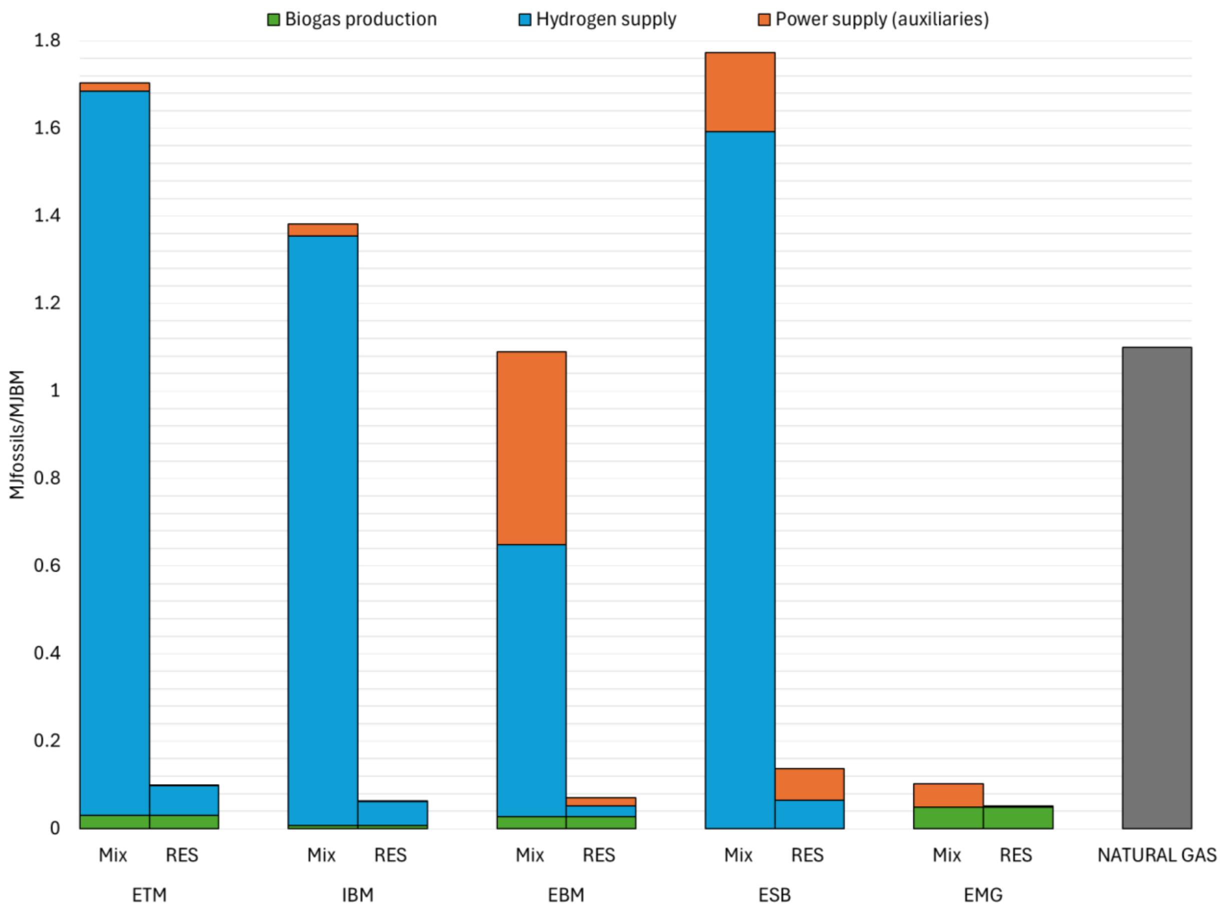

Figure 31 - Primary energy demand of all technologies

Regarding total GHG emissions, it is clear that using electricity from the grid generally results in lower emissions than fossil natural gas; however, shifting to renewables dramatically reduces emissions across all technologies.

Since environmental impacts are closely related to energy consumption, similarities between ETM and IBM are evident, with hydrogen supply accounting for the majority of GHG emissions, even when renewable sources are fully utilized. In contrast, EBM shows that hydrogen supply and power for auxiliaries contribute almost equally to GHG emissions, primarily due to the energy used by the ozone generator. Similarly, ESB's electricity consumption accounts for a slightly higher percentage of its total impacts than ETM and IBM. Finally, EMG, lacking an external hydrogen supply, demonstrates a strong reduction in environmental impacts, even when using electricity from the grid.

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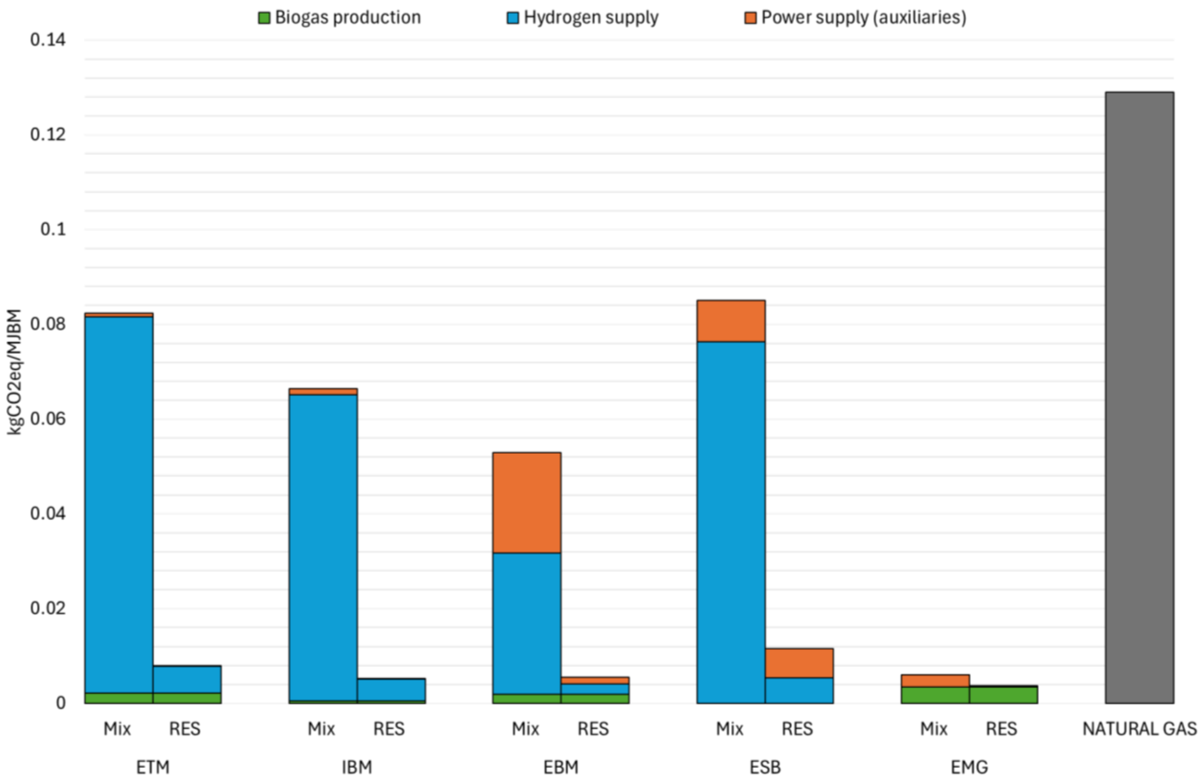

Figure 32 - GHG emissions of all technologies

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9. Social impacts

The deployment of innovative biomethane technologies presents not only technical and environmental challenges but also a wide range of social implications. These include effects on employment, land use, rural economies, and the relationship between energy infrastructures and local communities. Understanding such impacts is crucial to ensure that biomethane contributes to a just and inclusive energy transition, particularly in the rural and peri-urban areas where most plants are located.

In the *Biomethaverse* project, social impacts are assessed through a multi-level, mixed-method approach that reflects the complexity and territorial variability of the five demo sites. This approach includes:

- Literature review to establish the conceptual basis of the analysis.
- Qualitative and semi-quantitative methods, including surveys and participatory expert focus groups, aimed at capturing local perceptions, expectations, and concerns.
- Quantitative tools, including Social Life Cycle Assessment, to systematically analyse risks and benefits across the value chain.
- Comparative insights, to highlight how social impacts differ across countries, technologies, and regulatory frameworks.

This integrated methodology is designed to complement the technical and economic analyses carried out in other work packages and to ensure that social sustainability is fully integrated into the evaluation and design of biomethane innovations.

9.1. Review

This Section includes a comprehensive literature review aimed at identifying, systematizing, and critically assessing the main social implications of biomethane production. This review serves as a conceptual foundation for the project's social impact assessment and clarifies how various configurations of biomethane technologies, particularly when combined with green hydrogen, may generate positive or negative effects across different territorial contexts. Academic research on this topic has increased in recent years, reflecting the growing acknowledgment that technological transitions must be accompanied by socially inclusive and regionally balanced policies. The literature addresses a wide array of issues, including job creation, rural revitalization, stakeholder engagement, environmental trade-offs, and local acceptability.

Positive social impacts

The literature identifies several key social benefits associated with biomethane systems:

- **Employment creation**, both during the construction and operation of biomethane plants, and in upstream supply chains (Dvořák et al., 2017; Guenther-Lübbers et al., 2016)
- **Income diversification** for farmers, waste managers, and local SMEs involved in supplying organic feedstocks (D’Adamo and Sassanelli, 2022)
- **Support for local economies and territorial resilience**, through short supply chains and reinvestment of energy revenues at the community level (Niang et al., 2022; Rocha-Meneses et al., 2023)
- **Integration into circular economy models**, by recovering value from livestock manure, food waste, agricultural residues, and urban biowaste (D’Adamo and Sassanelli, 2022; Ellacuriaga et al., 2021)

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Risks, trade-offs, and challenges

Despite their potential, biomethane systems also present several risks and trade-offs that must be carefully considered:

- **Land use competition** between energy crops and food production, with associated effects on biodiversity and land tenure (Britz and Delzeit, 2013; "Cite Report — Special Report on Climate Change and Land," n.d.; Magnolo et al., 2024).2024)
- **Social concerns related to odours, noise, and truck traffic**, especially in proximity to residential areas (Bourdin et al., 2020; Soland et al., 2013)
- **Water consumption** for electrolysis-based hydrogen production, which may exacerbate stress in water-scarce regions (Patonia, 2025; Shi et al., 2020)
- **Digestate risks**, including groundwater contamination and soil degradation, in the absence of proper treatment and monitoring (Tucho et al., 2016)
- **Dependence on policy incentives**, which may affect the long-term economic sustainability of small-scale or community-based projects.

Social acceptability and local inclusion

A recurring topic in the literature is the importance of social acceptability, which depends not only on the intrinsic features of the technology but also on perceived fairness, transparency, and community participation. Factors such as plant size, proximity to homes, and the distribution of socio-economic benefits play a crucial role in shaping attitudes (Bourdin and Delcayre, 2024). These factors highlight the need for inclusive governance models and context-specific engagement strategies in biomethane deployment.

Based on the findings of the literature review, the table below provides a synthetic overview of the main opportunities and challenges associated with biomethane production. Impacts are grouped into six key categories reflecting the main social dimensions identified in the literature and relevant to the Biomethaverse assessment framework.

Table 31– Key Social Impacts of Biomethane Production (Literature Review)

IMPACT CATEGORY	OPPORTUNITIES / BENEFITS	RISKS / CHALLENGES
EMPLOYMENT & ECONOMY	- Local job creation during construction and operation - Income diversification for farmers and SMEs	- Long-term reliance on subsidies - Uneven distribution of economic gains
TERRITORIAL DEVELOPMENT	- Reinforcement of rural economies - Strengthening of short supply chains and local autonomy	- Land use conflicts with food production - Risk of excluding small producers
CIRCULAR ECONOMY	- Valorisation of waste and by-products - Integration into local resource cycles	- Digestate management issues - Environmental trade-offs if poorly regulated
COMMUNITY WELL-BEING	- Improved local infrastructure and services (indirect effects)	- Odours, noise, and traffic near plants - Perceived negative impacts on quality of life
SOCIAL ACCEPTABILITY	- Increased trust through participatory processes - Transparent sharing of benefits and risks	- Public opposition in case of poor consultation - Distrust arising from lack of local engagement

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RESOURCE USE & ENVIRONMENT	- GHG reduction through renewable gas CO_2 and H_2 valorisation pathways	- High water consumption in hydrogen production - Risks of soil and water contamination from digestate

Overall, the literature shows that biomethane production is socially relevant not only for its environmental contributions but also for its capacity to generate employment, support local economies, and foster circularity. However, these benefits can be undermined by social and territorial risks, especially if projects are implemented without proper stakeholder engagement, governance transparency, and environmental safeguards. These findings provide a baseline for the site-specific assessments carried out in the *Biomethaverse* project.

9.2. Social LCA

Social LCA is a life cycle-based approach for assessing social performance, with the objective of identifying social hotspots, and investigating social issues more comprehensively at different stages of the life cycle of a product. As the SLCA structure is rooted in LCA, this feature provides a foundation for preliminary studies that draw upon LCA inventories and models. Consequently, as a preliminary phase in the study, we utilised this data from the LCA to model the five pilot cases. The social data was provided by the PSILCA database.

The iterative nature of SLCA will provide a basis for integrating this model with the results of qualitative methodologies characteristic of the social sciences – see the sections below -- in subsequent stages of the study. This will facilitate a more comprehensive understanding of the social issues involved and the stakeholders concerned.

The present study builds upon the work conducted for the LCA, in which the anaerobic digestion and methanation processes plant was modelled for each pilot, with the distinctive characteristics of BIOMETHAVERSE technologies being taken into account. It is assumed that all plants are located in Italy. The following table displays the processes that are part of the model along with the economic sectors in the PSILCA database to which they have been associated.

Table 32 - Relevant PSILCA sectors associated with the product system processes

Process	**PSILCA sector**
• Anaerobic digestion with ozonolysis • Anaerobic digestion	Sewage and refuse disposal, sanitation and similar activities
• ElectroMethanoGenesis (EMG) • Ex-Situ Thermochemical Methanation (ETM) • Ex-Situ Biological Methanation (EBM) • Ex-Situ Syngas Biomethanation (ESB) • In-Situ Biological Methanation (IBM)	Electricity, gas, steam and hot water supply

The product system for hydrogen production was modelled on the basis of relevant literature (Martín-Gamboa et al., 2024). Despite the fact that the BIOMETHAVERSE project proposes the utilisation of green hydrogen, in this preliminary phase, a model of hydrogen production from electrolysis using an energy mix has been employed.

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A comprehensive set of calculations was conducted, incorporating all relevant social indicators from the database. The results obtained from this analysis were then subjected to a comparative analysis, with the findings from the various project pilots being evaluated. The present report is informed by a selection of examples drawn from the relevant literature, and its focus is on the social impact indicators "Child Labor," "Gender wage gap," and "Health expenditure."

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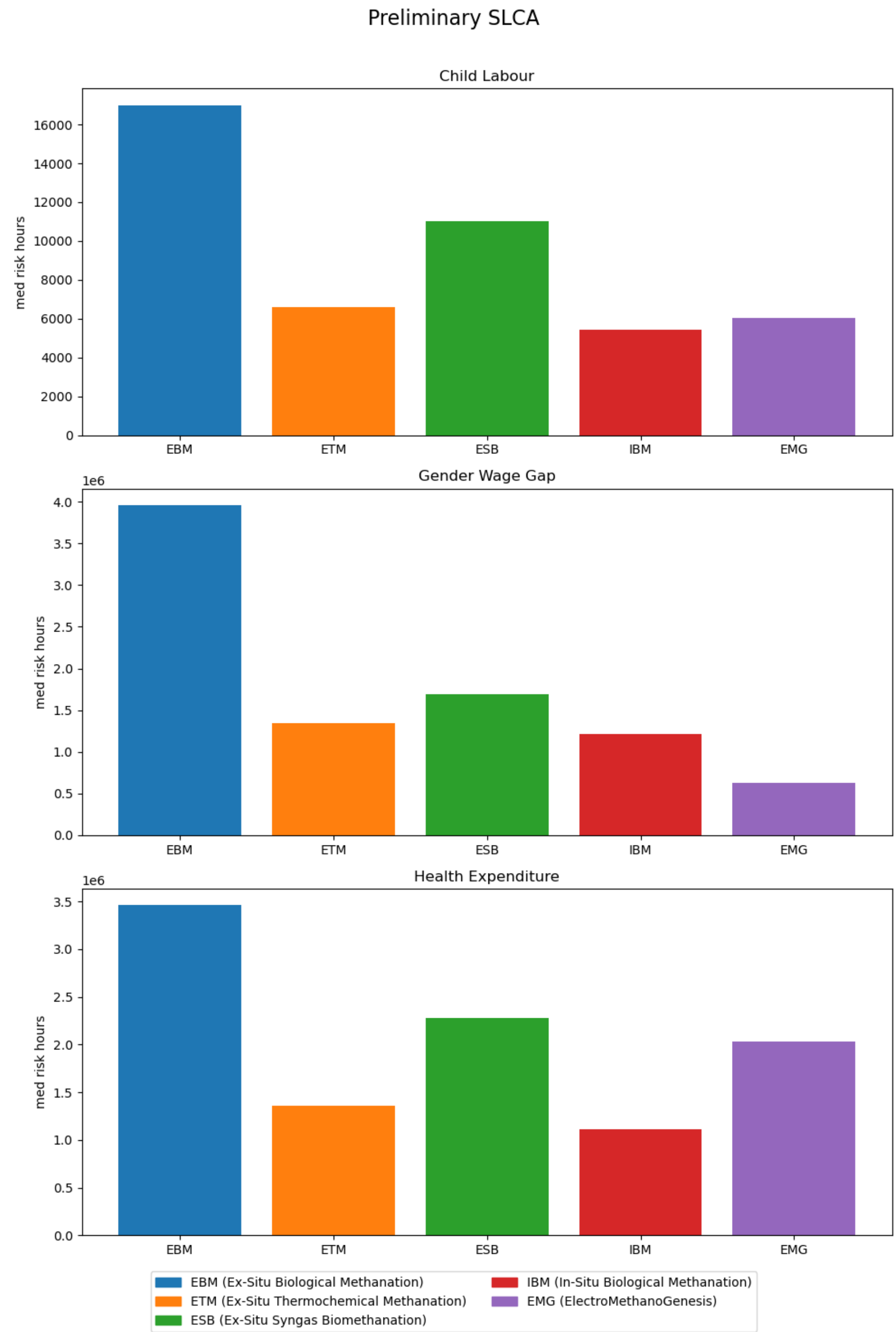

Figure 1:

Figure 33 - SLCA results (medium risk hours) for the following social indicators: Child Labour, Gender Wage Gap, Health Expenditure

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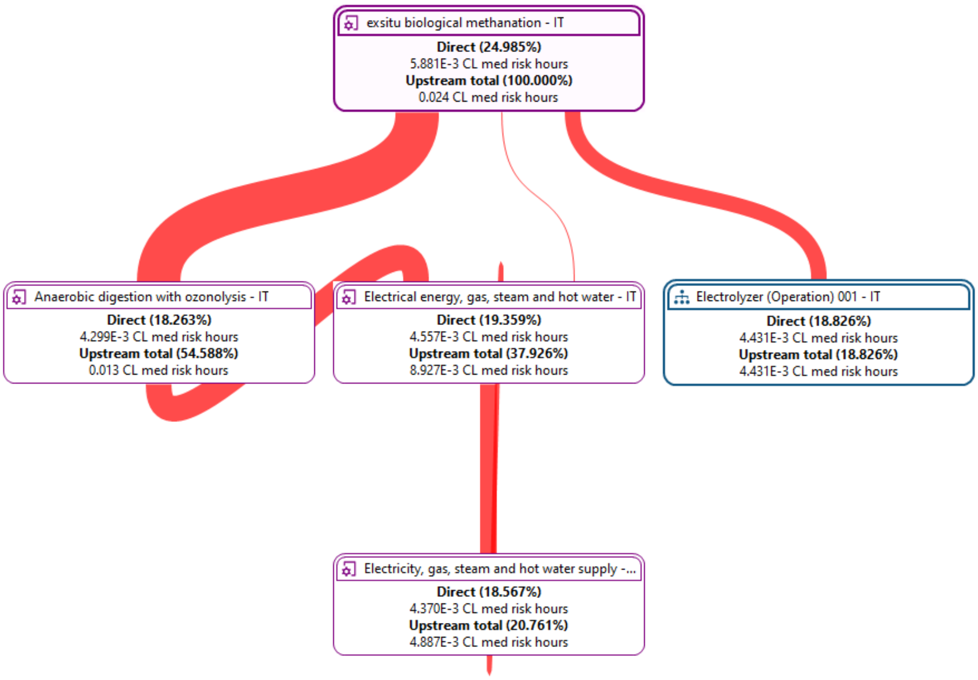

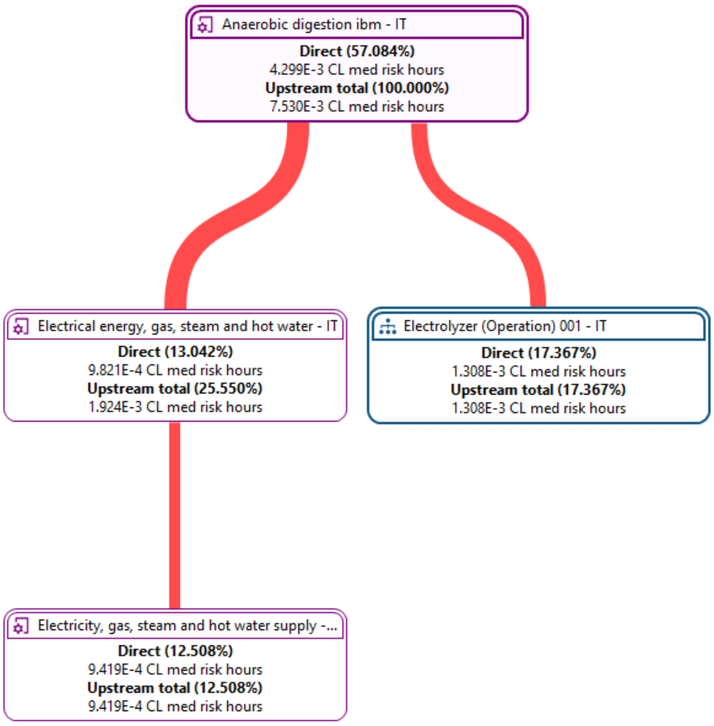

Figure 34 - SLCA results (medium risk hours) for the following social indicators: Child Labour, Gender Wage Gap, Health Expenditure

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Preliminary results indicate that, despite the similarities of the processes involved, different quantities of inputs and outputs can result in different outcomes. Subsequent research will concentrate on enhancing supply chain models, comprehending their social performance, and examining social hotspots.

9.3. Survey

To complement the analysis of the social dimensions associated with the BIOMETHAVERSE technologies, a stakeholder survey was developed and implemented in the form of an online questionnaire. The objective of the questionnaire is to collect insights into stakeholders' perceptions regarding the key factors that influence the local social acceptability of e-biomethane production facilities within the broader biomethane sector.

The questionnaire is a structured Likert-scale survey designed for participants of the May 14, 2024, Biomethaverse Workshop in Brussels. i.e. industry representative from companies engaged in e-biomethane projects. To gather further opinions, including those from additional types of stakeholders in the e-biomethane environment, the questionnaire was also disseminated through EBA's mailing lists. The questionnaire was administered online by distributing a web link that pointed to a Microsoft Forms page[1].

Its first block of statements examines anticipated benefits. Seven items, grouped under four headings—job creation, new income for farmers and waste-handling firms, extra market value for residues and digestate, and knock-on growth in local supply chains—measure how far participants expect deployment to boost local economies.

A larger section turns to potential drawbacks. Around eighteen prompts, arranged in thematic clusters on odour and air quality, water demand and contamination, traffic and noise, pathogen and heavy-metal hazards in digestate, landscape aesthetics, property values and planning delays, and broader social acceptance, invite respondents both to voice concern and to indicate confidence in the effectiveness of mitigation measures.

The questionnaire concludes with forward-looking items regarding whether a larger share of biomethane in the energy mix will garner policy and community support, as well as respondents' overall optimism for the sector's future. In essence, the instrument provides organisers with a clear, data-ready overview of stakeholder expectations, fears, and willingness to grant social licence, which is useful for tailoring project design, communication strategies, and policy framing. Across all 30-plus statements, respondents indicate their agreement on a five-point scale (from Strongly Agree to Strongly Disagree), enabling the quantification of perceived benefits, risks, and social licence of e-biomethane. The questionnaire results will feed into the process of triangulating the analysis of the S-LCA and the expert focus group.

To date (24/06/25), 28 respondents have participated in the questionnaire with the largest share being "researchers" and "technology providers" (Figure 35). Most respondents declared themselves to be experts of biogas and biomethane (Figure - 36). The Survey will stay open until the end of September 25 to gather further responses.

[1]https://forms.office.com/Pages/ResponsePage.aspx?id=phgU8LwI_Ue0QGzXAYPRM8K4l5q4JuBDoUlmzQ3aCj1UN0g2UUs0RUNDV0c4VDRSVTlCSU81NjMzUyQlQCN0PWcu

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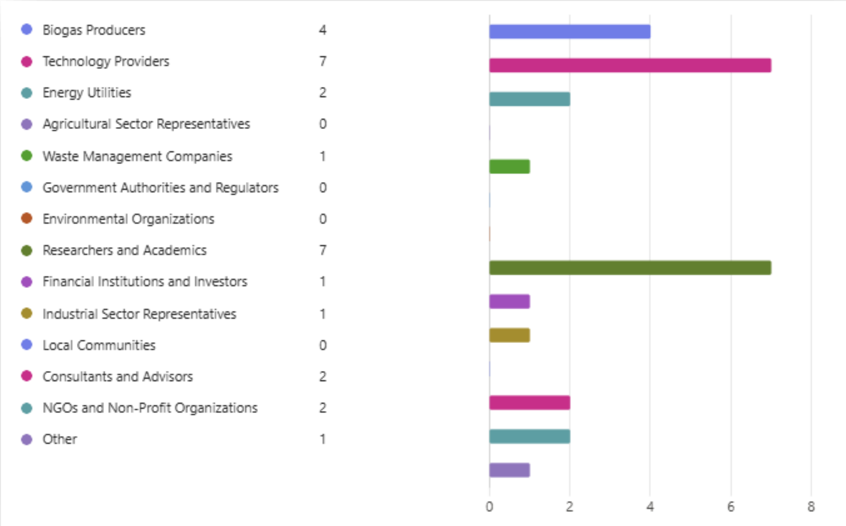

Figure 35 - Respondents' stated category of stakeholders

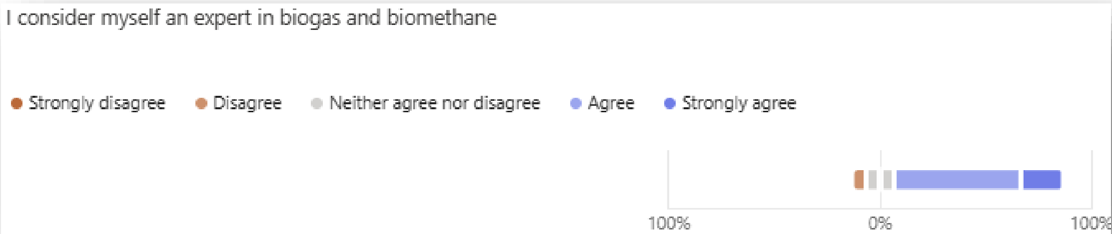

Figure - 36 Declared expertise regarding biogas and biomethane

9.4. Expert focus group

The “Expert focus group on Social Hotspots of Biomethane Implementation” was held online on 20 May 2025 as an additional preparatory activity for the S-LCA described in Task 3.3.

Seventeen contributors participated over two hours and fifteen minutes, with seven of them belonging to ENEA, the partner organising the event. The participants can be described as follows: 2 ENEA facilitators, 5 ENEA researchers, one representative of a local Italian association of biomethane producers, one representative of the European biomass association, 1 researcher of the European Commission, 5 representatives of environmental and energy NGOs and associations, 1 academic, and 2 researchers. The group was deliberately diverse, but each participant had developed expertise on the subject through their activities. The diversity enabled exchanges that spanned advocacy, technical, and policy perspectives.

The expert focus group was recorded, transcribed and yielded about thirty-three thousand words of text. The transcript was coded with codes relevant to the thematic analysis performed. When

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quotations appear below, the speaker is mentioned only as a participant so that no individual, or even occupational group, is identifiable.

Economic value and risk were discussed first. The group quickly set aside the familiar claim that a forty-three-gigawatt-hour plant creates sixty jobs. One participant argued that what really matters is the chain of services that grows around a digester: extra waste-collection routes, new district-heating loops, long-term maintenance for combined-heat-and-power units and local outlets for fertiliser pellets. Concerns about safety changed the tone: accident data from Germany showing seventy-two per cent of inspected plants with serious faults led another voice to add that job numbers are meaningless if staff work in unsafe conditions. There was also unease about very large digesters because guaranteed off-take contracts can push farmers to enlarge herds and undermine the climate gains the plant is meant to deliver. Others stated that a mixed income, gas sales, heat charges, digestate products and eventually carbon credits, can keep finances solid as long as policy rules stay stable over the plant's lifetime.

Environmental performance was dominated by methane leakage. Field measurements at roughly two hundred European digesters suggest an average slip close to five per cent. "At five per cent, your climate advantage is gone," warned a participant, turning the figure into a hard line between success and failure. The forthcoming EU leak-detection-and-repair regulation was welcomed as technically adequate but only if inspection capacity on the ground is strong; another voice cautioned that "rules on paper don't seal valves in the field." The discussion then shifted from loss control to by-product use. A Canadian demonstration plant was mentioned where digester CO_2, currently worth about twenty euros a tonne, is combined with hydrogen from a sixty-megawatt electrolyser to make low-carbon methanol. In the same breath, the speaker noted that capturing CO_2 from fossil sources can cost four hundred euros a tonne, so treating biogenic CO_2 as a saleable product rather than a disposal problem changes the economics as well as the emission balance.

Social acceptance and fairness came next. The moderator asked what type of decision-making process earns public support, which signalled to everyone that procedure matters more than hardware. Evidence from Italy showed that projects revealed to residents only when the permit application is filed often face "NIMBY" (Not In My Back Yard) push-back from neighbours and also "NIMTO" reactions (Not In My Term of Office) from elected officials who prefer any controversy to fall outside their time in office. By contrast, projects that start talking to locals at concept stage move ahead far more smoothly. Ownership appeared as the strongest single lever. One participant said municipalities sometimes take a temporary share "until the citizens are ready," and another observed that farmer-led plants meet far less resistance than utility-led ones because the profit stays visible in the area. The danger of placing waste-treatment digesters in low-income districts with little lobbying power was raised; information campaigns alone were judged insufficient unless a fair share of benefits flows back to those neighbourhoods. Safety again coloured perceptions: high-profile incidents occur rarely but attract wide media attention, which means accident prevention and transparent reporting are part of social licence, not just engineering.

Policy and resilience closed the technical debate. A policy analyst explained that three EU measures are about to converge: stricter default greenhouse-gas values in the Renewable Energy Directive, a methane regulation that forces all operators to run leak-repair plans, and a draft framework that will pay for certified carbon removals. Clear metrics, the analyst said, should make it easier for banks to judge projects, but they also mean that plants with five-per-cent leaks "have no business case." The group then turned to grid reliability. Dispatchable biomethane can fill gaps when solar and wind output falls, and one participant recalled how local combined-heat-and-power units kept rural lights on during recent storms. That story reframed the gas as an energy-security asset in addition to a decarbonisation tool.

Integrated lessons

When the conversation is viewed as a whole, three conditions repeatedly emerge as critical to success.

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- Verifiable leak control is now the foundation of climate credibility, regulatory compliance and community trust.
- Early engagement combined with a path for local equity converts provisional tolerance into lasting legitimacy; late-stage consultation, by contrast, often stalls projects.
- Designing a plant to deliver several services (e.g. heat, fertiliser, e-fuels and flexible power) spreads both revenue and social benefit.

Where these three elements align, participants considered biomethane capable of delivering low carbon energy, rural income and stronger grids in one package. Where any element fails, if leaks continue, profits flow out of the region, or co-product markets are absent, digesters risk adding livestock emissions, stirring opposition and falling short of new EU rules.

The outcome of the expert focus group, together with the results of the survey, will be used to complement and guide the analysis of the social dimensions associated with the BIOMETHAVERSE technologies performed with the PSILCA.

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10. CONCLUSIONS

This report presented the updated results of refined modelling analyses based on the availability of new operational data from the pilot plants and has provided a preliminary sustainability assessment of the five innovative methanation technologies demonstrated within the BIOMETHAVERSE project. It synthesises the outcomes of process modelling, environmental evaluation, and social impact analysis for each demo plant, offering a structured comparison of performance indicators and critical sustainability dimensions.

The modelling structure developed, consistent with that used in Deliverable 3.2, is designed to integrate real operational data as it becomes available, allowing for refinement in the upcoming deliverables (D3.6–D3.8) focused on upscaling, optimization, and comprehensive sustainability assessments.

From a **technical and energetic perspective**, each methanation pathway was modelled using AspenPlus® to estimate mass and energy balances under consistent assumptions. These outputs were then used to calculate key performance indicators (KPIs), such as **carbon conversion efficiency** (i.e., the proportion of carbon in the feedstock converted into biomethane) and **overall energy efficiency** of the integrated plant systems.

The results show that most technologies achieve relatively high energy efficiencies, generally between **75% and 90%**, with the notable exception of EMG, which exhibits lower efficiency (~30%) due to the nature of the feedstock (digestate) and the internal electrochemical conversion process. Nevertheless, EMG presents important advantages, such as avoiding external hydrogen supply and valorising residual waste streams.

In terms of **hydrogen consumption**, significant differences were observed across the technologies. EBM exhibited the highest specific hydrogen demand, followed by ETM, IBM, and ESB, all within the range of 10-15 kWh_{H2}/MWh_{bm}. EMG stands out again for requiring no external hydrogen input, as it produces hydrogen in situ via electroactive bacteria.

The **environmental assessment**, carried out using *LCA for Experts* and applying the EF 3.1 methodology, focused on two mid-point indicators: **climate change (GHG emissions)** and **primary energy demand from fossil sources**. Preliminary results, based on literature data and model assumptions, highlight the critical role of the electricity mix and hydrogen production route. Technologies powered by renewable electricity significantly outperform fossil natural gas benchmarks in both indicators. EMG demonstrates strong potential even when powered by grid electricity, due to its lack of hydrogen dependency and use of residual feedstocks.

From a **social perspective**, the analysis included a literature review, a Social Life Cycle Assessment (S-LCA) using the PSILCA database, a stakeholder survey, and an expert focus group. Key findings include:

- Technologies are generally associated with **medium social risks**, especially related to supply chains and waste management.
- Local social acceptability is influenced by **procedural fairness, early engagement, and visible community benefits**.
- Concerns raised include **digestate management, safety, equity in benefit distribution**, and potential for NIMBY/NIMTO opposition if local actors are excluded.

The triangulation of quantitative (S-LCA) and qualitative (survey + expert focus group) insights provides a holistic view of the social dimensions of BIOMETHAVERSE technologies. These aspects will be further elaborated in subsequent deliverables, once demonstration data become available.

This preliminary assessment represents the first step in the broader evaluation of BIOMETHAVERSE innovations. Future work will involve:

- Incorporating **experimental data** from the demo plants once operational;

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- Refining **mass and energy balances**, especially for upscaled or optimised scenarios;
- Defining **mass and energy balances**, especially for upscaled or optimised
- Performing **techno-economic assessments**;
- Extending the **LCA** and **S-LCA** to a full suite of impact categories.

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