[D2.1] | Demonstrators Implementation Activity Plans

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1. BIOMETHAVERSE in a nutshell

BIOMETHAVERSE (Demonstrating and Connecting Production Innovations in the **BIOMETHA**ne uni**VERSE**) project will diversify the technology basis for biomethane production in Europe, by demonstrating increased cost-effectiveness of innovative biomethane production and upgrading pathways, increasing biomethane sustainability along the priorities of the SET Plan Action 8.

To this purpose five innovative biomethane production pathways which include one or a combination of thermochemical, biochemical, electrochemical and biological conversion processes will be demonstrated and implemented at plant scale in five European countries: France, Greece, Italy, Sweden, and Ukraine (Figure 1).

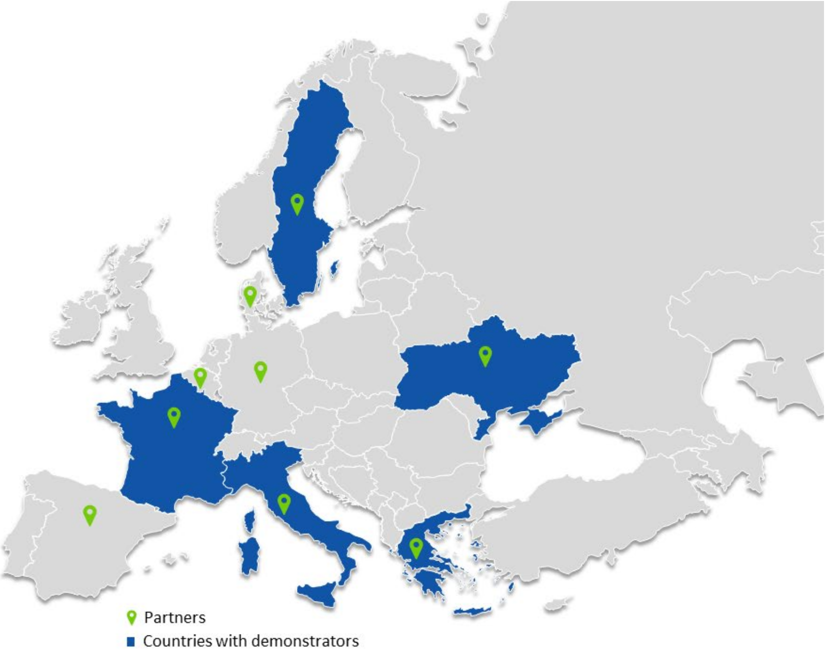

Figure 1- BIOMETHAVERSE countries and partners

The main objectives of the BIOMETHAVERSE project are:

- Demonstrate increased cost-effectiveness and innovative biomethane production.
- Increase biomethane sustainability by reducing GHG emissions.
- Ensure replicability and upscaling of the demonstrated biomethane production pathways.
- Ensure market penetration of the demonstrated technologies and produce policy recommendations.

In the BIOMETHAVERSE demonstrators, the CO_2 effluent in the biogas from anaerobic digestion (AD) or from gasification are combined directly with renewable power or in synergy with hydrogen to increase the overall biomethane yield, via thermochemical processes or by exploiting the biomethanation microbial potential.

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The five innovative technological concepts address sustainability and circularity as a whole, where waste, emission, and energy leakage are minimized by closing the energy and material loops while aiming at reducing the overall biomethane production costs and increasing biomethane production. In particular, all demonstrated production routes go beyond conventional technologies, contributing towards the European security of energy supply and increasing the biomethane production potential by about 60%. Using a participatory process involving stakeholders, BIOMETHAVERSE will ensure the replicability of demonstrated technologies and facilitate the market uptake for the five demonstrators by developing a strategic vision for project developers and insights guidance for ppolicymakers.

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

Table 1 - Innovative technological pathways in BIOMETHAVERSE and the related demonstration plants

Innovative Technological Pathway	Country and Demo leader
• *In-situ* and *Ex-Situ* Electro Methanogenesis **(EMG):** Electricity-enhanced biomethane production	France-ENGIE
• *Ex-situ* Thermochemical/catalytic Methanation (**ETM**): Thermochemical/catalytic upgrading of biogas using renewable hydrogen	Greece -BLAG
• *Ex-Situ* Biological Methanation **(EBM):** Biological upgrading of biogas using renewable hydrogen, including feedstock pre-treatment via ozonolysis	Italy-CAP
• *Ex-Situ* Syngas Biological methanation **(ESB):** biological methanation of syngas from thermal gasification with renewable hydrogen	Sweden-RISE
• *In-situ* Biological Methanation **(IBM):** Renewable hydrogen integration in the AD reactor	Ukraine-MHP

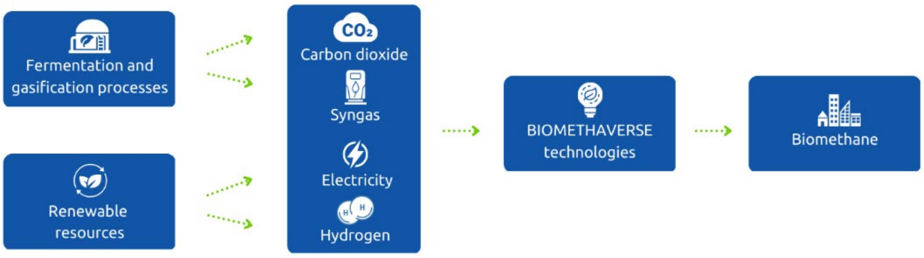

Figure 2 - Overview of innovative technological concepts in BIOMETHAVERSE

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2. Introduction

The present deliverable D.2.1 (Demonstrators Implementation Activity Plans), lies under the scope of Work Package WP2 – 'Demonstration of Innovative Biomethane Pathways' and complies with Task 2.1 description in Grant Agreement - Preparation and Planning of Demonstration Activities during the first six months' period from the start of the project.
A thorough implementation activity plan is presented for each demonstrators' concepts, addressing the timeframe (i.e. chronogram for implementation including the timeline for the preparation and execution of the demonstration), milestones, risks , and initial business perspective, thus enabling a global view on the innovative technological concepts.

General objectives of the implementation plan are the following:

- Detailed setting timeframe plan of activities for each demonstrator
- Promote discussion among demonstrator leaders and partners
- Gather results measurable and comparable for accurate analysis (WP4)
- Exchange experiences between demonstrators

European Biogas Association (EBA), WP2 coordinator, will perform a comprehensive management and monitoring of the five demonstrators and is entrusted to keep an active support channel catalyzing all queries and calling for the support of project experts based on their specific expertise (Figure 3). This task will take advantage of the ttransnationalopportunities afforded by the BIOMETHAVERSE project by sharing and discussing with each other demonstrator and partner in thematic dedicated workshops and site visits of the pilot solutions (see Task 1.1).

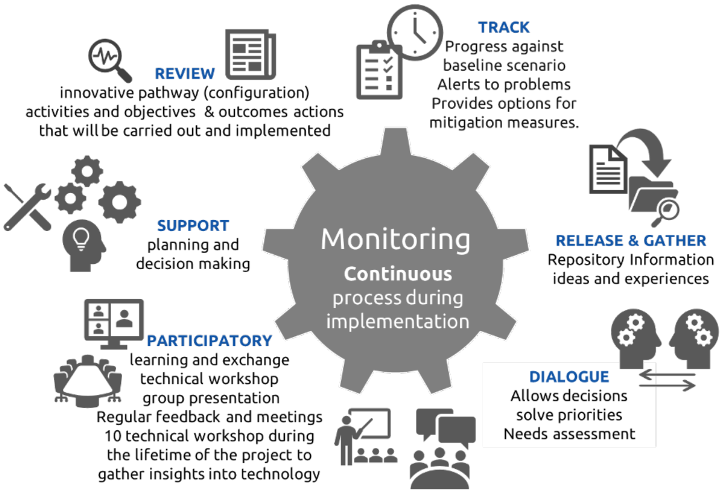


Figure 3 - EBA' monitoring strategy framework to ensure effective implementation of project activities

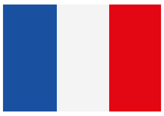
The demo monitoring is prepared in close cooperation with WP3. In particular, a crucial objective of this implementation plan is to ensure the evaluation phase, thus, that the results will be, in a future stage, measurable and comparable (WP3), also fitting the purposes of the replication analysis (WP4). Therefore, this work aims to optimize the outputs from each demonstrator. To comply with this objective, this document presents in detail the activities that the five demo leaders intend to compute, as next described.

3. FRENCH INNOVATIVE BIOMETHANE DEMONSTRATOR

3.1. *In-situ* and *ex-situ* Electro-methanogenesis (EMG): an electrochemical/biochemical route to produce biomethane from CO_2 and renewable electricity

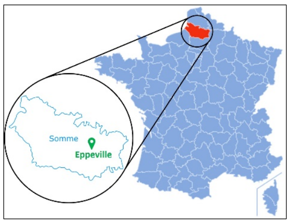
- **Production pathway**: electrochemical in combination with biochemical
- **Inputs**: CO_2 + electricity + water

3.2. Biogas and biomethane production in France



France is the fastest-growing biomethane market in Europe. By the end of 2021, 945 biogas plants and 365 biomethane plants are operational, of which 316 are connected to the distribution grid and 49 to the transport grid. Moreover, 151 new biomethane plants started operation in 2021, while another 112 plants were installed between January and September 2022. A further 1,149 projects are currently in various stages of development, representing a combined production capacity of 25.46 TWh/year. According to the EBA Statistical report (2022)[1], the total biogas production in 2021 amounted to 6,083 GWh and the biomethane production was 4,337 GWh. 460 GWh of biomethane produced (11%) is used in the transport sector. The country is home to a total of 153 filling stations supplying biomethane as a transport fuel.

3.3. Brief description of the site



The anaerobic digestion plant of ENGIE is located at Eppeville, in **Hauts de France** region, covers a 2.5 ha surface and produces 1,815,000 m^3 of CH_4 per year (18 GWh, gas consumption of 5,000 persons). Around 230 Nm3 h^{-1} are injected into the natural gas grid. Biogas is produced from 30,000 tons y^{-1} of agro-industrial and agricultural residues. The plant has a 6,000 m3 digestion volume with a hydraulic retention time higher than 50 days. The digestate is valorized through land-spreading (6,000 ha, 31 farms).

3.4. 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 AD microorganism's 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

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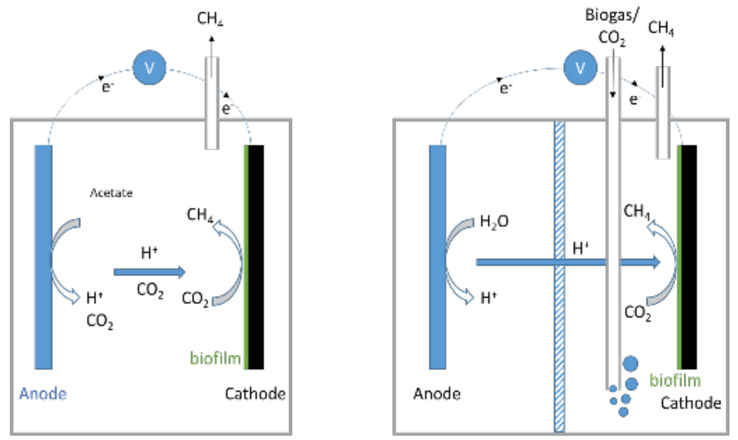
[1] EBA Statistical Report, 2022

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.[2]

Two configurations will be evaluated (Figure 4):

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 will be implemented to produce biogas with a biomethane content of 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**.



Single chamber reactor (1c-AD-BES) Double chamber reactor (2c-AD-BES)

Figure 4 - Two possible configurations of electro-methanogenesis

3.5. State of the art of the demonstrated technology

a) **Single chamber reactor (1c-AD-BES)**

For the past two years, the LEITAT laboratory has acquired a dozen 1 L **1c-AD-BES lab-scale reactors** to investigate the operating parameters and determine optimal reactor configurations. In addition, it has built two larger demonstrators: one 200 L reactor was built to treat sewage sludge in a wastewater treatment plant, where it operated for more than 6 months in the frame of the Smart Green Gas project.[3]

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[2] Geppert F, Liu D, van Eerten-Jansen M, Weidner E, Buisman C, Ter Heijne A. Bioelectrochemical Power-to-Gas: State of the Art and Future Perspectives. Trends Biotechnol. 2016 Nov;34(11):879-894. doi: 10.1016/j.tibtech.2016.08.010..

[3] www.nortegas.es/assets/uploads/2019/03/proyecto-smart-green-gas-en.pdf

Another reactor of 32 L was built in 2019 for biomethane production from wastewater, being further developed in the H2020 project ROBINSON[4] (2022-2024).
Although different from the AD-BES system due to the use of liquid wastewater substrate implying very different constraints in terms of flow management and reactor design, this system also relies on the bio-electrochemical working principle. The demonstration plant(s) built in the BIOMETHAVERSE project will capitalize on the research done in LEITAT to use streams with high organic contents from AD to increase their biomethane yield. Graphitic-carbon materials and stainless steel, especially those with three-dimensional structure, have been demonstrated to constitute superior biocathodes compared to other electrode materials.[5] Therefore, commonly commercial carbon brushes or felts are planned to be used.

FAU develops optimized bioelectrode structures for maximized extracellular electron transfer and is currently designing a platform for parallel electrode performance comparisons within the Emerging Talents Initiative.[6] High-performing bioelectrodes were identified to be one of the key factors for the industrial competitiveness of EMG technology. The fitting of electrode geometries and surface treatment protocols to the demonstrator plants will build on FAU's experience in bioreactor modelling with computational fluid dynamics.[7]

b) Double chamber reactor (2c-AD-BES)

DTU has developed several **lab-scale double chamber EMG systems** (0.5-20 L), focusing on optimizing the performance and exploring the maximum CH_4 production capacity. In one of the recent studies, an alternative and promising biocathode was demonstrated in the double chamber EMG reactor.[8] The maximum methane production rate was 202.15 L CH_4/m^2cat. per day, over three times higher than the maximum value reported so far.

3.5.1. Ambitions and progress beyond the state of art

The aim of this innovation is to increase biomethane production on the AD unit using the effluent digestate, biogas of the main digestor and external green electricity from solar and wind. Compared to the sole AD reactor, the goal is to produce up to 43% more biomethane thanks to the combination of both 1c-AD-BES (+20% compared to sole AD reactor) and 2c-AD-BES acting as an upgrading system to reach gas grid quality biomethane up to 95% CH_4. The pilot will be composed of two subsystems, both relying on electro-methanogenesis with the aim of evaluating their performances.

1) Single chamber reactor (1c-AD-BES)

The electrodes are directly immerged in the digestate. The planned pilot is a reactor of 1 m^3 with upstream and downstream digestate storage of 500 L. The storage is needed for ensuring continuous substrate feeding and will be used for reference measurements in terms of biogas/biomethane productions and influent/effluent digestate analysis. The reactor will be working at the same mesophilic temperature of the main AD plant. An electrical power source will be used for applying the needed voltage (< 2 V), driven by a renewable energy mix from local wind and photovoltaic electricity generators. The current performances of this system show that 1c-AD-BES can increase the biogas production rate by up to 96% compared to a sole AD reactor of equal volume, with coulombic efficiency (CE) of about 50%.[9] With the enhancement of the bioelectrode geometry and

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[4] Smart integRation Of local energy sources and innovative storage for flexiBle, secure and cost-efficIent eNergy Supply ON industrialized islands (GA number 957752) https://www.robinson-h2020.eu/

[5] https://www.sciencedirect.com/science/article/pii/S1385894719331043

[6] www.fau.eu/research/outstanding-individual-research/emerging-talents-initiative/grantees/

[7] https://www.evt.tf.fau.eu/research/schwerpunkte/2nd-generation-fuels/bmwi-projekt-power-to-biogas/; https://www.evt.tf.fau.eu/research/schwerpunkte/research-topics-prof-herkendell/bmwi-project-hy2biomethane/; https://www.evt.tf.fau.eu/research/schwerpunkte/research-topics-prof-herkendell/bmbf-project-multikulti/; https://www.evt.tf.fau.eu/research/schwerpunkte/energiesysteme-energiewirtschaft/bmwi-project-klaffizient/

[8] https://www.sciencedirect.com/science/article/abs/pii/S0306261920306139

[9] Coulombic efficiency is calculated based on the methane production over the electrical input in coulomb, in our case a 100% coulombic efficiency means that all the electron injected to the system will be involved in the CO_2 reduction into CH_4.

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electron transfer properties by prior surface treatment, the CE is aimed to be increased to above 67%.
By coupling the 1c-AD-BES downstream of the main digester, the aim is to have a surplus production of 100 L-CH_4/m^3d^{-1} to the already existing production. The system will be equipped with recirculation pumps and a set of pressure, temperature, and level sensors to ensure the monitoring and control of the pilot. Additionally, the outlet of the reactor will be equipped with a biogas analyzer. The gas outlet will be connected to the gas entrance of the second subsystem.

2) **Double chamber reactor (2c-AD-BES)**
The electrodes are separated by a membrane, which thus deconvolutes water oxidation (anodic part) and CO_2 reduction (cathodic part). This system will use water (in anode), digestate (in cathode), and biogas (from the main digestor first and then from 1c-AD-BES reactor), therefore enabling an efficient power-to-gas (P2G) process in an H_2O/CO_2 electrosynthesis cell. While the 1c-AD-BES step is aiming to maximize the biogas production rates, the 2c-AD-BES is an upgrading step towards maximum biomethane purity output. At the lab scale, the current 2c-AD-BES system can produce 200-1000 L CH_4 per day per m^3 reactor volume. Like the 1c-AD-BES reactor, the system will be equipped with recirculation pumps and a set of pressure, temperature, and level sensor to ensure the monitoring and control of the pilot as well as a gas analysis system to quantify the production of the pilot. The green-electricity enhanced biogas upgrading in the unique downstream coupling with the AD and 1-c-AD-BES is designed to yield grid-quality biomethane concentrations without further need for post-processing and conventional upgrading steps.

The expected methane content after the single chamber reactor is 70 – 80%.
Further biogas upgrading towards 95% CH_4) will be done by the double chamber reactor, installed in series to the single chamber one.

3.6. Challenges

Previous lab experiences showed that **two parameters contribute to increase biogas/biomethane production in AD-BES**: **(i)** the **increased available surface for biofilm growth**, due to electrodes presence, and **(ii)** the **application of an optimal voltage** for the stimulation of electro-active microbes. It is still an open challenge to optimize these two parameters together, to sum their beneficial effects in an upscaled AD-BES plant.
Next, **feeding the 1c-AD-BES with an already digested feedstock represents a challenge**, as some physical-chemical characteristics are sub-optimal (e.g., basic pH, low carbon/nutrients ratio, low biodegradability, and high viscosity). Moreover, **inoculation of anode and cathode with proper electro-active biofilms represents a challenge** as well, when targeting upscaled, industrial systems. The ideal solution is to cope with both electrodes' inoculation directly onsite, by direct voltage application (i.e., not using a potentiostat, which is quite common in lab experiments).
The key challenge of 2c-AD-BES is retaining high biomass in the cathode chamber and limited mass and electron transfer between microbes and electrodes. The potential solution is to develop novel electrode designs and more efficient and resilient biocatalysts in the cathode chamber. Recent work conducted at DTU showed that granular anaerobic sludge is an efficient cathodic biocatalyst, but the mass and electrons transfer from electrodes to the granular anaerobic sludge far in the cathode chamber need to be further optimized.
Thus, the aim is to optimize the mass and electrons transfer or more efficient methane production rate through novel electrodes materials and design and its interactions with microbes.

Previous work done by LEITAT and ENGIE showed that this approach is possible, but **biofilm populations are highly sensitive to applied operation conditions** (e.g. inoculum mixture, feedstock temperature, voltage). Especially on the cathode site, it is challenging to grow a specific biofilm catalysing CO_2 reduction to CH_4. For these reasons, **the current proposal foresees initial**

laboratory trials on digestate pre-treatment and electrodes surface treatment solutions for optimized biocatalyst-transducer interface and overpotential minimization.
Treatment protocols are aimed towards **(i)** enhancing electrical conductivity, **(ii)** increasing the surface area **(iii)** increasing the hydrophilicity **(iv)** doping positive surface charges, **(v)** incorporating porosity (micro-/nanostructures), and **(vi)** increasing biocompatibility and microbial adhesion.
Besides, the interaction between the cathode electrode, and novel viable biocatalysts such as granular sludge could be better understood and manipulated to boost biomethane production.
The process will be computationally modelled to identify critical electrode parameters limiting the heterogeneous electron transfer kinetics throughout the EMG process.
At lab scale, the aim is to:

- test continuous feeding conditions
- estimate an energy balance of the AD-BES processes
- perform a preliminary economic analysis.

Although it is clear from the literature that the energy produced in biomethane form, by such systems, is higher than the electricity input provided to the electrodes, a global balance including all auxiliary equipment, at pilot scale, is required.

3.7. Economic Viability and Business Outlook

The direct usage of electricity to produce additional biomethane will allow for a cheap option of energy storage: excess renewable electricity cannot always be injected into the electricity grid or is not economical at peak production times. **The EMG systems can be operated intermittently according to the availability of renewable electricity**.

Microbial methane formers used in biological methanation are currently the only catalyst sources able to provide biomethane purities of gas-grid quality without expensive post-processing steps, even though at lower space-time yields than with thermochemical biomethanation. The use of cheap excess electricity for the proposed bio-electrochemical methanation route combines the high yieldable purity with largely enhanced production rates.
1c-AD-BES offers a possible adds-on solution for already existing AD plants. The 1c-AD-BES commercial size will need a moderate investment in terms of CAPEX and low OPEX, a significant increase in biogas production can be achieved which could lead to a **decrease of about 13% in biomethane** cost compared to our previous results.
On the other hand, **2c-AD-BES represents a solution for biogas upgrading**, CO_2 emissions reduction and valorisation to additional CH_4, yielding high purities that qualify for natural gas grid injection without further processing steps. The coupling of 1c- and 2c-AD-BES enables the separate optimization of high throughput and high purity with the help of green electricity resulting in a **total increase in biomethane production of about 43%**. The high tolerance of the microbial communities in the AD-BES towards feed impurities (e.g., H_2S), the selective metabolic pathways towards CH_4 production, and the low thermal input requests at operating stages between 38-65°C, as well as the effortless adjustment of the AD-BES systems to varying loads (AD feed, electricity supply) offer unparalleled economic advantages over conventional biomethanation routes.

An additional major factor for the economic feasibility and broad applicability of the proposed EMG coupling is the **absent need of green hydrogen supply**. Unlike other biomethanation routes, the protons needed for CO_2 reduction are generated *in-situ* by electrochemical oxidation of digestate (1c-AD-BES) and water (2c-AD-BES) directly with the applied voltage. **Conversion losses in H_2 production (e.g., via electrolysis) and H_2 storage and supply to remote AD locations are omitted**, therefore increasing the cost-effectiveness of decentral AD units.

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The technology of 1c-AD-BES is consolidated at TRL4, with biological and electrochemical reactions well understood, and operational parameters optimized at the laboratory scale. During the last years, we have made experimental trials with different digestate substrates and inoculum types, different temperatures and applied voltages. Biogas production rate and its CH_4 content can be estimated based on adopted feedstock and operational conditions.

The technology of 2c-AD-BES is consolidated at TRL4. We have successfully developed and investigated a novel EMG system using intact anaerobic granular sludge as cathodic biocatalysts in an attempt to achieve high-efficiency CH_4 production. The 2c-AD-BES technology was further optimized and achieved the highest record of biomethane production in the field of EMG.

The initial strategy for electro-methanogenesis penetration on the market is based on strong communication with the different actors of the sector such as farmers, local authorities and industries. The first identified segment is the French market quickly followed by other EU countries. Thanks to the positioning of ENGIE group in the sector of biomethane and its affiliated entities, several potential scenarios and opportunities for commercialization of AD-BES technology will be investigated as in the following examples.

- **ENGIE Bioz's target market**, i.e. large units (>250 Nm^3h^{-1} of biomethane) that valorize biogas in the form of biomethane for injection into gas networks towards natural gas substitution (versatility of usages such as cookers, boilers, heat generation and gas mobility). To this end, ENGIE has strong territorial anchoring in France thanks to its subsidiary ENGIE Bioz and its "Sales and Territory Department" (Direction Commerciale et Territoire-DCT). Furthermore, ENGIE is established through its geographical Business Units in countries where biomethane is a booming market, namely: ENGIE Brasil, ENGIE Asia Pacific, ENGIE NECST (North, South and Eastern Europe).
- **Electro-methanogenesis (1c-ADBES) technology is suitable for direct implementation in digestor**. However, for practical reasons the foreseen commercialization is mostly envisaged either for new AD unit construction and /or implementation retrofitting of digestate storage towards maximizing the biomethane production of the unit with one given amount of feedstock. ENGIE Bioz through the acquisition of Vol-V Biomass is the operator and owner of AD units and will therefore be able to include ADBES technologies in their requirement specification towards the implementation of the different technological solutions (1c-ADBES for increased biogas production and or 2c ADBES for biogas upgrading). In European and non-European markets, ENGIE has strong links with local equipment manufacturers to ensure the design and construction of these units.
- **Portage to the target market with Biogas Plus (ENGIE subsidiary)**. Biogas Plus is the manufacturer of AD units from small-scale farm units to large-scale ones (i.e., ENGIE Bioz). Biogas Plus is already established in this market of biogas plants and therefore has all the assets to market electro-methanogenesis technologies. Beyond carrying the commercial offer of the technology. As a manufacturer, Biogas Plus will therefore be able to take charge of the design and construction of AD-BES solutions that fit client requirement needs. Thanks to the usage versatility of these power-to-bio approaches, the commercialization and manufacture of scaled AD-BES technical solutions (adapted to feedstock or required biomethane production) would represent a strong asset for this ENGIE subsidiary AD unit manufacturer.
- **Portage with manufacturers of biogas plants** who would be able to sell AD-BES solutions via a system of Royalties or Licensing with different companies (such as example valogreen or Naskeo which are two companies well integrated in the AD plant construction ecosystem in France). Towards the portage of electro-methanogenesis solutions to these manufacturers, technical and economical communication will be realized at the French level by participating in different conferences and expositions (e.g. Bio360 Nantes 2023).

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BIOMETHAVERSE project will enable us to shed light on the necessary steps towards increasing TRL level (Figure 5). Thanks to the project activities, the goal of the research is to achieve a TRL of 8 enabling the deployment of electro-methanogenesis technology in a reproducible way in all regions concerned by the development of AD, whether in France, Europe or worldwide. International development will also be driven by all subsidiaries present in most European countries and in nearly 70 countries around the world, the vast majority of which are interested in anaerobic digestion as illustrated in Figure 6.

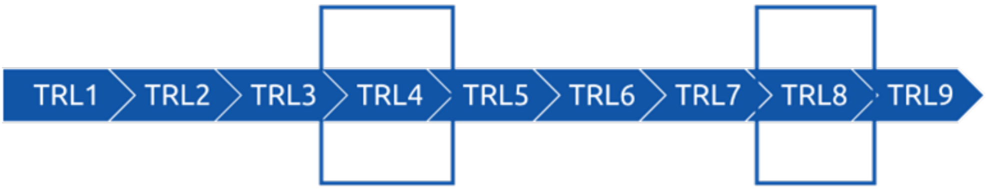

Figure 5 - TRL (Technology Readiness Level) for In-Situ and Ex-Situ Electro-methanogenesis

Figure 6 - Development of the number of biogas plants (Source SCG Consulting/CEDIGAZ)

3.8. Timeline -Implementation Schedule- Chronogram for implementation

The innovative production pathway (EMG) will be developed through the application of different approaches and will be divided into specific activities/tasks that will contribute to improving the conversion into biomethane and its cost-effectiveness.

These activities/tasks will be:

- **Activity 1: Pre-treatment of the feedstock and lab scale study**

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- **Activity 2 Electrodes characterization/treatment**
- **Activity 3: Reactor engineering and pre-pilot testing**
- **Activity 4: Micro-organisms/electrode interactions**
- **Activity 5: Pilot construction and safety study**
- **Activity 6: Testing of the pilot in separated mode**
- **Activity 7: Full pilot testing**

A Gantt chart for planning the project with all the activities is presented in Figure 7. All activities and tasks are described in detail in Tables 2-3-4-5-6-7-8.

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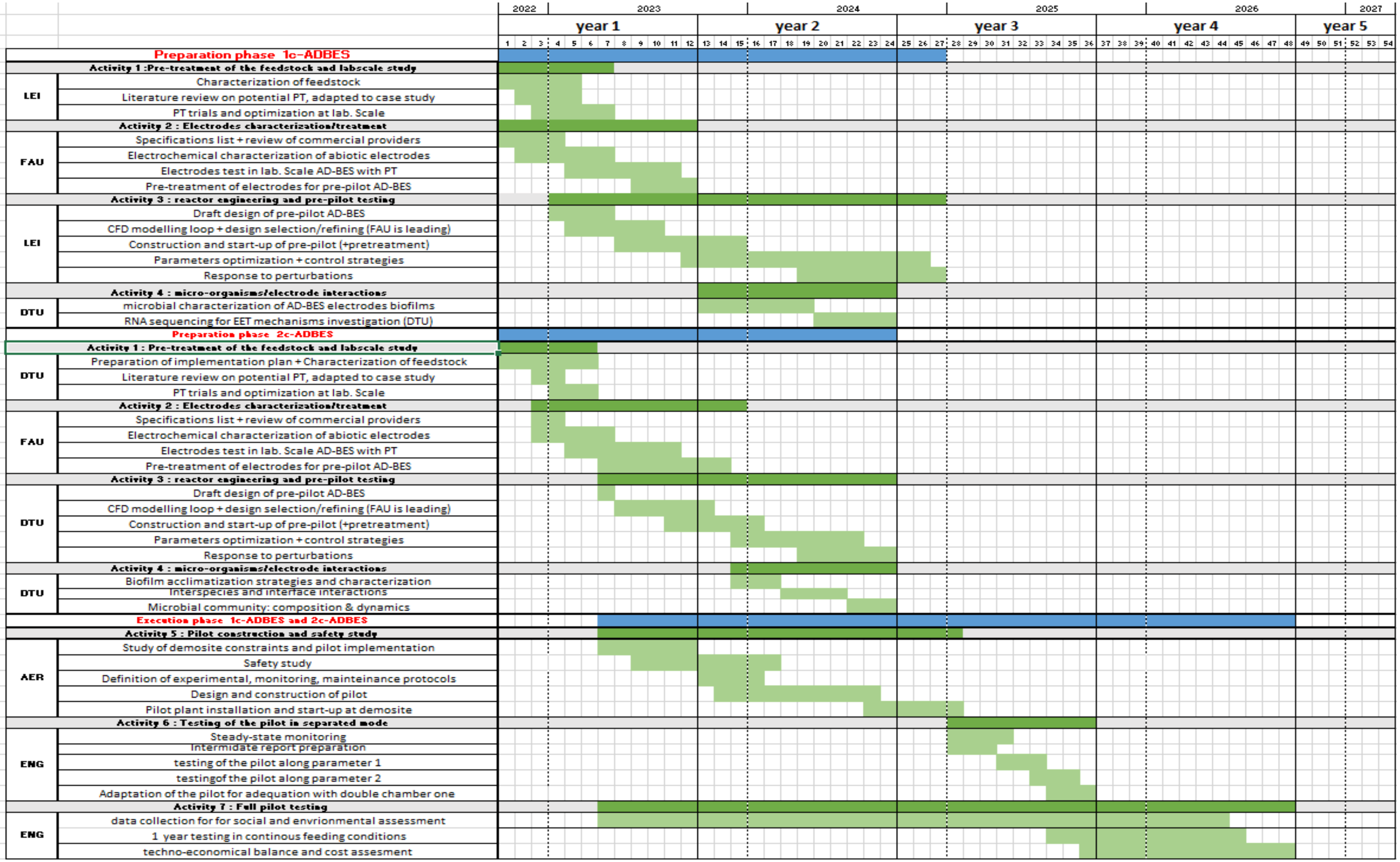

Preparation phase 1c-ADBES	
Activity 1 :Pre-treatment of the feedstock and labscale study	
LEI	Characterization of feedstock
	Literature review on potential PT, adapted to case study
	PT trials and optimization at lab. Scale
Activity 2 : Electrodes characterization/treatment	
FAU	Specifications list + review of commercial providers
	Electrochemical characterization of abiotic electrodes
	Electrodes test in lab. Scale AD-BES with PT
	Pre-treatment of electrodes for pre-pilot AD-BES
Activity 3 : reactor engineering and pre-pilot testing	
LEI	Draft design of pre-pilot AD-BES
	CFD modelling loop + design selection/refining (FAU is leading)
	Construction and start-up of pre-pilot (+pretreatment)
	Parameters optimization + control strategies
	Response to perturbations
Activity 4 : micro-organisms/electrode interactions	
DTU	microbial characterization of AD-BES electrodes biofilms
	RNA sequencing for EET mechanisms investigation (DTU)
Preparation phase 2c-ADBES	
Activity 1 : Pre-treatment of the feedstock and labscale study	
DTU	Preparation of implementation plan + Characterization of feedstock
	Literature review on potential PT, adapted to case study
	PT trials and optimization at lab. Scale
Activity 2 : Electrodes characterization/treatment	
FAU	Specifications list + review of commercial providers
	Electrochemical characterization of abiotic electrodes
	Electrodes test in lab. Scale AD-BES with PT
	Pre-treatment of electrodes for pre-pilot AD-BES
Activity 3 : reactor engineering and pre-pilot testing	
DTU	Draft design of pre-pilot AD-BES
	CFD modelling loop + design selection/refining (FAU is leading)
	Construction and start-up of pre-pilot (+pretreatment)
	Parameters optimization + control strategies
	Response to perturbations
Activity 4 : micro-organisms/electrode interactions	
DTU	Biofilm acclimatization strategies and characterization
	Interspecies and interface interactions
	Microbial community: composition & dynamics
Execution phase 1c-ADBES and 2c-ADBES	
Activity 5 : Pilot construction and safety study	
AER	Study of demosite constraints and pilot implementation
	Safety study
	Definition of experimental, monitoring, mainteinance protocols
	Design and construction of pilot
	Pilot plant installation and start-up at demosite
Activity 6 : Testing of the pilot in separated mode	
ENG	Steady-state monitoring
	Intermidate report preparation
	testing of the pilot along parameter 1
	testingof the pilot along parameter 2
	Adaptation of the pilot for adequation with double chamber one
Activity 7 : Full pilot testing	
ENG	data collection for for social and envrionmental assessment
	1 year testing in continous feeding conditions
	techno-economical balance and cost assesment

Figure 7 - Gantt chart showing overview of timeline and schedule of the phases and the activities for innovative production pathway (EMG)

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3.8.1. Activity 1: Pre-treatment of the feedstock and lab-scale study

Firstly, the focus will be on the characterization of digestate obtained from the demo-site, with an investigation into the various streams available within the biogas plant (M1-M6).

The feedstock will be characterized in terms of chemical oxygen demand (COD), biological oxygen demand (BOD_5), NPK nutrients, pH, electrical conductivity, solids alkalinity among other physical-chemical parameters. The focus will be on identifying potential inhibition factors that could limit AD/electro-methanogenesis process. Parameters such as C/N ratio, ammonium, or potassium concentrations, VFAs profile, etc and the pre-treated solution will drive the evaluation and the selection of the feedstock.

Tow potential pre-treatments (PT) will be tested at 1-5 L -scale, with the possibility of upscaling the, based on literature studies that confirm a positive energy balance. The focus will be on selecting physical pre-treatments that increase the surface area of the biomass by reducing particle size without generating secondary inhibitory compounds.

Sieving is one of the proposed pre-treatments as it has been reported that the filtered liquid fraction produces higher biomethane yields compared to untreated manure (agricultural residues)[10,11].

Furthermore, the solid-liquid separation pre-treatment, which removes the solid fraction, could hhelp prevent electrodes clogging.

The other planned pre-treatment will be grinding the feedstock with a mechanical cutter system of 1500 W since reduction of particle size have a positive impact on biogas production[11]. This activity will be performed by LEITAT, with constant feedback from ENGIE Crigen and ENGIE Bioz. The target of this activity is to select the optimum pre-treatment that allows improving biomethane production.

The time planning and summary of tasks for Activity 1 are shown in Table 2.

Table 2 - Summary of tasks, schedule and responsible for the Activity 1- Pretreatment of the feedstock and lab scale study

Activity 1: Pretreatment of the feedstock and lab scale study				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Preparatory/Design Preparation 1c ADBES	• Characterization of feedstock	M1	M5	LEITAT
	• Literature review on potential PT, adapted to case study	M2	M5	
	• PT trials and optimization at lab-scale	M3	M7	
Preparatory/Design Preparation 2c ADBES	• Characterization of feedstock	M1	M6	DTU
	• Literature review on potential PT, adapted to case study	M3	M4	
	• PT trials and optimization at lab scale	M4	M6	

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[10] Woraruthai, T., Jiemanukunkij, T., Tirapanampai, C., Weeranoppanant, N., Chaiyen, P., & Wongnate, T. (2022). Solid-Liquid separation through sieve mesh for enhancing biogas production in a swine farm. *International Journal of Energy Research*, *46*(11), 15362-15375. https://doi.org/10.1002/er.8236

[11] Li, Y., Zhao, J., Krooneman, J., & Euverink, G. J. W. (2021). Strategies to boost anaerobic digestion performance of cow manure: Laboratory achievements and their full-scale application potential. Science of The Total Environment, 755, 142940. 10.1016/j.scitotenv.2020.142940

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3.8.2. Activity 2: Electrodes characterization /treatment

The first task in this activity will be to search for suppliers of carbon brushes and their manufacture (the main options are Mill-Rose and BAUMGARTNER). Then, electrochemical characterization and pre-treatment of electrodes will be carried out. In doing so, physical and electrochemical analyses will be performed before and after the pre-treatment of electrodes.

Possible pretreatments may include the modification of electrode with nanoparticle catalysts, applying heat or chemical or mechanical treatments. The final selection will consider the costs, effects on the biofilm and the digestate, the environmental impacts and its long-term stability.

Electrochemical characterization consists in cyclic voltammetry, where different reactions and their overpotentials could be distinguished, and electrochemical impedance spectroscopy (EIS), where charge transfer resistance of the electrodes with different pretreatments and the capacity of the systems can be compared.

Moreover, a set of batch trials with 1 L scale AD-BES will be tested, evaluating the effectiveness of the digestate pretreatment options proposed during Activity 1.

Six reactors are available at LEITAT and will be used for this activity (Figure 8).

Figure 8 - Laboratory set-up for activity 2 with 6 1L reactors available at mesophilic conditions and connected to gas collector bags

Performance of the lab-scale AD-BES system will be monitored in terms of biogas/biomethane production rate, solids removal from digestate, current density at a defined potential and cyclic voltammetry for electroactive biofilms characterization.

Based on these results, FAU will conduct a Computational Fluid Dynamics (CFD) simulation to analyze the species interactions and the flow distribution in order to identify any potential for optimization in the design. ICEM 19.1 software will be employed for the geometry and mesh of the reactors and electrodes. For the setup of the cells and the final results, Fluent 19.1 software will be used.

Biofilm samples from the electrodes will be collected at different stages, during laboratory tests, to evaluate how digestate and/or electrode pretreatment can affect the ability (and selection) of microorganisms to attach to the surface of the electrodes.

The 16s region of DNA content will be amplified and sequenced in order to determine microbial population diversity and taxonomical composition. In addition, the possibility of studying the microbial population at the functional level by whole-genome shotgun sequencing analyses or by qPCR of specific genes related to electro-methanogenesis (e.g. *ehaB, ehbL, mvhA, hdrA.*) will be evaluated.

Target of this activity is to define digestate and electrodes pre-treatment that will be upscaled to pre-pilot level, the base performance of 1c-ADBES system and the composition and metabolic potential of the microbial populations colonizing the electrodes.

The time planning and summary of tasks for Activity 2 are shown in Table 3.

Table 3 - Summary of tasks, schedule and responsible for the Activity 2- Electrodes characterization /pre-treatment

Activity 2- Electrodes characterization /pre-treatment				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Preparatory/Design Preparation 1c ADBES	• Review of commercial providers	M1	M4	FAU
	• Electrochemical characterization of abiotic electrodes	M2	M7	
	• Electrodes test in lab-scale AD-BES with PT	M5	M11	
	• PT of electrodes for pre-pilot AD-BES	M9	M12	
Preparatory/Design Preparation 2c ADBES	• Specifications list + review of commercial providers	M3	M4	FAU
	• Electrochemical characterization of abiotic electrodes	M3	M7	
	• Electrodes test in lab-scale AD-BES with PT	M5	M11	
	• PT of electrodes for pre-pilot AD-BES	M7	M14	

3.8.3. Activity 3: Reactor engineering and pre-pilot testing

Activity 3 will consist of 3 stages:

- draft design of the pre-pilot,
- adaptation to BES systems
- operation of BES systems

The first draft will combine the designs based on previous knowledge of LEITAT, the literature found about electrodes/surface ratio, distance and position and also the CFD modelling calculations. Then, the reactor will be modified to be able to fit all electrodes and necessary electrochemical equipment securely. Following the inoculation of the system, parameters such as voltage, on the pre-pilot will be optimized and control strategies such as a start-up, switch-off or voltage cycling will be developed.

Target of this activity is to evaluate the performances of 1c-ADBES at an intermediate scale between lab and pilot, in continuous feeding conditions.

Performance in terms of yields, mass and energy balance, and physicochemical characterization relative to different bioconversion scenarios will be compared. The data obtained will be used to

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inform techno-economic models, life-cycle cost and environmental impact assessment.In the 2c-ADBES, the aim of this activity is to increase the mass and electron transfer between electrode and microbes for more efficient CO_2-to-CH_4 conversion. The optimization will be first done on lab-scale and then based on the knowledge, a pre-pilot reactor will be designed.

The time planning and summary of tasks for Activity 3 are shown in Table 4.

Table 4 - Summary of tasks, schedule and responsible for the Activity 3- Reactor engineering and pre-pilot testing

Activity 3- Reactor engineering and pre-pilot testing				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Preparatory/Design Preparation 1c ADBES	• Draft design of pre-pilot AD-BES	M4	M7	LEITAT
	• CFD modelling loop + design selection/refining	M5	M10	FAU
	• Construction and start-up of pre-pilot (+PT)	M8	M15	LEITAT
	• Parameters optimization + control strategies	M12	M26	
	• Study of the response to perturbations	M19	M27	
Preparatory/Design Preparation 2c ADBES	• Draft design of pre-pilot AD-BES	M7	M7	DTU
	• CFD modelling loop + design selection/refining (FAU is leading)	M8	M13	
	• Construction and start-up of pre-pilot (+PT)	M11	M16	
	• Parameters optimization + control strategies	M15	M22	
	• Response to perturbations	M19	M24	

3.8.4. Activity 4: Micro-organisms/electrode interactions

For a better understanding of the performance of microbial acclimatization on the electrodes, it is necessary to identify the hydrogenotrophic methanogens and evaluate their abundance.

Besides, to investigate the cell-electrode interaction, it is also important to reveal the distribution of each culture as the function of electrode materials and pre-treatments. In this light, high-throughput sequencing will be used to analyse the microbial community composition during the acclimatization period in the different parts of the system (cathode electrode, liquid, interior surface of the reactor and membranes) including both 1c-ADBES and 2c-ADBES. The biofilm will be characterised using optical/confocal microscopy and electrochemical cell impedance spectroscopy.

The unveiled correlation between microbial community/activity and electrodes will guide the selection of electrodes and the operation of pilot-scale reactors. DTU has extensive experience and access to the facilities for this activity.

The time planning and summary of tasks for Activity 4 are shown in Table 5.

Table 5 - Summary of tasks, schedule and responsible for the Activity 4- micro-organisms/electrode interactions

Activity 4 : Micro-organisms/electrode interactions				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Preparatory/Design Preparation 1c ADBES	• Microbial characterization of AD-BES electrodes biofilms	M13	M19	DTU
	• RNA sequencing for Extracellular Electron Transfer (EET) mechanisms investigation (DTU)	M20	M23	
Preparatory/Design Preparation 2c ADBES	• Biofilm acclimatization strategies and characterization	M15	M17	DTU
	• Interspecies and interface interactions	M18	M21	
	• Microbial community: composition and dynamics	M22	M24	

3.8.5. Activity 5: Pilot construction and safety study

The pilot construction will be realized by AERIS based on the technical recommendations of LEITAT, DTU and FAU regarding the design and operation of the reactor. Towards the proper implementation of the pilot plant on the ENGIE Bioz unit, 2 safety studies will be realized.

The first one (M9) will be a HAZID study aiming at identifying the risk associated with the implementation of pilots at the demo site (joint action between ENGIE teams-Bioz/Crigen and AERIS). The results of this study as well as the description of the demo site constraints and interface (e.g. digestate, water, electricity) as well the required civil work will be capitalized in an internal deliverable summing-up this different information. On the basis of this deliverable, the final Piping and Instrumentation Diagram (P&ID) as well as the user manual will be done by AERIS in order to realize the second safety study (HAZOP). This HAZOP will focus on the safety associated with the direct operation of the pilot. Upon completion of the aforementioned safety study, the pilot design will be finalized and the pilot construction will commence. Prior to the installation of the pilot (M23), commissioning will be realized at AERIS in order to check the proper functioning of the 2 subsystems.

The time planning and summary of tasks for Activity 5 are shown in Table 6

Table 6 - Summary of tasks, schedule and responsible for the Activity 5- micro-organisms/electrode interactions

Activity 5: Pilot construction and safety study				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Execution 1c ADBES +2c ADBES	• Study of demo site constraints and pilot implementation	M7	M12	ENGIE
	• Definition of experimental, monitoring, maintenance protocols	M13	M16	AERIS
	• Design and construction of pilot	M14	M23	AERIS
	• Safety studies (HAZID and HAZOP)	M9	M17	ENGIE
	• Pilot plant installation and start-up at the demo site	M23	M28	AERIS

3.8.6. Activity 6: Testing of the system in separate modes (single chamber reactor and double chamber reactor)

The pilot-scale 1c-AD-BES and 2c-AD-BES will be operated continuously for 9 months (M28-M36), feeding it with the selected digestate stream from the main AD plant, at the optimized organic loading rate from pre-pilot experiments. This activity will allow achieving information regarding biomethane production rate and quality, digestate treatment efficiency, process yield, and energy efficiency.

The collected data will allow a mass and energy balance of the system as well as inform techno-economic models, life-cycle cost and environmental impact assessment and will be shared with WP3 for further analysis and comparison with the other demo sites. It will be possible to estimate the biomethane surplus generation potential of a commercial plant, treating all the digestate streams available from the main AD plant.

Target of this activity is to calculate CAPEX, OPEX and biomethane production cost of the pilot electro-methanogenesis technology developed through previous activities.

The time planning and summary of tasks for Activity 6 are shown in Table 7

Table 7 - Summary of tasks, schedule and responsible for Activity 6 Testing of the pilot in separated mode

Activity 6: Testing of the pilot in separated mode				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Execution 1c ADBES + 2c ADBES	• Steady-state monitoring	M28	M31	ENGIE
	• Testing of the pilot along parameter 1	M31	M33	
	• Testing of the pilot along parameter 2	M33	M35	
	• Adaptation of the pilot for connecting 2 subsystems	M34	M36	
	• Steady-state monitoring	M28	M31	

3.8.7. Activity 7: Full pilot testing

The activity of full pilot testing will focus on 2 aspects: delivery of necessary data for WP3 and WP4 and testing of the pilot in its relevant environment.

Three periods are planned for the delivery of economic, social and environmental data: M18 M35 and M41. These dates have been set in accordance with the delivery date of WP3 deliverables (M28, M33, M36, M38, M42 and M44)

The last part of experimental trials at pilot scale will be performed with the two technologies of 1c and 2c-ADBES hydraulically coupled (M34-M51). The digestate treated by the 1c-ADBES will be tested as electrolyte in the cathode chamber of the 2c-ADBES system. The biogas produced by the 1c-AD-BES will be upgraded by injecting it into the cathode chamber of the 2c-AD-BES, where the residual CO_2 content will be converted to additional methane.

Target of this activity is to evaluate the long-term performance of the system, stability of electrodes, maintenance requirements of the plant, both steady state and transition performance depending on punctual digestate quality, weather conditions, a necessity to switch off the plant periodically. To do so a dedicated testing plan will be built jointly with the partners based on the first results obtained at the pre-pilot scale. The different results that will be gathered during the testing phase will serve for a technical-economic analysis aiming at evaluating both the cost of the technological solution towards a full upscaled pilot and the associated biomethane cost.

The time planning and summary of tasks for the Activity 7 are shown in Table 8

Table 8 - Summary of tasks, schedule and responsible for the Activity 7 Testing of the pilot in separated mode

Activity 7 : Testing of the pilot in separated mode				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Execution 1c ADBES + 2c ADBES	• Data collection for social and environmental assessment	M7	M44	AERIS
	• 1 year testing in continuous feeding conditions	M34	M45	ENGIE
	• Techno-economical balance of the pilot towards cost assessment for technology and produced biomethane	M36	M48	

3.9. Milestones

The specific milestones the project are shown in the Table 9.

Table 9 - Milestones of EMG

Milestone N°	Key Milestone name	Month of completion	Major Tasks
MS2	Lab scale readiness	M12	Lab scale study for digestate and electrode adequacy with EMG.
MS6	HAZOP study, pilot construction implementation	M24	HAZOP study and guidelines to start the operation of the pilot.

3.10. Risks

Several risks are defined with their probability and impact and mitigation measures. The delay in materials, electrodes or reactor delivery is very probable (the only electrode supplier lasts 6-8 months for the delivery) and it has a high impact on the developed activities as they will be delayed without materials. To mitigate that possible scenario, within the first months of the project new suppliers and other alternative solutions are searched to be able to have all necessary equipment for 2nd and 3rd years of the project.

Another setback could be the impossibility of continuous feed the reactor due to tubes, pumps or electrodes clogging. Its probability is low although its impact is high. To avoid it, the feedstock could be sieved to remove the solid fraction or a strategy for electrodes cleaning could be implemented. When investigating the performance of the digestate pre-treatments, could be that neither of them leads to a positive energy balance. Mechanical pre-treatments can be an energy-intensive process; therefore, the probability of a negative energy balance is medium. However, the impact is low because if the pre-treatment gets a negative energy balance, other pre-treatments are going to be

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searched and will focus on other effects like pathogen inhibition, dewaterability or reduction of odour.

Last, the pre-treatment for electrodes could also not lead to higher biomethane production. Its probability of occurrence is medium, but its impact is low. To avoid that lower biomethane production, pre-treatments must be studied and characterized carefully before introducing them to the reactor. If in that stage a lower activity is seen, pre-treatment will be changed.

The list of risk factors that may occur during the demo phases along with mitigation measures are shown in Table 10.

Table 10 - Risk probability/ impact on the EMG Innovative technological pathway and potential risk mitigation strategies

Risk	Probability of Risk	Impact of Risk	Mitigation measures
R8: Electro-methanogenesis sub-systems are not well integrated	Low	High	Clear technical specifications of sub-systems are to be defined before construction and installation onsite.
R9: Slow growth of electroactive bacteria on the electrodes, a decrease of their activity, limited current density, limited CH_4 production	Medium	Medium	If failure analysis through electrochemical, engineering, microbiological techniques, process operation modifications will be applied accordingly. Bioaugmentation strategies using inoculum available at LEITAT/DTU.

3.11. Exploitation

An energy provider will test and operate the pilot with the production of biomethane (ENGIE), while research entities will perform lab scale study (LEITAT and DTU), accompanied by a university (FAU) to study the electrode/digestate adequation, as well as performing modelling study to facilitate the setting up of the final pilot design. The pilot design and construction will be performed by AERIS. Once implemented on the AD plant, the testing of the pilot will be realized by ENGIE. The appropriate policy and commercial exploitation will be ensured mainly by ENGIE.

The results of the project demonstrator (through ENGIE) will contribute to carbon neutrality by 2050 of the Climate Plan of France (National Low-Carbon Strategy) of the PPE (multiannual energy programming), and to the adjustment of those plans if the effective decarbonization can take place before this date. They will also support the national scheme to diversify the energy mix by developing the P2G sector (objective of 140 TWh in 2050) and contribute to the implementation of policy decisions of the CRE (Energy Regulatory Commission) in the biogas production targets for 2050 (the 2030 objective being production to represent 10% of gas consumption). After the project, this will involve, in particular, studies of complementarity with existing biomethane plants, with the objective to recover the CO_2 effluents at the outlet of these units.

ENGIE skills in the accounting of the gas produced with the injection networks will pave the way for the commercialization of tested innovations. The objective during the last year of the project will be to define and frame the different aspects (technical and contractual) of the injection of biomethane produced by electro-methanogenesis technology into the network of the specific plant pilot, regarding connection procedures, traceability and guarantee of origin, gas quality, and changes in energy systems. An assessment of the various network links, as well as the potential avenues for adapting downstream infrastructure for the biomethane produced by the technology and

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equipment, will be necessary to mitigate the potential obstacles of technology on the road to commercial exploitation. Moreover, the following measures will be engaged:
Patents of the different technology components (integrated bio electrochemical system unit for 1 chamber configuration within the digestor/post digestor; - electrode manufacturing/electrode geometry for 2 chamber configurations; - 2 chamber configurations adopted for the upscaled system)
Complete business plan: the electro-methanogenesis could be commercialized by ENGIE's subsidies as having some Business units to build and/or operate AD units, with options for licensing system;
Integrating the electro-methanogenesis into a real scale post-digester.

3.12. Block Flow Diagram

The Block Flow Diagrams (BFD) as well as the initial Process Flow Diagram (PFD) of both pilot' subsystems are presented in Figure 9 and 10.

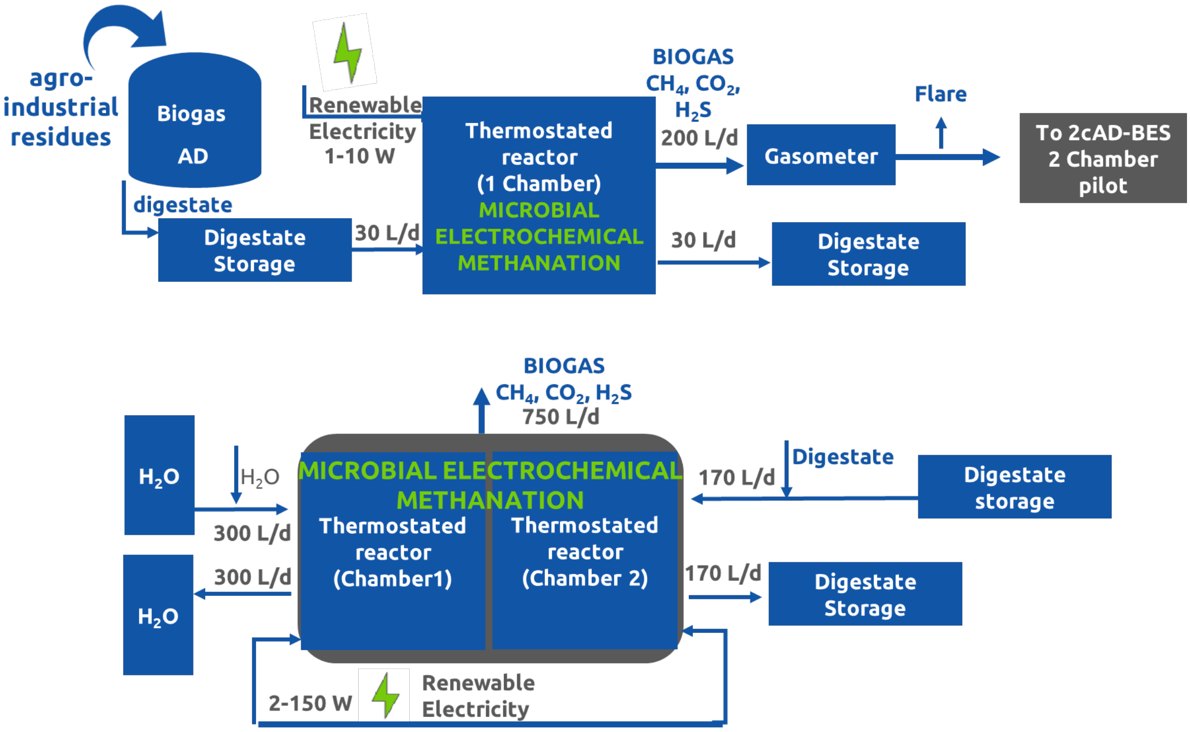

Figure 9 - Block Flow Diagram for 1c-ADBES (single chamber reactor) and 2c-ADBES (double chamber reactor)

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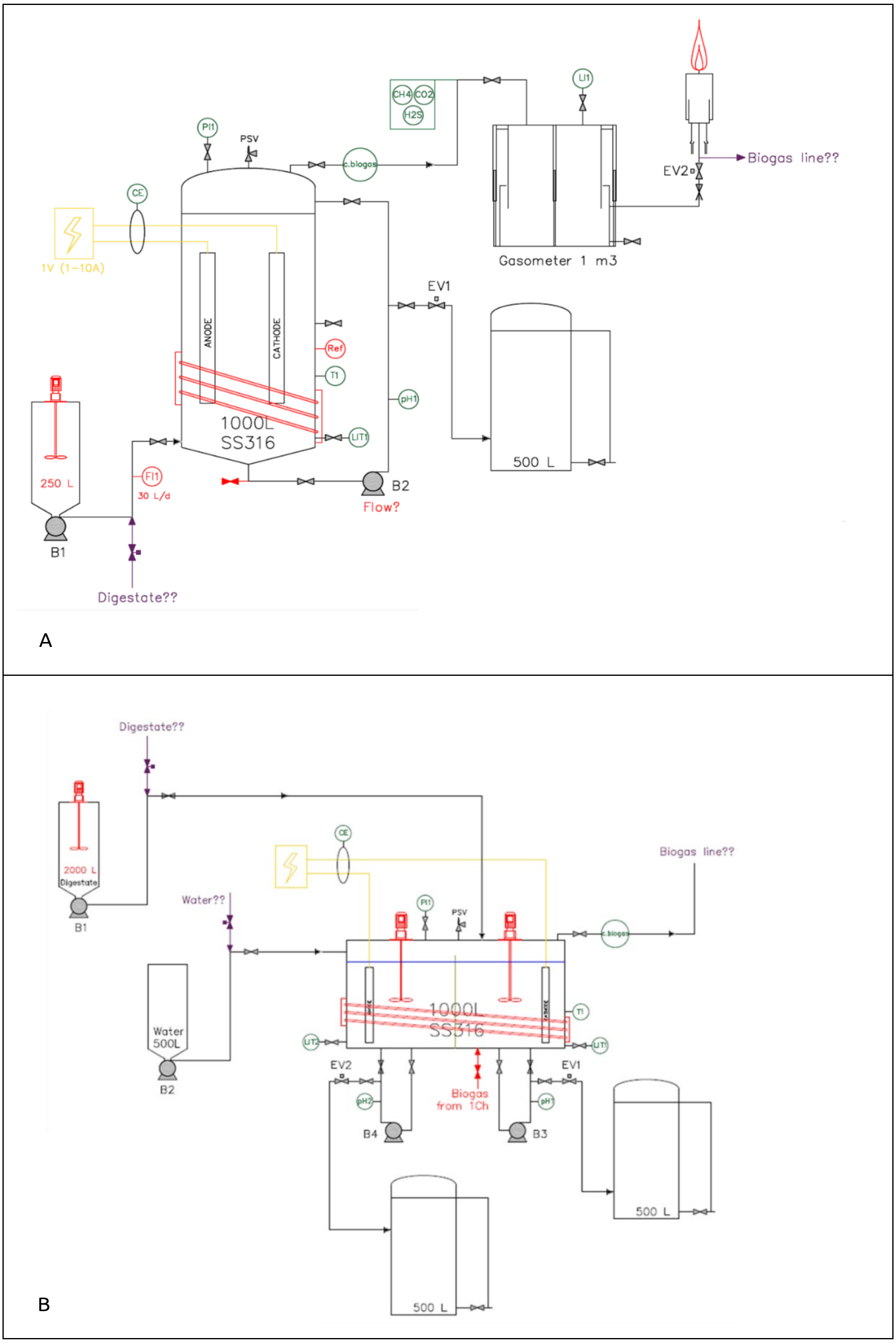

Figure 10 - Process Flow Diagram for A. 1c-ADBES (single chamber reactor) B. 2c-ADBES (double chamber reactor)

4. GREEK INNOVATIVE BIOMETHANE DEMONSTRATOR

4.1. *Ex-Situ* - Thermochemical/catalytic Methanation (ETM)

- **Production pathways**: thermochemical
- **Inputs**: CO_2 + hydrogen

4.2. Biogas and Biomethane production in Greece

In 2021, Greece was home to **67 operational biogas plants** and the total reported Greek biogas production for 2021 was 1,199 GWh. The support mechanism in place since 2016, encouraged growth in the Greek biogas sector with steady growth in the number of agriculture-based biogas plants and the production that has reached 465 GWh in 2021.

There is currently **no biomethane market** in Greece. Discussions are underway with the ppolicymakers and the transmission system/gas distribution network operators for the injection of the biomethane into gas network. Due to the fact of competitive feed-in tariff prices for electricity production (L.4414/2016)[12], the equivalent price for biomethane should be estimated based on the existing tariff prices for electricity.

4.3. 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 80,000 tonnes of livestock waste per year, yielding 8,400 MWh of electricity and 75,000 tonnes of organic soil improver suitable for fertilizing 5,000 acres of agricultural land. The plant has a capacity of 290 m^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 $1MW_e$.

4.4. 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:

- Cleaning and compressing step of the biogas
- catalytic methanation reaction,
- dehumidification of the final biomethane stream.

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[12] http://www.hellenicparliament.gr/en/Vouleftes/Vouli-ton-Ellinon-Vouleftes/Βιογραφικό-Σημείωμα/?MPId=8387a012-57a2-4d74-b14a-4f4c9099ec9a

The final product is biomethane already reaching pipeline quality gas standards (e.g., 96-98 vol-% CH_4), no further upgrading is necessary.

4.5. State of the art of the demonstrated technology

The biomethane production of the pilot plant is based on **catalytic technology**, with a well-proven equipment, i.e., fixed bed reactors and tube heat exchangers. The technology is being **demonstrated** in China combined **with coal gasification** and there have as well been conceptual designs for bio-syngas. However, **the technology has not yet been demonstrated on biogas**. Hence, the technology starts from TRL5.

4.5.1. Ambition and progress beyond the state of the art

The examined technology will be transferred for the first time to the biogas application at TRL7. In specific, a catalytic technology will be **integrated into the industrial LAGADA biogas plant**. The produced biomethane will meet the requirements of pipeline quality (96- 98 vol-% CH_4). The target is to produce a total of 15,000 m^3 of biomethane. The input biogas flow will be 6 Nm^3/h, while the output flow of the upgrading unit will yield an additional 2.4 Nm^3h^{-1} biomethane corresponding to the conversion of the CO_2 stream into biogas stream.

The CH_4 contained in biogas stream (3.5 Nm^3h^{-1}) will be incorporated into the output flow as well. **Hence, via the thermochemical/catalytic methanation, the methane content will be increased from 60% in the input stream towards more than 95% in the output stream.** T

The aim is to operate the pilot plant for a total of **6,000 hours**. The target for the total energy efficiency of the process is 61%, defined as the energy content of the biomethane produced divided by electricity consumption to produce renewable hydrogen by electrolysis.

4.6. Challenges

The most attractive configuration for the methanation section will be identified taking into consideration several factors, including but not limited to **heat exchange**, **catalyst type**, **process temperature and pressure**.

Essential aspects which must be considered amongst others are (i) **catalyst deterioration and contamination** (ii) **safe distribution of H_2** to the pilot unit and tank replenishment (iii) **appropriate automation** with the respective controller unit, and finally (iv) **successful operation with regeneration cycles of the catalyst**.

The catalyst has been extensively tested for the treatment of syngas produced from the gasification process, so relevant protocols and step-by-step methodology have already been developed and to be used for the biogas case study at TRL 7. In addition, renewable hydrogen has a significant contribution to the process. Hence, accurate and secure handling and provision are considered critical for the implementation of the project. The basic engineering includes a safety study for the hydrogen storage at biogas plant facilities, distribution through piping system to the upgrading plant and the blending stage. The hydrogen supply will be evaluated within the project.

Finally, **the operation parameters, such as temperature, pressure, biogas composition will be controlled during the demo activities**, in order to evaluate the process itself and recognise any deviations (lower biomethane yield than expected, lack of hydrogen, no ideal conditions for the catalyst). During the BIOMETHAVERSE project, all the aforementioned measures will be investigated to **identify possible edge effects at scale** for the transition of the biogas Lagada plant to a full-scale biomethane production plant.

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4.7. Economic viability and Business Outlook

In contrast to other available technologies, biogas separation before the catalytic process is not required, and there is no need for product recycle compressors. This strategy of avoiding the rrecyclingof reaction gases reduces the high operating and maintenance costs associated with conventional upgrading, as well as the respective capital costs. A preliminary economic analysis was carried out in order to estimate the cost savings compared to conventional technologies (mainly membranes). The analysis was carried out for the full scale of the biogas plant located at Lagada.
The CAPEX is expected to increase by 5-10%, due to additional elements required such as the electrolyzer, and hydrogen tank will be taken into consideration as well.

In addition to the initial capital investment, it should be noted that the operating expenses (OPEX) for this technology will also increase by approximately 10% compared to conventional technologies. The challenges posed by the current energy crisis and the likelihood of inflationary pressure mean that rising logistics costs also need to be taken into account. Therefore, in general, the increase in OPEX can be attributed to the higher maintenance and energy cost required, but it should be weighed against the potential benefits and savings that can be achieved. In particular, the increase in the biomethane production of about 58% will significantly decrease the cost.

According to preliminary estimates, the total cost of (ETM) Innovative technological pathway is expected to be 20-25% lower compared to conventional technologies. A detailed cost analysis will be carried out in WP3 during the implementation of the project. The pilot campaign results (different composition of biogas, range of feedstock), obtained during the project, will allow BLAG to proceed to the feasibility and engineering studies for the scale-up activities at their facilities covering the full biogas potential capacity. The commercialization strategy behind this technology is to take advantage of the upcoming establishment of a regulatory framework for biomethane production in Greece, as it is anticipated that a competitive feed-in tariff mechanism will be applied. In addition, if successful, this technology could be replicated for similar retrofitting activities enabling the main stakeholders of BLAG to implement the same technology in an additional biogas plant that they operate at Serres (Nigrita biogas plant). Thanks to the project activities, the goal of the research is to achieve a TRL7 (Figure 11).

Figure 11 TRL for Ex-situ Thermochemical/catalytic methanation (ETM) Innovative technological pathway

4.8. Timeline- Implementation Schedule- Chronogram for Implementation

The innovative production pathway (ETM) will be developed through the application of different approaches and will be divided into specific activities/tasks that will contribute to improving the conversion in biomethane production and its cost-effectiveness.

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These activities/tasks will be:

- **Activity 1: Initial implementation plan**
- **Activity 2 Design package for the thermochemical technology and preparatory activities**
- **Activity 3: Pilot manufacturing**
- **Activity 4: Pilot commissioning**
- **Activity 5: Operational testing**

A Gantt chart for planning the project with all the tasks is presented and all activities are described in Figure 12. All activities and tasks are described in detail in Tables 10, 11, 12, 13 and 14.

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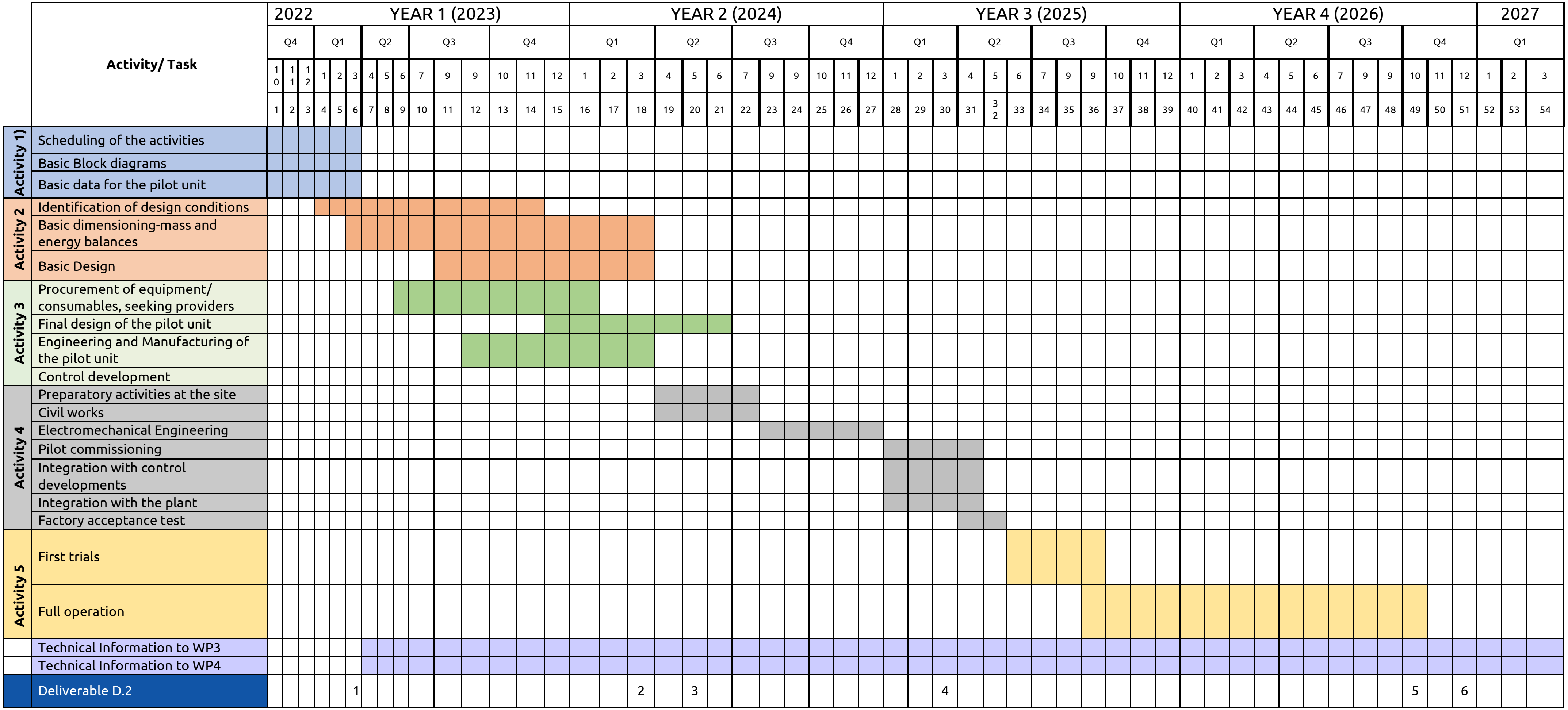

	Activity/ Task	2022			YEAR 1 (2023)												YEAR 2 (2024)												YEAR 3 (2025)												YEAR 4 (2026)												2027		
		Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1		
		10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Activity 1)	Scheduling of the activities	■	■	■	■	■	■																																																
	Basic Block diagrams	■	■	■	■	■	■																																																
	Basic data for the pilot unit	■	■	■	■	■	■																																																
Activity 2	Identification of design conditions				■	■	■	■	■	■	■	■	■	■	■																																								
	Basic dimensioning-mass and energy balances						■	■	■	■	■	■	■	■	■	■	■	■	■																																				
	Basic Design											■	■	■	■	■	■	■	■																																				
Activity 3	Procurement of equipment/ consumables, seeking providers									■	■	■	■	■	■	■	■	■																																					
	Final design of the pilot unit															■	■	■	■	■	■	■																																	
	Engineering and Manufacturing of the pilot unit												■	■	■	■	■	■	■																																				
	Control development																																																						
Activity 4	Preparatory activities at the site																			■	■	■	■																																
	Civil works																			■	■	■	■																																
	Electromechanical Engineering																							■	■	■	■	■																											
	Pilot commissioning																												■	■	■	■																							
	Integration with control developments																												■	■	■	■																							
	Integration with the plant																												■	■	■	■																							
	Factory acceptance test																															■	■																						
Activity 5	First trials																																	■	■	■	■																		
	Full operation																																				■	■	■	■	■	■	■	■	■	■	■	■	■	■					
	Technical Information to WP3							■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Technical Information to WP4							■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Deliverable D.2						1												2		3										4																			5		6			

Figure 12 - Gantt chart showing overview of timeline and schedule of the phases and the activities for innovative production pathway (ETM)

4.8.1. Activity 1: Initial implementation plan

This activity corresponds to all preparatory activities regarding the scheduling of the activities and providing of initial block diagrams for the technology, as well as the main mass and energy balances regarding the demo operation.

A categorization of activities will be carried out, in order to synchronize the work among the involved partners. In addition, basic block diagrams will be designed, in order to present the main components of the demo. Finally, energy and mass balances will be provided for the operation of the demo following the main exports obtained from lower TRL activities in the past regarding the application of the proposed technology.

The time planning and summary of tasks for Activity 1 are shown in Table 11.

Table 11 - Time planning of Activity 1- Design package for the thermochemical technology and preparatory activities

Activity 1: Initial implementation plan				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Preliminary description of the expected results	Scheduling of the activities	M1	M6	CERTH
	Basic block diagrams	M1	M6	CERTH, BLAG
	Basic data for the design of the pilot unit	M1	M6	CERTH, BLAG

4.8.2. Activity 2: Design package for the thermochemical technology and preparatory activities

Activity 2 concerns mainly the basic design of the technology. According to the initial calculations, the basic dimensioning of the demo, including all the relevant components, will be carried out. Based on data obtained from the biogas plant at Lagada the design conditions will be determined.

Therefore, the overall description of the demo plant and detailed description of the units in addition to the biogas plant without BIOMETHAVERSE technology. For each process unit: detailed mapping of biogas plant equipment, especially the piping system, will be carried out in order to provide a basic design for the pilot unit and its potential integration with the biogas plant. Based on data obtained from the biogas plant at Lagada the design conditions will be defined to address the selection of optimal process conditions. This will help to minimize the risk of unexpected failures that could impact performance or safety. Within this activity a detailed description of the reaction as well as their associated kinetics, along with a specification for the input and output flow will be provided.

Relevant mass and energy balances, including specifics on the input and output flow, will be implemented in line with the quantified targets of the project. The information and results collected during this phase and collected on a regular basis over the course of the project will be transferred to WP3 (M15) and it will be used for D.2.2.

For each process unit: Design-point, off-design and/or stand-by operation conditions.

The time planning and summary of tasks for Activity 2 are shown in Table 12.

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Table 12 - Time planning of the Activity 2- Design package for the thermochemical technology and preparatory activities

Activity 2: Design package for the thermochemical technology and preparatory activities				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Design of the technology, including all the relevant required components	Identification of design conditions	M4	M14	CERTH
	Basic dimensioning-Mass and energy balances	M6	M18	BLAG
	Basic design Overall description of the demo plant and detailed description of the demo plant units in addition to the biogas plant without the ETM technology.	M11	M18	BLAG, CERTH

4.8.3. Activity 3: Pilot manufacturing

Activity3 concerns mainly pilot manufacturing, including all the additional required components such as the required control systems. In specific, BLAG in collaboration with CERTH will seek providers of equipment and consumables required for manufacturing the prototype unit. A relevant market survey will be carried out.

Following up the updates received from biogas plant and corrective actions, the final design of the pilot unit will be completed. Control requirements, SCADA automation systems to be used in the pilot site will be developed.

To ensure that the process is operated safely, efficiently, and in compliance with regulatory requirements the following aspects will be considered:

- operating and control philosophy
- emergency scenarios followed by mitigation plans
- expected ramp-up/down rates in combination with the sizing and selection of sensors data sheet, control panel diagrams.

In the meantime, the engineering and manufacturing of the pilot unit will be in progress. The pilot unit will be constructed at a workshop under the supervision of BLAG and CERTH. The time planning and summary of tasks for Activity 3 are shown in Table 13.

Table 13 Time planning of the Activity 3- Pilot manufacturing

Activity 3- Pilot manufacturing				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Manufacturing of the pilot	Procurement of equipment/consumables	M9	M16	BLAG
	Final design of the pilot unit	M12	M18	CERTH, BLAG
	Engineering and Manufacturing of the pilot unit	M19	M27	BLAG
	Control development	M16	M27	BLAG, CERTH

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4.8.4. Activity 4: Pilot commissioning

The aim of Activity 4 is to perform the erection, installation, and commissioning of the pilot unit in Lagada area in accordance with the designed specification and work schedule. Preparatory activities, such as the preparation of the site, and licensing issues will take place in advance. Civil works infrastructures for access and connections will be provided as well. The pilot unit will be erected at Biogas Lagada plant. All the mechanical-electrical connections will be implemented accordingly.

The control system will be adapted to the pilot needs and integrated in SCADA systems. At the commissioning phase, the required tests will be performed to ensure the correct system operation according to the requirements.

The entire Commissioning process is developed as follows:

a) Mechanical Completion Check
b) Pre-Commissioning tests which shall include the appropriated inspections and functional tests
c) Commissioning and start-up.

During this activity, training for O&M personnel for the pilot unit will be organized about its operation and maintenance.

The deliverable D2.4 "Intermediate Implementation report" will be delivered on M30. Preliminary data for the manufacturing and commissioning stage will be collected as well within this deliverable in order to be used for the activities in WP3.

The time planning and summary of tasks for Activity 4 are shown in Table 13.

Table 14 - Time planning of the Activity 4- Pilot commissioning

Activity 4- Pilot commissioning				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Pilot Commissioning	• Preparatory activities at the site	M19	M22	BLAG
	• Electromechanical Engineering	M23	M27	BLAG,CERTH
	• Pilot commissioning	M28	M31	BLAG, CERTH
	• Integration with control developments	M28	M31	BLAG,CERTH
	• Integration with the plant	M28	M31	BLAG, CERTH
	• Factory acceptance test	M31	M32	BLAG

4.8.5. Activity 5: Operational testing

This task will manage and execute the demonstration ensuring that all relevant systems are operating according to the predefined specifications and identified risks. First trials will be taken place, in order to identify any problems. Measures to mitigate possible problems will be taken during the demonstration phase. BLAG and CERTH teams will undertake any maintenance/corrective actions that are required, while they monitor the demonstration phase during the relevant period.

The deliverable D2.5 Final Implementation Report (with Blueprints of the pilot plants) will be delivered on M49. The pre-final exports of the demo implementation will be gathered including the monitoring results which are directly linked to WP3 and WP4 activities regarding the environmental and economic assessment of the demo. In addition, an update of the data regarding the manufacturing of the pilot and commissioning of the pilot will be carried out as well based on the demo activities.

The time planning and summary of tasks for Activity 5 are shown in Table 15.

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Table 15 - Time planning of the Activity 5 - Operational testing

Activity 5- Operational testing				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Operation of the pilot unit	First trials	M33	M36	BLAG
	Full operation	M37	M49	BLAG

4.9. Milestones

The demonstration of ETM includes two main milestones shown in Table 16. MS9 refers to the pilot manufacturing of the unit, while MS10 refers to the factory and site acceptance of the unit. Then first trials will be carried out, in order to set up the operational procedure of the unit.

Table 16 – Milestones of ETM

Milestone N°	Key Milestone name	Month of completion	Major Tasks
MS9	Pilot manufacturing	M30	Assembly of the core equipment at Lagada site.
MS10	Integration-Factory Acceptance Test (FAT) and Site Acceptance Test (SAT)	M32	Integration with the biogas plant (including licensing and operational certifications).

4.10. Risks

The relevant risks are provided in Table 16. All the relevant engineering studies will take place in advance in order to avoid any technical issues regarding the integration of the pilot unit with the biogas plant at Lagada.

In addition, since this is a catalytic process, the selection of the appropriate catalyst will be carried out following the experience of BLAG and CERTH in previous projects that correspond to the treatment of syngas from the gasification process. The list of risk factors that may occur during the demo phases along with mitigation measures is shown in Table 17.

Table 17 - Risk probability/ impact on the ETM Innovative technological pathway and potential risk mitigation strategies

Risk	Probability of Risk	Impact of Risk	Mitigation measures
R10: Technical issues on integrating the new biomethane plant with the existing plant	Low	High	• Basic engineering studies by CERTH and BLAG to set up the new installations in an appropriate way
R12: Poor performance in biomethane yield	Low	High	• CERTH and BLAG is experienced on catalysts, so they will select the most appropriate ones for the investigated process

4.11. Exploitation

CERTH (research entity) has a solid background in the engineering and operation of the biomethane plant. BLAG in collaboration with CERTH will provide the design of the biomethane plant based on the specifications of the biogas plants. BLAG (biogas plant owner) will implement the pilot design, construction and full integration of the pilot plant with the support of CERTH, while the latter will take part in the operation of the pilot plant. Once the pilot plant is constructed, it will be tested for Factory Acceptance Test (FAT) and Site Acceptance Test (SAT) by the aforementioned Greek demo team.
The appropriate exploitation will be ensured by BLAG (for commercial one) and CERTH (for policy one).

From a policy perspective, the results of the project will contribute to the preparatory activities regarding biomethane penetration and the establishment of a regulatory/legislative framework for biomethane production in Greece. Those results for Greece will be exploited mainly by CERTH, which is involved in policy working groups with policy stakeholders (ministry, committee for renewable gases), and with all key stakeholders (gas distribution network operator, gas transmission operator and market GoO operators). In addition, CERTH will address dimensioning and location planning of new biomethane plants, including the BIOMETHAVERSE technologies, as well as the technical specification for the integration of the project results within existing AD plants in Greece.

As mentioned above from the initial business perspective the pilot campaigns results (different composition of biogas, range of feedstock), obtained during the project, will allow BLAG to proceed to the feasibility and engineering studies for the scale-up activities at their facilities covering the full biogas potential capacity. A relevant legislative framework is required to be established in prior in order to give economic initiatives to the BLAG stakeholders to proceed to the relevant activities. In particular, BLAG stakeholders are interested to proceed to similar retrofitting activities in Nigrita biogas plant that they operate as well.

4.12. Block Flow Diagram

The Block Flow Diagrams (BFD) of the *Ex Situ* Thermochemical/catalytic Methanation (ETM) process the is presented in Figure 13

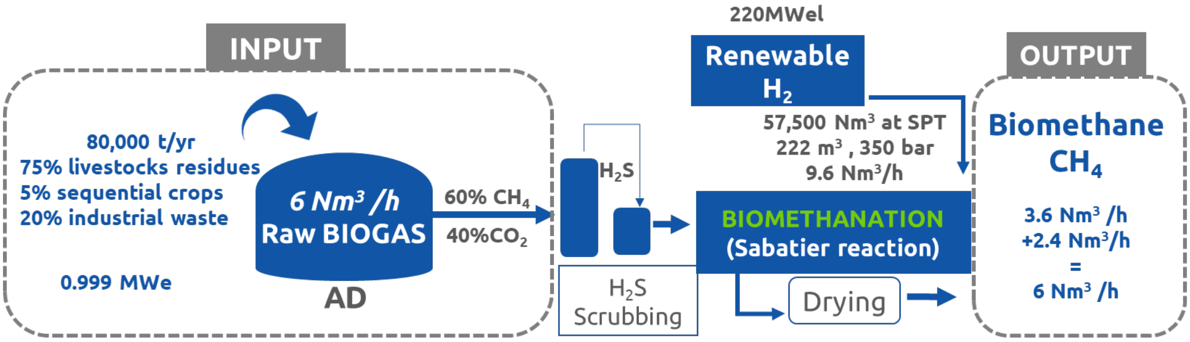


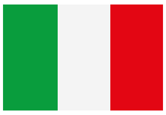
Figure 13 - Block Flow Diagram for the ex-situ Thermochemical/catalytic methanation (ETM) process

5. ITALIAN INNOVATIVE BIOMETHANE DEMONSTRATOR

5.1. *Ex Situ* Biological Methanation (EBM)

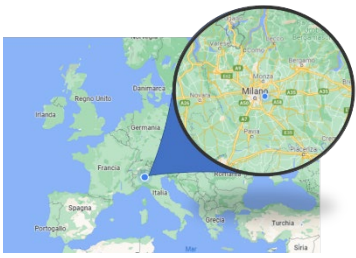
- **Production** pathway: biological
- **Input**: CO2 +hydrogen

5.2. Biogas and biomethane production in Italy



Italy, one of the top biogas-producing countries in the EU27, represents the 2nd EU biogas market after Germany in terms of the number of plants (over **1,900 operational anaerobic digestion plants in 2022**) With total biogas production of 24 TWh in 2021, Italy is one of the fastest growing biomethane markets in Europe The Italian biomethane sector grew from 12 plants in 2019 to reach **35 operational biomethane production plants** by end of 2022 that were able to produce about 320 million m^3 per year. A rapid grow of biomethane production is be expected in the coming years, as the achievement of 3.5 bcm/yr or 37 TWh has targeted. Projections suggest that Italy will become one of the leading bio-LNG-producing countries in Europe. Eight bio-LNG plants are currently in operation in Italy and about thirty plants are at different stages of development and under construction; all of these are due to become operational between 2022 and 2025. Having 1,542 CNG stations, 126 LNG ones, and more than 1 million CNG vehicles in 2020, Italy is the European country with the most extensive network of gas filling stations and the biggest market for gas vehicles. In 2023 the new regulatory framework (the New Biomethane Decree) in Italy for incentive measures will run and accompany the country's development of biomethane sector allocating 173 billion EUR partially funds from the Recovery and Resilience Facility ('RRF'/ NRRP), (introduced for coping impacts of the COVID-19 pandemic), and combines assets and reforms for additional biomethane production. Moreover, the incentive tariffs have an estimated budget of 2.8 billion over a 15-year operational period. Such measures aim at promoting investments in new plants or reconverted plants (from biogas to biomethane) and encourage biomethane injection into the national gas grid for use also in sectors other than transport (e.g., heating for industrial, tertiary, and residential sectors).

5.3. 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 neighbourhood 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^3h^{-1} of inflow from sewer, it currently produces about 90 m^3h^{-1} of biomethane.

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5.4. 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 of 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.

5.5. State of art of the demonstrated technology

As part of the PERFORM WATER 2030 project, funded by the Lombardy Region, **SIAD performed laboratory-scale and preliminary pilot-scale studies for the ozonolysis process as pre-treatment of the sludge** intended for AD to optimize the biogas production.
The lab-scale application involved the ozone treatment of both pre-thickened and digested sludge, at different dosages, ranging from 20 to 140 $gO_3\ kg^{-1}$ volatile solids (VS).
The increase in volatile solids biodegradability resulted in a 38% increase in biogas production and the higher ozone doses were a relevant factor in improving the biogas yields. The main objective of the pilot test was to evaluate any inhibition of the process. In a small AD reactor serving around 30,000 PE (Gruppo CAP), 30% of the sludge fed was pre-treated with ozone, at the lowest dosage. The preliminary test results showed that no inhibition occurred, lower H_2S content in the biogas and an increasing rate of solubilization of organic components.

POLIMI tested the biological biogas upgrade in previous projects, both *in-situ* (V = 15 L, fed with sludge) and *ex-situ*. In the latter case, a pilot (TRL3) was placed in WWTP managed by Gruppo CAP, operating in CSTR mode and was fed with raw biogas for approximately 32months This reactor rapidly increased the concentration of hydrogenotrophic methanogens in stable conditions, although low hydrogen transfer efficiency. Based on these results, the reactor concept (Figure 14) evolved to the one that will be demonstrated here, starting from a TRL3-4.

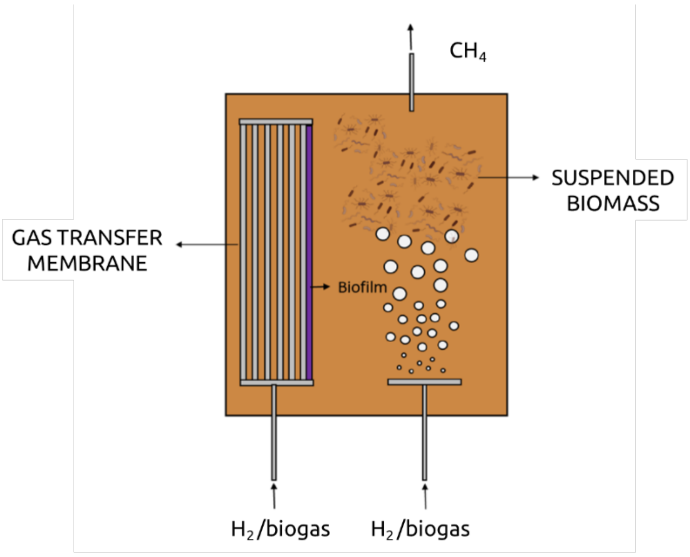

Figure 14 - Concept of EBM upgrade pilot scale reactor

5.5.1. Ambition and progress beyond the state of the art

The pilot will consist of **two main units**: the feedstock pre-treatment via ozonisation and the ex-situ biological upgrading. Furthermore, **two auxiliary units**, the micro-algae reactor and the co-digestion unit will complement the two main units. The **pre-treatment unit** will allow increasing **the biogas yield from sewage sludge**, the **upgrading unit** will **convert produced biogas into biomethane** via an ex-situ hydrogen-promoted biological upgrading process. **The pre-treatment unit and the upgrading unit will be integrated considering that hydrogen for the biological upgrading and oxygen for the ozone production will be obtained from a single water electrolyser**, also included in the demonstration plant. Furthermore, unconverted carbon dioxide will be sent to an algal pond to evaluate its recovery by means of biomass growth. Finally, co-digestion of sludge with microalgae, integrated with process modelling will be demonstrated as a technological approach for increasing the biogas yield and its CO_2 content optimization, by **controlling the effective mixing of two or more co-substrates** and operating conditions.

a) Feedstock pre-treatment via ozonolysis

New plant configurations for the contact reactor will be evaluated and designed to make the ozone transfer more efficient on a full scale. Achieving such a result would allow a consistent increase in biogas production even for low ozone doses, reducing costs and maximizing the economic viability of the integrated system. Therefore, such a **design improvement can allow a 20% increase in the biogas production yield** even for dosages of 25 gO_3 kg^{-1} VS as observed on a laboratory scale. Furthermore, this experimentation aims to evaluate the full-scale quality of the ozonolysis process as a treatment for digestate recirculation and evaluate the effects of ozone on sludge dehydration for both scenarios. The quantified data on the sludge reduction to be disposed of will constitute a fundamental element in confirming the economic sustainability of the process.

b) Ex-situ biological upgrading

The ex-situ prototype reactor (V = 160 L) is designed to **combine in a single tank the CSTR and Gas-Transfer Membrane biofilm reactor**. In this innovative configuration, H_2 is supplied in two ways: to the biofilm by the lumen of the membrane and to the suspended biomass, by gas diffusion. The inherent flexibility of this configuration will **maximize conversion and energetic efficiency under rapidly variable H_2 input flow, as expected because of the variable availability and cost of renewable energy**. Balancing the membrane contact transfer and the gas-liquid sparging will allow not just to optimize the energy consumption, but also a more dynamic response of the overall biological process. The reactor will operate at an overall hydraulic loading rate (HLR) of 20 m^3 $H_2 \cdot m^{-3}$ $reactor \cdot d^{-1}$ and above, with **expected biomethane content above 95% and very low residual H_2 content**. It will be equipped with automatic measure and control devices to maintain the desired operating conditions (pH, °T, HRT, Q gas in).

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c) Pilot-scale microalgae reactor

The pilot raceway (V = 1080 L, A = 5.8 m^2) will **treat the liquid fraction of digestate continuously, and it will be operated to allow for the full exploitation of digestate nutrients** (NLR = 50 g Nm^{-3} d^{-1}). The liquid depth of the raceway will be kept at 0.2 m, providing sufficient light penetration. An HRT of 10 d will be set, to be further adapted according to influent nutrient loads and environmental conditions. The intensity of paddlewheel rotation will be regulated to guarantee a minimum liquid velocity of 0.2 m/s and sufficient mixing while minimizing the overall mass transfer to reduce unwanted gaseous emissions.

d) Pilot-scale co-digestion reactor

A **CSTR pilot anaerobic reactor** (V = 60 L), with online temperature, pH, and redox monitoring in the liquid phase and online acquisition of the biogas and methane production rates, will be adapted to operate in co-digestion mode. Based on substrates composition (e.g., analysis of carbohydrates, proteins, and lipids), process modelling (IWAADM1 based) will be used to modulate the proportion of co-substrates fed to the digester in order to control the carbonic acid equilibria in the liquid phase, and thus the gaseous CO_2 yield. The digester will be fed in a semicontinuous mode, according to an HLR of 2-4 kg COD·m^{-3}·d^{-1}, and a hydraulic retention time (HRT) in the range of 15-20 days.

5.6. Challenges

The challenging aspects that need to be considered during the EBM innovative technological pathway are:

- **Feedstock pre-treatment via ozonolysis**

The main challenge for the full-scale ozonolysis application is related to the design configuration of the contact reactor to avoid ineffective transfer yields and malfunctions related to clogging problems and to the degassing unit of the ozonated sludge to avoid inhibition phenomenon of the AD process linked to the oxygen presence. A critical element to be assessed is the **ozonolysis effect on sludge dewaterability**. The AD process is expected to mitigate the worsening of the sludge dewaterability after ozonolysis: if this is not the case, the polyelectrolytes optimal dosage will be evaluated and taken into consideration in the process economic viability.

- **Ex-situ biological upgrading**

Ex-situ hydrogen-promoted biological upgrading efficiency is highly influenced by the **mass-transfer of hydrogen** into the medium. This aspect will be investigated thoroughly in the pilot, optimizing finding best performing solution on a scaled-up commercial system.

- **Co-digestion pilot**

Fast and reliable analytical tools for supporting digester modelling are currently one of the main bottlenecks for process modelling integration at real scale facilities. Further investigation will involve multiple analytical techniques such as near infrared (NIR), X-ray fluorescence (XRF) thus the comprehensive characterization would be beneficial for providing biogas plants with feasible and affordable process control and optimization tools.

5.7. Economic viability and business outlook

The first economic evaluation carried out by CAP indicated that taken by themselves, feedstock pre-treatment by ozonolysis and ex-situ biological upgrading is not economically sustainable on a large scale, considering a WWTP of more than 100,000 P.E., because of the energetic cost required for the production, respectively, of ozone and hydrogen. **The alternative solution, demonstrated here, is the integration of the two technologies: a single electrolyser will produce the hydrogen for the ex-situ biological upgrading and the ozone for the feedstock pre-treatment.**

In this case, the summed increase in biogas productivity and conversion of CO_2 into biomethane should produce enough value to more than cover the cost for energy consumption, with a total cost reduction for the biomethane of about 44% and a total increase in biomethane production of 78%. The goal of this innovation testing is to confirm these preliminary economic considerations.

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The proposed technologies are an evolution of a previous scheme tested for about a year in separate non-integrated 500 L pilot plants within the WWTP of San Giuliano Milanese Ovest on a campaign basis (TRL3-4). The proposed technologies will be tested on integrated pilot plants installed within an operational environment (WWTP of Bresso Niguarda) for an estimated operational time of about 10,000 hours and in continuous mode.
Thanks to the project activities, the goal of the research is to achieve a TRL7-8. (Figure 15)

The ideal market segment for ozonolysis and EBM technology is that of biogas producers from organic matrices. It can therefore be applied to all companies and industries that exploit the process of AD to employ various waste feedstocks such as sewage sludge, organic fraction of municipal solid waste (OFMSW, agro-zootechnical waste and other organic industrial waste. Ozonolysis technology finds its optimal application where renewable energy sources are present to power the ozone generator and combined with biogas upgrading to biomethane. Moreover, it is a technology in synergy with other activities carried out by SIAD S.p.A., such as upgrading and recovery plants for biomethane and biogenic CO_2 and for renewable H_2 production.

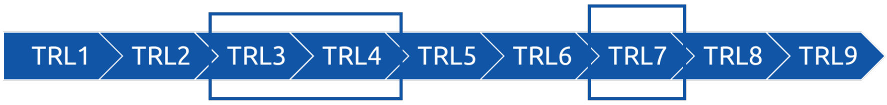

Figure 15 - TRL Ex-Situ Biological Methanation (EBM) Innovative technological pathway

5.8. Timeline-Implementation Schedule-Chronogram for implementation

The innovative production pathway (EBM) will be developed through the application of different approaches and will be divided into specific activities/tasks that will contribute to improving the conversion in biomethane production and its cost-effectiveness. Along with the implementation of the project demonstrators, a thorough monitoring plan will be set in order to collect and analyse yields data and allow an assessment of the economic viability of the integrated process considering also the ongoing macroeconomic trends (inflation, commodity volatility prices)

These activities/tasks will be:

- **Activity 1: Feedstock pre-treatment via ozonolysis**
- **Activity 2: Ex-situ biological upgrading**
- **Activity 3: Pilot-scale microalgae operation**
- **Activity 4: Pilot-scale co-digestion operation**

A Gantt chart for planning the project with all the tasks is listed and all activities are presented in Figure 16. All activities/tasks are described in detail in Tables 17-18-19. Activity 2-4 will generate the data needed for the overall ESB cost analysis.

The activities will provide data and information according to the planned deliverables as specified below.

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Overall description of the demo plant and detailed description of the demo plant units (including pre- and post-treatment, if needed, up to the delivery to the gas grid) in addition to the biogas plant without BIOMETHAVERSE technology [M18; D.2.2].
For each process unit [M18; D.2.2]:

- Design-point, off-design and/or stand-by operation conditions,
- Main reactions/biological process description and kinetics
- Input and output flow specification,
- Energy, auxiliary energy and materials consumption
- Detailed bill of materials (a comprehensive list with the identification and quantification of all the materials constituting the equipment and maintenance needs, with a focus on critical raw materials)

Identification and quantification of structural emissions to the atmosphere, if any (methane and other pollutants, e.g. from off-gases, overpressure valves, boilers, CHP, auxiliaries) [M49; D2.5];

Estimation of the materials needed for civil works (e.g. concrete and steel), piping, auxiliaries, management and control devices [M30; D2.4].

Cost estimates, including capital costs (for each unit); maintenance costs (for each unit); labour costs and other costs (e.g. insurance, management and control system) [M30; D2.4].

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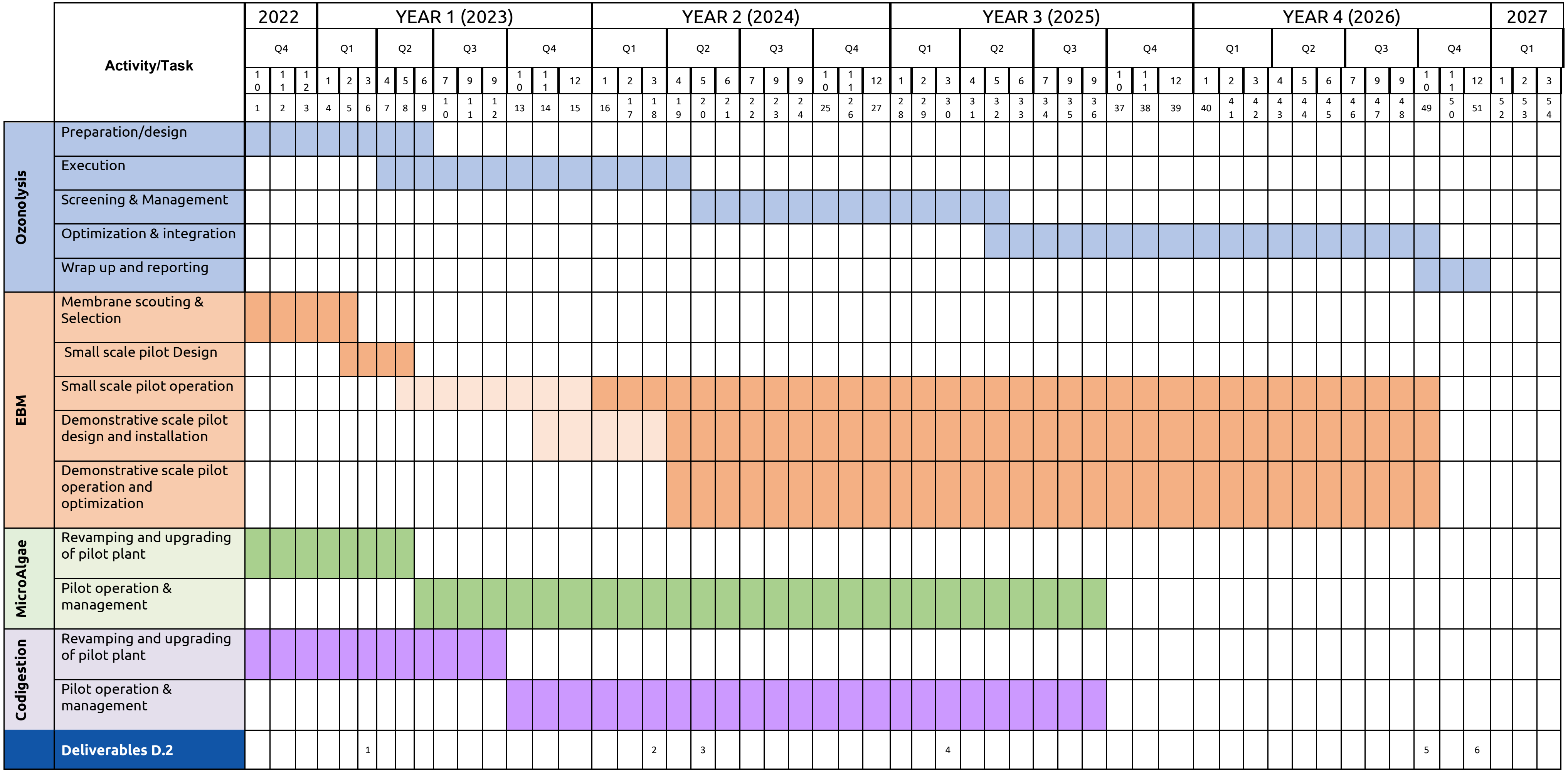

		2022			YEAR 1 (2023)												YEAR 2 (2024)												YEAR 3 (2025)												YEAR 4 (2026)												2027		
	Activity/Task	Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1		
		10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Ozonolysis	Preparation/design	■	■	■	■	■	■	■	■	■																																														
	Execution							■	■	■	■	■	■	■	■	■	■	■	■	■																																				
	Screening & Management																				■	■	■	■	■	■	■	■	■	■	■	■	■																						
	Optimization & integration																																■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
	Wrap up and reporting																																																	■	■	■			
EBM	Membrane scouting & Selection	■	■	■	■	■																																																	
	Small scale pilot Design					■	■	■	■																																														
	Small scale pilot operation								▒	▒	▒	▒	▒	▒	▒	▒	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
	Demonstrative scale pilot design and installation														▒	▒	▒	▒	▒	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
	Demonstrative scale pilot operation and optimization																			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
MicroAlgae	Revamping and upgrading of pilot plant	■	■	■	■	■	■	■	■																																														
	Pilot operation & management									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■																		
Codigestion	Revamping and upgrading of pilot plant	■	■	■	■	■	■	■	■	■	■	■	■																																										
	Pilot operation & management													■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■																		
Deliverables D.2							1												2		3										4																			5		6			

Figure 16 - Gantt chart showing overview of timeline and schedule of the phases and the activities for innovative production pathway (EBM)

5.8.1. Activity 1: Feedstock pre-treatment via ozonolysis

The ozonolysis sludge pre-treatment aims to increase the biogas production up to +20-40% with ozone dosages in the range of 20-40 gO_3kg^{-1} VS.

As observed in previous experimental campaigns, the process should also reduce the quantity of sludge to be disposed of by about 10-15%. The process is composed of an ozonator that converts the oxygen stored in a tank into ozone that is consequently sent into a contact reactor where itis diluted into the sludge stream entering the anaerobic digester (4.5 kgO_3 h^{-1} at 10% wt for fresh sludge or 4.5-7 kgO_3 h^{-1} al 10%wt for digested sludge).

The main process parameters that will be monitored in order to evaluate the technology and its sustainability will be:

- Analytical characterization of the sludge pre and post-treatment (COD, TKN, TSS/VS)
- Biogas production (BMP tests)
- Sludge quantities pre and post-treatment
- Economics associated with the above parameters.

Activity 1 will focus on the following tasks

[M1-6]

a. Coordination with the partners to define the installation of the ozonolysis plant in the WWTP and the safety aspects.
b. Ozonolysis plant layout definition and contact reactor design.
c. Procurement of necessary equipment, appliances, and materials.
d. Support for permits for oxygen tank installation.
e. Construction of the contact reactor.
f. Preparation of use, operation, and safety documents
g. Ozonolysis plant on-site installation complete of the ozone generator, contact reactor, control system, and oxygen tank.

[M10-51]
g. Ozonolysis plant on-site installation complete of the ozone generator, contact reactor, control system, and oxygen tank.
h. Ozonolysis plant testing and start-up.
i. Plant management and monitoring including laboratory analysis and field tests.
j. Optimization of full-scale plant processes.
k. Integration of activities 1, 2, 3, and 4 through adequate-sized ozonolysis plants in accordance with other technologies (pilot-scale).
l. Data collection and processing.

[M32-51]

l. Data collection and processing.
m. Drafting of reports and articles and dissemination.

The time planning and the summary of tasks for Activity 1 is shown in Table 18.

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Table 18 - Time planning of the Activity 1- Feedstock pre-treatment via ozonolysis

Activity 1: Feedstock pre-treatment via ozonolysis				
Phase	**Actions/ steps description**	**Time (start date)**	**Time (due date)**	**Responsible**
Preparation/ Design	• Coordination with the partners to define the installation of the ozonolysis plant in the WWTP and the safety aspects. • Ozonolysis plant layout definition and contact reactor design. • Procurement of necessary equipment, appliances, and materials. • Support for permits for oxygen tank installation. • Preparation of use, operation, and safety documents.	October '22	June '23	SIAD S.p.a.
Execution	• Construction of the contact reactor. • Ozonolysis plant on-site installation complete of the ozone generator, contact reactor, control system, and oxygen tank. • Ozonolysis plant testing and start-up.	July '23	April '24	SIAD S.p.a., Gruppo CAP
Screening / Management	• Plant management and monitoring including laboratory analysis and field tests. • Data collection and processing.	May '24	April '25	SIAD S.p.a, Politecnico di Milano, Gruppo CAP
Optimization	• Optimization of full-scale plant processes through the variation of process operating parameters. • Data collection and processing.	May '25	October '26	SIAD S.p.a.
Integration	• Integration of activities 1, 2, 3, and 4 through adequate-sized ozonolysis plants in accordance with other technologies (pilot-scale).	March '26	October '26	SIAD S.p.a, Politecnico di Milano, Gruppo CAP
	• Data collection and processing.	October '26	Dec. '26	
Final Report	• Data collection, processing and assessment: technology yields and economic sustainability. • Drafting of reports and articles and dissemination.	October '26	Dec '26	SIAD S.p.a, Politecnico di Milano, Gruppo CAP

5.8.2. Activity 2: Ex-situ biological upgrading

Activity 2 is divided into two parts: The first part focus on the preparation and planning of the demonstration activities, and the second on their implementation and management.
Technical scouting on membranes for gas bubbles transfer has been completed, a small hollow fiber unit has been procured while the small-scale unit design is currently in progress with the aim to provide the maximum flexibility of operation. The unit will consist of two separate elements (V = 40–60 L each), one containing the membrane on which the biofilm will develop and one operating with suspended biomass. The 40-40 L scale pilot unit will have on-line measurements of the fed flow rates and, separately, of the flow rate and composition of the gases generated.

Operating conditions:

- Independent feeding of each reactor with a mixture or single flows of H_2 and CO_2,
- H_2 input (overall): 1 to 10 NL H_2 h^{-1}

The main key performance indicators for the EBM technology include:

- H_2 transfer efficiency (H_2 transferred/H_2 feed for each reactor, NLH_2/NLH_2)
- H_2 transfer utilization (CH_4/H_2 transferred, $NLCH_4/NLH_2$)
- Methane production rate, overall and specific (NL CH_4 $m^{-3}h^{-1}$; $NLCH_4$ m^{-2} membrane/h^{-1};)
- COD mass balance closure (%)

The demonstration plant will be located in the same pilot area in Bresso WWTP where the pilot scale microalgae will be placed. The information and technical results obtained during the operation of the small-scale unit will form the basis for the design of the demonstration plant in terms of volumes, a number of membranes installed and gas and liquid flow patterns.

During the experimental period, at first the results obtained at small scales will be validated.

Then the behaviour of the plant to a time-varying supply pattern of H_2 and to different distributions between the suspended biomass and biofilm elements will be studied. Relevant elements needed for the process modelling will be determined, for the biological and physico-chemical processes involved.

After validation, the model will be applied to additional scenarios to comprehensively evaluate and determine the suitability and benefit of the EBM process.

The time planning and the summary of task for Activity 2 are shown in Table 19.

Table 19 - Summary of task, schedule and responsible for Activity 2- Ex-situ biological upgrading

Activity 2 : Ex-situ biological upgrading				
Phase	**Actions/ steps description**	**Time (start date)**	**Time (due date)**	**Responsible**
Membrane scouting & Selection	• Literature review and case studies analysis. • Membrane selection and testing.	October '22	February '23	Politecnico di Milano
Small scale pilot Design	• Reactor design. • Materials and equipment procurement. • Small scale EBM construction.	February '23	May '23	Politecnico di Milano
Small scale pilot operation	• Small scale EBM Plant management and monitoring including laboratory analysis and tests. • Data collection and processing.	May '23	October '26	Politecnico di Milano
Demonstrative scale pilot design and installation	• Design of demonstrative-scale plant. • Materials and equipment procurement. • Demonstrative scale EBM construction and site installation.	October '23	December '23	Politecnico di Milano Gruppo CAP.
Demonstrative scale pilot operation and optimization	• Demonstrative scale EBM Plant management and monitoring including laboratory analysis and tests. • Integration and optimization of the processes. • Data collection, processing and assessment: technology yields and economic sustainability.	April '23	October '26	Politecnico di Milano, Gruppo CAP SIAD S.p.a,

5.8.3. Activity 3: Pilot-scale microalgae operation

Activity 3 aims at demonstrating the feasibility of culturing microalgae using the liquid fraction of digestate ad nutrient source and the CO_2 from biogas upgrading as inorganic Carbon supplementation and pH regulation. As reference technology, a raceway pond is used, as a compromise between productivity and costs.

The main key performance indicators for this technology include:

- Biomass productivity [g DW /m^2 d^{-1}]
- Specific nitrogen, ammonium and phosphorus removal rate [g N/m^2/d] or [g P /m^2 d^{-1}]
- Specific CO_2 uptake rate [g C/m^2/d $^{-1}$]

A performance matrix will be created for each tested approach computing both annual and monthly averages of relevant *key performance indicators* (KPIs) to facilitate a comparative analysis (in terms of yields, efficiency and environmental impact).

Activity 3 is divided into 2 phases:

1. revamping the existing pilot plant. The electromechanics of the existing pilot plant will be revised in order to allow continuous operation for a minimum of 450 days. A gas line will be implemented to guarantee the feeding of a CO_2 stream from the full-scale biogas upgrading section as an inorganic carbon source. Plant operation and its monitoring plant will be defined, according to previous experiences.

2. pilot plant operation for a minimum of 450 days. During this phase, the pilot-plant will be operated for 420-450 days to collect operational data required to quantify the above-listed KPIs. Moreover, during this phase, the algal biomass will be harvested and sent to the co-digestion pilot plant to assess the anaerobic degradability and co-degradability of the algal biomass and waste sludge. The pilot plant is expected to have seasonal productivity (8-9 months per year) and to be discontinued during the winter months.

The time planning and the summary of the task for Activity 3 are shown in Table 20.

Table 20 - Summary of task, schedule and responsible for the Activity 3 -Pilot-scale microalgae operation

Activity 3: Pilot-scale microalgae operation				
Phase	**Actions/ steps description**	**Time (start date)**	**Time (due date)**	**Responsible**
Revamping and upgrading of pilot plant	• Materials and equipment procurement • Pilot plant revamping • Experimental design definition	October '22	May '23	Politecnico di Milano
Pilot operation /management	• Plant management and monitoring including laboratory analysis and tests. • Integration and optimization of the processes. • Data collection, processing and assessment: technology yields and economic sustainability.	June '23	August '24	Politecnico di Milano

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5.8.4. Activity 4: Pilot-scale co-digestion operation.

Activity 4 aims at demonstrating the efficiency of co-digesting waste sludge with microalgae biomass. Process optimization will be targeted via process modelling aiming at defining the most appropriate mixing between co-substrates (wastes sludge, microalgae and potentially sugar-rich industrial by-products) aiming at maximising biogas yields and CO_2 content in the biogas.

The main *KPIs* for this technology to be optimized by defining the ideal blending of co-substrates include:

- Biomethane yield [L $CH_4 g^{-1}$ VS_feed]
- CO_2 concentration in the biogas [%]

Activity 4 is divided into 2 phases:

- [M1-12] revamping of the existing pilot plant and its installation at the pilot site. The electromechanics of the existing pilot plant will be revised in order to allow continuous operation for a minimum of 450 days. During this phase, preliminary activities will be run in parallel including:
    - Development of an operational ADM1 model running in Open Modelica and adequate to simulate co-digestion scenarios.
    - Preliminary characterization of untreated waste sludge and microalgal biomass in order to compute the ADM1 state variables for each substrate.
    - First attempt a model-based simulation of ideal sludge-algae blending, based on literature ADM1 parameters and preliminary substrates characterization.
    - First attempt a model-based definition of the monitoring champaign in order to collect relevant data for ADM1 parameter identification.
- A4.2 [M13-36]– pilot plant operation for a minimum of 450 days. During this phase, the pilot-plant will be operated under different feeding scenarios:
    - Mono-digestion of untreated sludge - baseline
    - Co-digestion of untreated and microalgae
    - Mono-digestion of O_3-treated sludge
    - Co-digestion of O_3-treated sludge and microalgae

Each scenario will be maintained till a steady-state is reached in about 2-3 months. During this phase, the monitoring campaign previously defined will be implemented in order to collect data for model calibration and validation. Moreover, data for *KPIs* calculation will be made available.

Data collection will start accordingly with the planned starting schedule of each activity.

After approximately one year [M12] of plant operation and on regular basis over the course of the project until M30 the data of operational parameters and results will be transferred to WP3.

After the second year of plant operation at [M42] it will be available optimization data for WP3 and WP4.

Data on the total integration of the processes of Italy demo case will be available at M49.

The time planning and the summary of the task for Activity 4 are shown in Table 21.

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Table 21 - Summary of tasks, schedule and responsible for the Activity 4- Pilot-scale co-digestion operation

Activity 4: Pilot-scale co-digestion operation.				
Phase	**Actions/ steps description**	**Time (start date)**	**Time (due date)**	**Responsible**
Revamping and upgrading of pilot plant	• Materials and equipment procurement • Pilot plant revamping • Experimental design definition	October '22	Sept '23	Politecnico di Milano
Pilot operation/management	• Plant management and monitoring including laboratory analysis and tests. • Integration and optimization of the processes. • Data collection, processing and assessment: technology yields and economic sustainability.	October '23	August '24	Politecnico di Milano

5.9. Milestones

The demonstration of EBM includes one main Milestone MS3 (Table 22). The aim of MS3 "Demo plant up and running" is to achieve the Existing plant in the Bresso WWTP is fully operational smoothly functioning and producing the results as intended.

Table 22 - Milestones of EBM

Milestone N°	Key Milestone name	Month of completion	Major Tasks
MS3	Demo plant up and running	M13	Existing of plant in the Bresso WWTP

5.10. Risks

The ozonolysis treatment as well as the co-digestion process could be affected by the quality of the inlet sewage sludge. Due to its intrinsic variability in composition and characteristics, a poor-quality sludge treated in the processes could determine low performances and yields of the technology. In order to determine the quality of the sludge treated, the substrate will be monitored in its VS content and chemical characteristics. In case of necessity, mitigation actions have been planned, providing the co-feeding of the sludge with richer substrates (e.g., waste from food industries).

Regarding the EBM, one of the main parameters affecting the efficiency and yields of the technology is the capacity of distribution of the H2 inside the reactor. The risk of low hydrogen distribution could significantly limit biological upgrading effectiveness. The reactor has been designed to enhance a uniform and capillary hydrogen distribution and different systems will be evaluated to improve the capacity if needed.
Due to the global situation such as volatility and increase in energy and raw material costs delays in the procurement of material and equipment are expected.

The list of risk factors that may occur during the demo phases is shown it Table 23.

Table 23 - Risk probability/ impact on the EBM Innovative technological pathway and potential risk mitigation strategies

Risk	Probability	Impact	Mitigation measures
R13: Low performances of innovative production due to sewage sludge quality.	Medium	Medium	Co-feeding of sewage sludge with richer substrates (e.g., waste from food industries) will be evaluated to solve the problem.
R14: Limited biological upgrading effectiveness due to low distribution of hydrogen within the reactor.	Medium	Medium	More efficient gas distribution systems will be evaluated to solve the problem.

5.11. Exploitation

A demonstrator (CAP Group) ensures the production of biomethane from biowaste recycling, a research institution supports the demonstrator in their path to transform their technology from lab-scale to pilot scale (POLIMI), and a technology provider (SIAD) deals with the pre-treatment of sludge through ozonolysis. CAP will ensure appropriate exploitation from a commercial perspective while CIC will ensure it from a policy perspective.

In particular, CAP will assess internal exploitation, evaluating the replicability within its other managed WWT plants (39 in total, roughly 15 of a meaningful size). Moreover, to widen the exploitation audience, the results obtained from the demonstrators can be adapted to other feedstocks than sewage sludge (e.g., OFMSW) through the use of process models developed during the project. Technology developers will be collecting feedback from stakeholders regarding the commercial potential of the process structure to develop a specific intellectual property protection strategy.

In addition, CIC will exploit the results of the different project demonstrators as valuable examples to consolidate and reinforce the Italian legislation and support schemes for the development of biomethane projects, specifically considering the already planned investments included in the National Recovery and Resilience Plan (1,92 bn €).
Moreover, Italian partners will actively share the experimentation results with local policymakers, in particular with the Lombardy Region, which is already highly promoting the use of anaerobic digestion as an alternative process to treat sewage sludge and other organic substrates (e.g., OFMSW), in order to support the diffusion of this model in the water utility sector. Specifically, CAP will use the results of the demonstrators through their specific stakeholder channels (e.g., Water Alliance -Acque di Lombardia, the association of water utilities of Lombardy Region).

5.12. Block Flow Diagram

The Block Flow Diagrams (BFD) of the whole EBM process the is presented in Figure 17.

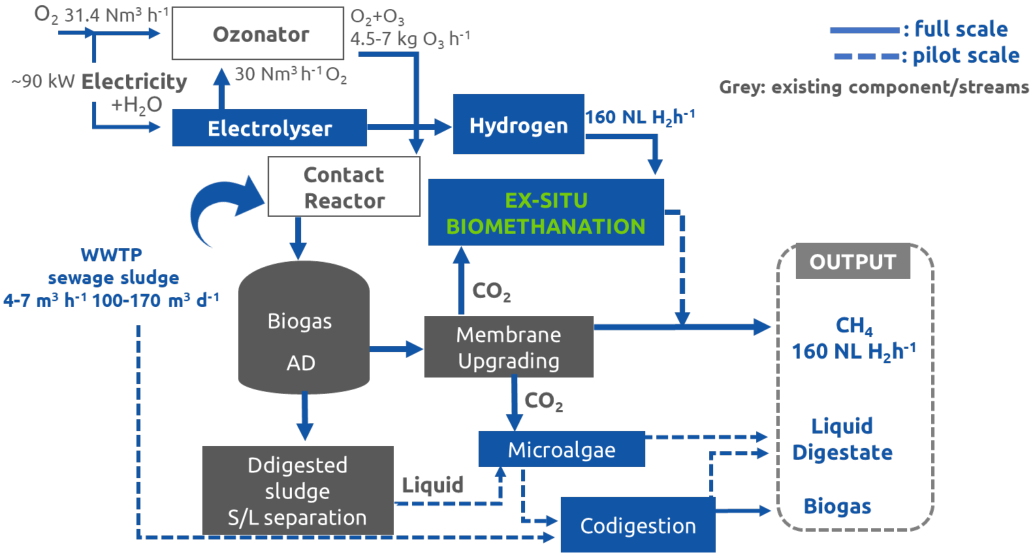

Figure 17 - Block Flow Diagram for innovative production pathway (EBM)

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6. SWEDISH INNOVATIVE BIOMETHANE DEMONSTRATOR

6.1. *Ex-Situ* Syngas Biological methanation (ESB)

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

6.2. Biogas and biomethane production in Sweden

Sweden has 207 biogas plants and saw a total biogas production of 758 GWh in 2021. Most of the biogas (525 GWh) was produced at biogas-only plants, while the remaining 233 GWh was produced at "biogas + biomethane" installations but not upgraded.

There are 72 active biomethane plants, which in 2021 produced a total of 1,508 GWh biomethane. The Swedish biomethane market is to a large extent off-grid, comprising several small local and regional grids as well as stand-alone plants with on-site filling stations. Sweden's gas pipeline infrastructure is limited to the south-western part of the country, A long-term support scheme for both biomethane and biogas from anaerobic digestion was approved by the Swedish parliament and its implementation, starting in 2022, is included in the national 2022 funding. The support scheme is intended to help Sweden achieve a biomethane production of 10 TWh by 2030. Even though the support scheme starting in 2022 only applies to renewable gas production related to anaerobic digestion, it is well recognized that other technologies are required to reach the 10 TWh biomethane goal. A dedicated governmental inquiry to develop a suitable support policy for other technologies, such as thermochemical conversion followed by subsequent methanation, was recommended and could be expected to be commissioned and ongoing during the BIOMETHAVERSE project. Most of the biomethane produced in Sweden (73% in 2021) is used in the transport sector, thanks to a favourable tax exemption. By the end of 2021, there were 272 Bio-CNG filling stations in Sweden and 26 Bio-LNG filing stations. Sweden, is one of the few European countries to report more biomethane than biogas production).[13]

6.3. 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 a CO/H2 ratio of approximately 1:2. Additionally, the gas contains CO_2 (14%) and some CH4 (1%). The 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 the 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 industry.

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[13] EBA Statistical Report 2022

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6.4. 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. The 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 the conversion of all CO_2 to methane. **The planned trials will demonstrate biological methanation of syngas both without and with the addition of external H_2.**

6.5. State of the art of the demonstrated technology

The technology is **currently being tested in the laboratory** in 4 x 5 L scale and 1 x 35 L scale TBR. Two nationally funded projects are ongoing concurrently. The first one is a PhD project (“Biological methanation of syngas in a TBR”) that focuses on the **nutrient composition and microbiology of the TBR** for process robustness and optimization. The second one is an implementation project (“Biological methanation of syngas from gasification and pyrolysis – promising concept towards implementation”), where empirical work is being done to **assess the process ability to deal with impurities in the fed syngas,** as well as finetuning of techno-economics, including two specific case studies. The second project also includes a thorough IPR evaluation to lay the groundwork for the most prudent route towards commercialization.

6.5.1. Ambition and progress beyond the state of the art

The demonstration plant for this technology will be mobile: this will allow for testing and demonstration of the process at separate sites and show that the process is flexible enough to be relevant for different syngas qualities and integration options. During the BIOMETHAVERSE project, the mobile pilot will be tested at its first host gasification plant (see description of demonstration site above). Rejecting water from a nearby municipal wastewater treatment plant will be used as the nutrient solution. Both the host gasification plants as well as the municipal wastewater treatment plant are existing facilities in full operation. The gasification plant is WoodRoll® 6 MW gasification plant from CORTUS which supplies syngas to Höganäs to produce fossil-free iron powder. The wastewater treatment plant is a standard tertiary WWTP dimensioned for 35,000 PE. The mobile pilot plant for biological methanation of syngas will consist of a 30 ft technology container including housing, pumps, valves, controllers, heating, cooling, gas management, measurement equipment, etc. and a separate vertical TBR. The final design is yet to be determined, but the effective reactor volume will be 2-5 m^3 (1-2 m diameter and 3-4 m high). The pilot plant will also include a small electrolyser for the local production of additional green hydrogen, which will widen the scope of possible production conditions demonstrated. **This demonstration project is a scale-up by 2-3 orders of magnitude** compared to what has already been tested and will be the first of its kind globally. **The ambition of this demonstration is to achieve pipeline injection specifications for biomethane**

through biological methanation of syngas with the addition of external hydrogen, but without the addition of conventional upgrading.

6.6. Challenges

TBR is a relatively under-utilized reactor type which makes a theoretical assessment of practical scale-up cost challenging since there is not much in the real world to compare with. The concept is dependent on both a local source of syngas and a nutrient solution. During the BIOMETHAVERSE project, there will be a need to **identify possible edge effects at scale** to enable the properly designing a full-scale plant.

6.7. Economic viability and business outlook

The current state of development (at TRL 3-4) would indicate an all-inclusive production cost of grid injection-ready biomethane via this route of approximately 103 €/MWh without any type of public support, compared to 135 €/MWh with external addition of h2 (thus potentially doubling the amount of biomethane produced when all the C in the syngas can become CH_4). If adding the support systems currently in place in Sweden that would be applicable to this concept (competitive CO_2-reduction-based capital grant), it would be down below 88 €/MWh (support and no external H_2). If the recently passed production support scheme for biomethane could be applied also to thermochemical technologies, or if a complementary support scheme for other technologies than digestion is implemented, as recommended in the biogas market inquiry, production costs would reduce even further.

These forecasted production costs have increased by 10% since they were originally estimated in the proposal and this is due to the inflation and supply line challenges.

Thanks to the project activities, the goal of the research is to achieve a TRL of 6 (Figure 18).

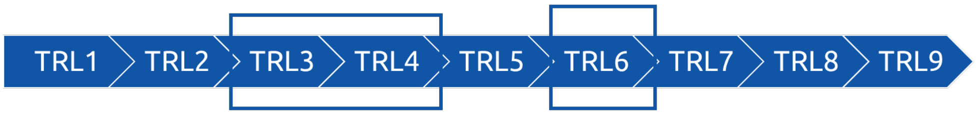

Figure 18 - TRL (Technology Readiness Level) for Ex-situ syngas biological methanation (ESB) Innovative technological pathway

As syngas is the substrate in *ex-situ* Syngas Biological methanation (ESB), the business case lies with syngas producers. Syngas can be produced in many ways. One example is the thermochemical conversion of a carbon-rich material by pyrolysis or gasification. Within each production pathway (e.g pyrolisis) there exist many different technologies leading to grand variations in syngas quality (purity). Given that biological methanation (BM) has proven to be tolerant towards impurities, all types of syngas plants could be a possible business case. The total production of biogas in Sweden amounts to 2 TWh. Considering the syngas potential in available residues, such as low-quality forestry residues and sewage sludge, the Swedish methane production could increase by 1TWh through syngas methanation. Biological methanation however has a scaling-up limit due to reactor size, cost proportion of carriers and technical issues like pressure drop, etc. BM is likely practically feasible up to 30 MW. As catalytic methanation cannot scale down these two concepts complements each other quite well, and BM can play a key role in lowering the investment threshold for industrial methanation implementation as the technology is economically feasible on a smaller scale where no existing technology is available.

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The technology of *ex-situ* biological methanation in TBR reactors is not limited to syngas as substrate. BM on raw biogas together with external hydrogen supply produces biomethane. Thus, the market segment for Ex-Situ Biological methanation also includes biogas plants that want to produce upgraded biogas without using conventional upgrading technology. This could be new biogas plants, existing biogas plants without upgrading or existing biogas plants with upgrading with a need for re-investments. During the BIOMETHAVERSE project, an external partner Gasum (a vertically integrated project developer, plant owner/operator as well as the largest biomethane distributor in Scandinavia), will perform a specific site-based conceptual study based on the BIOMETHAVERSE results. Gasum may be the first commercial client for the technology under development.

6.8. Timeline – Implementation Schedule – Chronogram for implementation

The innovative production pathway (ESB) will be developed through the application of different approaches and will be divided into specific activities/tasks that will contribute to improving the conversion in biomethane production and its cost-effectiveness.
These activities/tasks will be:

- **Activity 1: Design of pilot demonstration plant**
- **Activity 2: Mobile pilot demonstration plant installed and commissioned**
- **Activity 3: 1,000 and 2,000 h of total intermittent demonstration plant operation**
- **Activity 4: 500 h of intermittent demonstration plant operation with external H_2**

A Gantt chart for planning the project with all the tasks is listed and all activities are presented in Figure 19.

All activities/tasks are described in detail in Tables 23-24-25. Activity 2-4 will generate the data needed for the overall ESB cost analysis.

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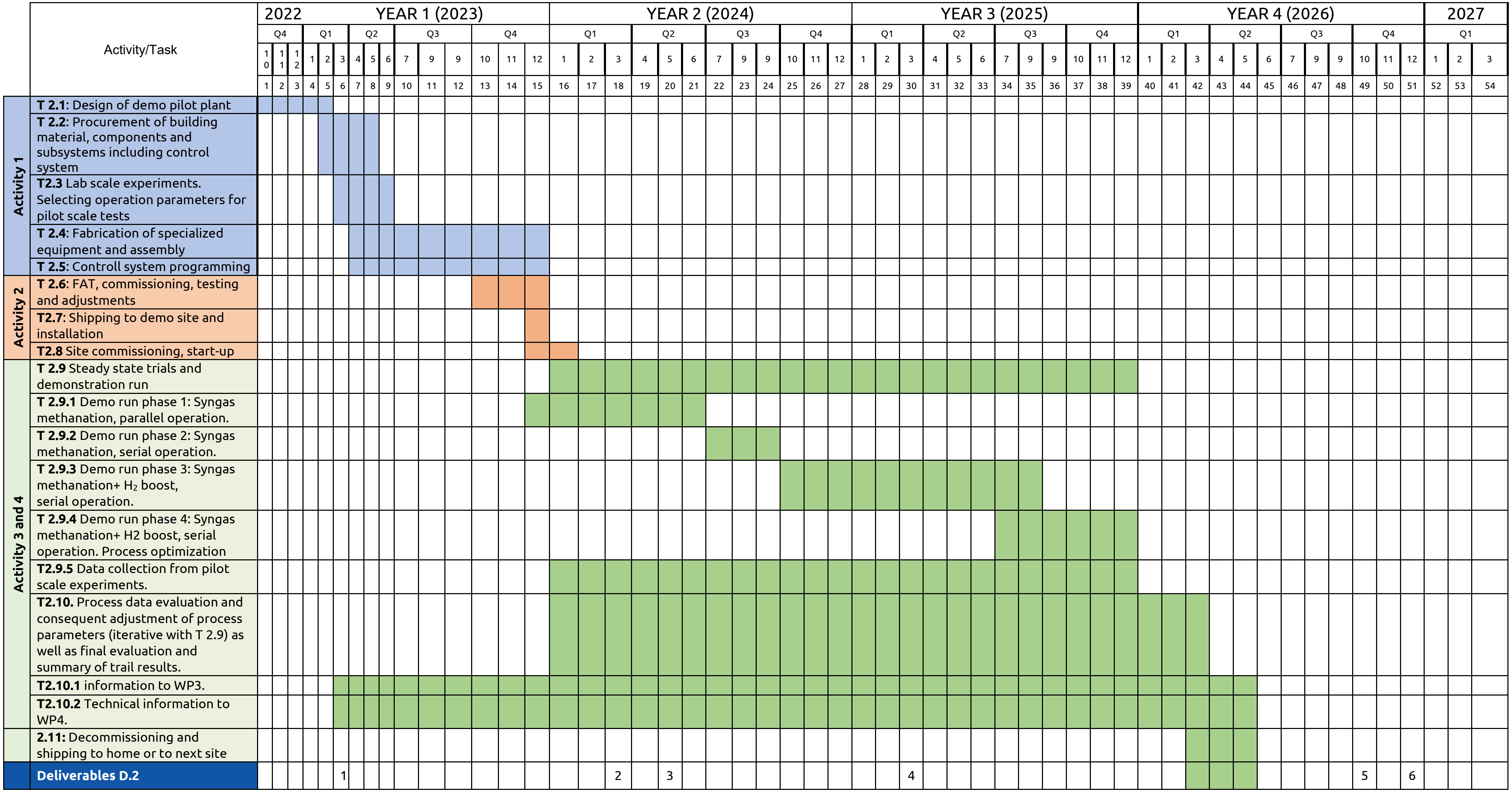

	Activity/Task	2022			YEAR 1 (2023)												YEAR 2 (2024)												YEAR 3 (2025)												YEAR 4 (2026)												2027		
		Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1		
		10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Activity 1	**T 2.1**: Design of demo pilot plant	🟦	🟦	🟦	🟦	🟦																																																		
	T 2.2: Procurement of building material, components and subsystems including control system				|🟦 |🟦 |🟦 |🟦																																																
	T2.3 Lab scale experiments. Selecting operation parameters for pilot scale tests						🟦	🟦	🟦	🟦																																														
	T 2.4: Fabrication of specialized equipment and assembly							🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦																																								
	T 2.5: Controll system programming							🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦																																								
Activity 2	**T 2.6**: FAT, commissioning, testing and adjustments													🟧	🟧	🟧																																								
	T2.7: Shipping to demo site and installation														|🟧																																								
	T2.8 Site commissioning, start-up															🟧	🟧																																						
Activity 3 and 4	**T 2.9** Steady state trials and demonstration run																🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩															
	T 2.9.1 Demo run phase 1: Syngas methanation, parallel operation.															🟩	🟩	🟩	🟩	🟩	🟩	🟩																																	
	T 2.9.2 Demo run phase 2: Syngas methanation, serial operation.																						🟩	🟩	🟩																														
	T 2.9.3 Demo run phase 3: Syngas methanation+ H_2 boost, serial operation.																									🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																			
	T 2.9.4 Demo run phase 4: Syngas methanation+ H2 boost, serial operation. Process optimization																																		🟩	🟩	🟩	🟩	🟩	🟩															
	T2.9.5 Data collection from pilot scale experiments.																🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩															
	T2.10. Process data evaluation and consequent adjustment of process parameters (iterative with T 2.9) as well as final evaluation and summary of trail results.																🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩												
	T2.10.1 information to WP3.						🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩										
	T2.10.2 Technical information to WP4.						🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩										
	2.11: Decommissioning and shipping to home or to next site																																										🟩	🟩	🟩										
	Deliverables D.2						1												2		3										4												🟩	🟩	🟩					5		6			

Figure 19 - Gantt chart showing overview of timeline and schedule of the phases and the activities for ESB innovative production pathway

6.8.1. Activity 1: Design of pilot demonstration plant

The design of the pilot will be based on empirical data from pervious experiments on lab scale where bio methanation has been running for more than four years and with up to four reactors in parallel. In addition, data from previous techno-economic evaluations will contribute to the design of the pilot, e.g. choice of carriers, nutrient media management, heat and cooling capacity etc. Cortus and RISE will determine and prepare the site integration, (i.e. exact location of the pilot plant, ground preparation, supply of water, syngas and electricity). RISE and Wärtsilä will set the design of the trickle bed reactors and then Wärtsilä will manufacture this equipment. Different H_2 production units will be evaluated based on availability, price and service organization. RISE will do a lot of construction in-house in our workshop (e.g. welding of tanks). All assembling will take place at RISE and the system will be tested before shipping to Cortus. RISE will design and deliver the control system to the plant. The pilot plant will contain a lot of online sensors, have remote access and will be fully automated giving good conditions for stable and longtime operation. Safety issues and risk management are important aspects of the design and engineering of the pilot and it will of course fulfil all relevant directives and relevant legislation.
The time planning and the summary of tasks for Activity 1 is shown in Table 24.

Table 24 - Time planning of Activity 1- Design of pilot demonstration plant

Activity 1: Design of pilot demonstration plant				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Preparatory/ Design	• T2.1 Design of demonstration pilot plant.	2022-10-01	2023-02-28	RISE Wärtsilä
	• T2.2 Procurement of building material, components and subsystems including control system.	2023-02-01	2023-05-31	RISE Wärtsilä
	• T2.3 Lab scale experiments. Selecting operation parameters for pilot scale tests.	2023-03-01	2023-06-30	RISE
	• T2.4 Fabrication of specialized equipment and assembly.	2023-04-01	2023-12-31	RISE Wärtsilä
	• T2.5 Control system programming.	2023-04-01	2023-12-31	RISE

6.8.2. Activity 2: Mobile pilot demonstration plant installed and commissioned

After the final assembling the pilot will be tested at RISE before being shipped to Cortus. It will be a kind of internal factory acceptance test where different parts of the pilot will be examined under relevant operation conditions, for example, pumping of liquid, gas tightness, gas measurements, trigging alarms, heating and cooling, etc. When the tests are done the pilot will be transported to Cortus and installed next to the gasifier. The mobile pilot plant will to a large extent be a plug-and-play unit which will make the installation on-site quick and easy. Syngas, water and electricity will be connected and thereafter the system will be checked before starting the process (e.g. checking gas tightness). Operators from Cortus and Wärtsilä will be introduced to the system and educated to conduct specific tasks, for example, sampling of liquid, a manual restart of some machines etc.
The time planning and the summary of tasks for Activity 2 is shown in Table 25.

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Table 25 - Summary of tasks, schedule and responsible for Activity 2- Mobile pilot demonstration plant installed and commissioned

Activity 2- Mobile pilot demonstration plant installed and commissioned				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Installation and commissioning	- T2.6 FAT, commissioning, testing and adjustments (RISE, Uppsala).	2023-10-01	2023-12-31	RISE (Uppsala)
	- T2.7 Shipping to demo site and installation.	2023-12-01	2023-12-31	RISE
	- T2.8 Site commissioning, start-up. Including deliveries: Overall description of the demo plant and detailed description of the demo plant units in addition to the syngas plant without technology. For each process unit: -Design-point, off-design and/or stand-by operation conditions, -Main reactions/biological process description and kinetics -Input-output flows specification -Energy, auxiliary energy and materials consumption -Detailed bill of materials (for equipment and maintenance)	2023-12-01	2024-01-31	RISE

6.8.3. Activity 3: 2,000 and 1,000 h of total intermittent demonstration plant operation

The pilot scale experiments are divided into different phases.

Phase 1: Firstly, the two trickle bed reactors will be inoculated with a mix of different digestates and thereafter syngas will be supplied gradually. At the beginning, there is an adaption period where the syngas flow is low. As the conversion of syngas increase over time the feeding of syngas is increased as well pushing the system to establish more biofilm on the carriers in the reactors. During phase 1 the two reactors are run in parallel making it possible to evaluate and validated different operation parameters. The milestone for phase 1 is to reach 2000 h of stable operation with high conversion of CO and H_2.

Phase 2: In phase 2 the reactors will be connected in serial mode. Based on the results from phase 1 the best-performing reactor will be the first reactor in serial followed by the second one. The aim is to push reactor 1 to achieve even higher specific methane production per reactor volume than before (Phase 1). By doing so it is expected that there will be more unconverted CO and H_2 leaving reactor 1 (due to the higher inlet flow). Reactor 2 will then act as a polishing reactor converting the rest of H_2 and CO.

The milestone for phase 2 is to reach 1000 h of stable operation with high specific methane production in reactor 1 and with a good overall (reactor 1+2) conversion of H_2 and CO.

6.8.4. Activity 4: 500 h of intermittent demonstration plant operation with external H_2.

As described in Activity 3, the pilot scale experiments are divided into different phases.

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Phase 3: In phase 3 the reactors will be run in serial and with H_2 boosting in order to convert the remaining CO_2 in the gas to CH_4. H_2 will be produced on-site by electrolyzers (part of the pilot plant) where the flow can be adjusted over time. Adding H_2 will affect the pH and other process parameters and therefore there will be an adaption period where the H_2 feeding is increased over time. If needed there will be an active pH control in order to stay within certain biochemical constraints.
The milestone for phase 3 is to reach a high CH_4 concentration in the product gas (grid injection quality) during 500 h of operation.
The time planning and the summary of tasks for Activity 3 and 4 are shown in Table 26.

Table 26 - Time planning of Activity 3--2,000 and 1,000 h of total intermittent demonstration plant operation and Activity 4 - 500 h of intermittent demonstration plant operation with external H2 respectively

Activity 3: 2,000 and 1,000 h of total intermittent demonstration plant operation Activity 4: 500 h of intermittent demonstration plant operation with external H_2.				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Operation (+data collection)	• T2.9.1 Steady state trials and demonstration run (at Cortus Höganäs).	2024-01-01	2025-12-31	RISE Wärtsilä Cortus
	• T2.9.2 Demo run phase 2: Syngas methanation, serial operation.	2024-01-01	2024-06-01	
	• T2.9.3 Demo run phase 3: Syngas methanation+ H_2 boost, serial operation	2024-07-01	2024-09-31	
	• T2.9.4 Demo run phase 4: Syngas methanation+ H_2 boost, serial operation. Process optimization.	2024-10-01	2025-06-30	
	• T2.9.5 Data collection from pilot scale experiments Including deliveries • Identification and quantification of structural emissions to the atmosphere • Estimation of the materials needed for civil works, piping, auxiliaries, management and control devices	2024-01-01	2025-12-31	RISE
	• T2.10. Process data evaluation and consequent adjustment of process parameters (iterative with task 2.9) as well as final evaluation and summary of trial results. Including delivery • Cost estimates, including capital costs (for each unit); maintenance costs (for each unit); labour costs and other costs.	2024-01-01	2026-03-31	RISE Wärtsilä Cortus
	• T2.10.1 Technical information to WP3 and cost analysis. Process data from pilot scale experiments relevant for techno-economic assessment. Mass and energy balance and key figures like specific methane production, conversion rate, the demand of nutrients etc.	2023-03-01	2026-05-31	RISE
	• T2.10.2 Technical information to WP4. An iterative process where data from ESB system is delivered to WP4 (based on the dialogue of what is requested).	2023-03-01	2026-05-31	RISE Energigas Sverige
Decommissioning	• T2.11 Decommissioning and shipping to home.	2026-01-01	2026-03-31	RISE Cortus

6.9. Milestones

The demonstration of ESM includes one main Milestone MS4. The aim of MS4 “Mobile pilot demonstration plant installed and commissioned” is to realize the plant at Höganäs location (Table 27).

Table 27 - Milestones of ESB

Milestone N°	Key Milestone name	Month of completion	Major Tasks
MS4	Mobile pilot demonstration plant installed and commissioned	M19	Existence of plant at Höganäs location.

6.10. Risks

The largest identified risk associated with being able to complete the trials is related to the dependency on the syngas producer.

If there are obstacles with placing the *ex-situ* Syngas Biological methanation (ESB) containerized facility near the syngas source, a need for longer gas transport arises.

There is also a dependency on the syngas producer for continuous substrate feed for our steady-state trials and demonstration run.

During the demonstration run phase with H_2-boost there is also a dependency on the electrolyser (as part of the ESB facility) for on-time green hydrogen supply.

The risk related to syngas supply stems primarily from the possibility of periodical production problems at the host plant. It could also potentially be caused by repairs and maintenance needs within the gasification plant that must be prioritized higher than the timing of deliverables within the BIOMETHAVERSE project.

Another risk associated with the trials is delayed. Unpredictable delivery times risk delaying the construction of the ESB demonstration plant and thus the start-up of the methanation trials.

A volatile market with high inflation and currency value changes risk increasing not only the project costs but also the cost of ESB.

To mitigate the risk of changing business outlook, an emphasis on data processing can enable the best possible data basis to be provided to SGA for the overall cost analysis.

An accurate cost analysis is crucial to enable the usage of the policy work in WP4 as a tool to ensure economic viability for ESB.

The major technical risks factors along with their probability, impact and mitigation measures that will be undertaken in case of their occurrence during the demo phases are shown in Table 28.

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Table 28 - Risk probability/ impact on the ESB Innovative technological pathway and potential risk mitigation strategies

Risk	Probability	Impact	Mitigation measures
R11: On time green hydrogen supply	Medium	Medium	A small hydrogen tank is foreseen to be erected to avoid multiple transportation routes concerning the green hydrogen.
R15: Temporary loss of syngas supply at the gasification plant	Medium	High	Compression stations and high-pressure gas storage racks to mitigate this risk. With a full gas rack(s), a continuous supply from the gasification plant can be operated.
R16: Site in immediate proximity of the gasification plant is unavailable or unsuitable due to compounded industrial risks	High	Medium	Pilot plant placed distant from the gasification plant. Gas transfer from the latter to the first by virtual pipeline (move-filled gas racks) instead of actual direct pipes.
Delays due to unpredictable delivery times	High	Medium	Produce a priority list of purchases where components that risk causing bottlenecks are given the highest priority and ordered first. Allowing delivery times to be an important metric during supplier comparison.
Changed business outlook and economic viability due to volatile markets	High	Medium	Data processing to achieve a good basis for SGA to proceed with cost analysis and policy development within WP3 and WP4. Data processing is a scheduled activity. Focus on technical simplification and cost-efficient process control to ensure the best possible business case.

6.11. Exploitation

A national research institute will play as the inventor/early developer of syngas biomethanation technology (RISE) and an industrial partner, as the intended late-stage developer of the industrialisation. and commercialisation of the technology (WARTSILA). Since the feedstock for the technology is syngas from gasification or pyrolysis, the consortia also include a gasification technology developer and plant owner/operator (CORTUS).

The appropriate exploitation will be ensured by RISE (for commercial one) and SGA (for policy one). From a commercial perspective, utilization of pilot scale experiences during the project will allow identifying edge effects and any other relevant engineering input for designing commercial scale TRB reactors and processes for biological methanation of syngas. The demonstration plant is containerized and fully mobile. This means that the process can be proven at different sites, using different input syngas quality and different locally available nutrient solutions as input. Thus, the robustness of the process and its adaptability to various local conditions can be conveniently tested and demonstrated, which reduces the technical risk of commercial implementation on a project-to-project basis.

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From the policy perspective, the project will allow SGA and RISE to participate in an expected national government inquiry to add biomethane production from thermochemical conversion technologies to the biomethane support scheme that will be implemented from 2022 and onwards. The project results will directly inform the inquiry on state-of-the-art, the research front, and economic conditions for viability. SGA, with support from RISE, will feed in technical data and reference publications into the inquiry and participate in the formed working groups, as well as transferring knowledge through one-to-one meetings with policymakers. Moreover, externally from the project, a potential first customer for the technology has already been initially identified and will facilitate the market introduction, in the form of a vertically integrated biomethane project developer and plant owner/operator (Gasum), who is also a biomethane distributor and the most important investor in BIO-LNG filling stations in Scandinavia.

6.12. Block Flow Diagram

The Block Flow Diagrams (BFD) of the ESB process the is presented in Figure 20:

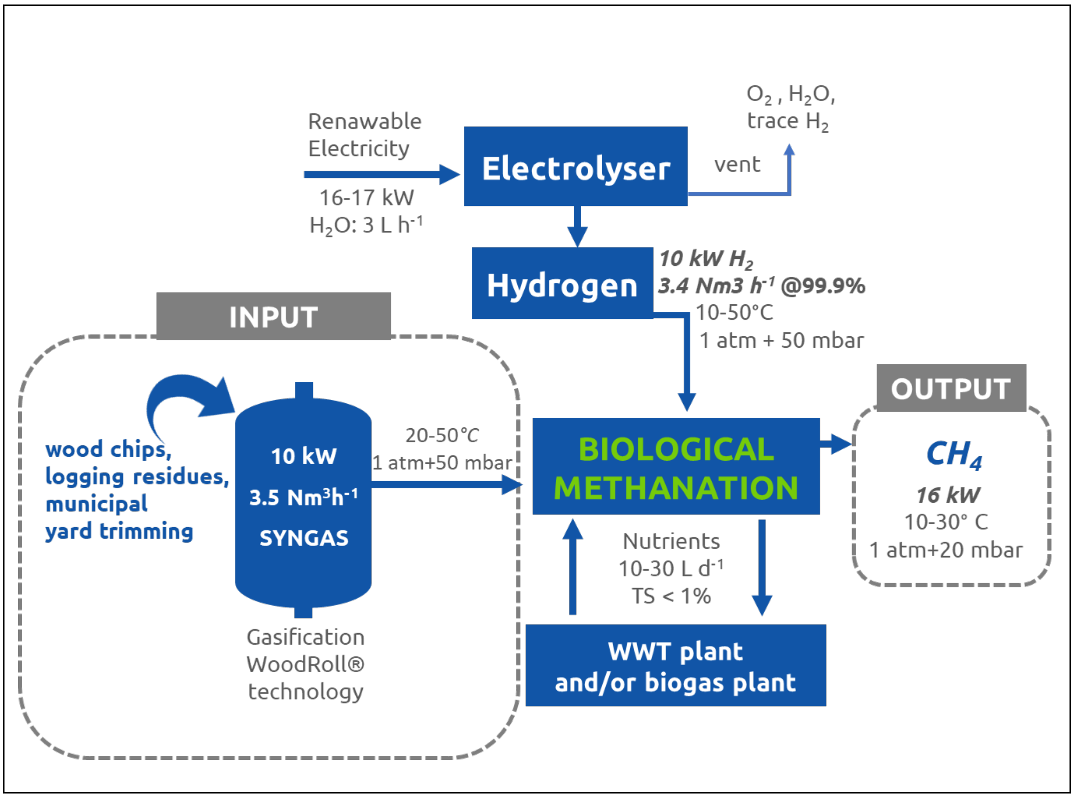

Figure 20 - Block Flow Diagrams (BFD) of the ex-Situ Syngas Biological methanation (ESB) process

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7. UKRAINE INNOVATIVE BIOMETHANE DEMONSTRATOR

7.1. *In-Situ* Biological methanation (IBM)

- **Production pathway**: biological
- **Input**: CO_2 +hydrogen

7.2. Biogas d biomethane production in Ukraine

The Ukrainian biogas sector started growing in recent years. By the end of 2021, there were **73 operational biogas plants in Ukraine**, with an average plant electric capacity in the range of 125 kWe to 12 MWe producing a total of 1,366 GWh of biogas The reported biogas production capacity amounts to 124 MW. The actual electricity generated from the available biogas in 2021 amounted to 553 GWh. With its extensive agriculture sector, Ukraine enjoys the significant potential for large-scale biomethane production. Ukraine has the largest area of agricultural land in Europe and one of the highest agricultural areas per capita. A significant part of the agricultural land could be used for sustainable biogas and biomethane production, without affecting Ukraine's self-sufficiency for food and feed production.

The traditional use of CNG in Ukraine is as a motor fuel. In 2011, more than 200,000 CNG vehicles existed and the country offers a good network with around 300 CNG gas filling stations distributed all over the country. This infrastructure could be used for biomethane, for example, to enable renewable public transportation and for agricultural vehicles as well. The Ukrainian biogas market can be considered as emerging and promising and it is estimated that the total biomethane production potential in Ukraine is of the order of 9.7 bcm of biomethane corresponding to 35% of the domestic natural gas consumption[1]. There is, however, no **biomethane production in Ukraine** yet.[2]

7.3. 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.

7.4. 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 be prevailing 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.

7.5. State of art of the demonstrated technology

Biological *in-situ* methanation has been validated on lab scale and is widely described in the literature[14,.15]
Major constraints related to biological *in-situ* methanation are:

1. influencing metabolic pathways in AD by adding hydrogen (the **H_2 concentration needs to be carefully adjusted to prevent process disturbances** and inhibition of acetogenesis as well as methanogenesis from available volatile fatty acids in the digester).
2. the low solubility of H_2 in aqueous solutions (also relevant for ex-situ systems (in this case, it is necessary to **increase the surface of the gas/liquid interface**).

The latter is usually achieved using trickle bed reactors, intense mixing using high stirrer speed and/or application of overpressure.
In this project, we validate and demonstrate an alternative way of H_2 transfer into the liquid phase by **using an existing gas circulation mixing system instead of conventional stirrers**. **Biogas from the headspace of the reactor is pumped to the bottom of the fermenters to achieve mixing of the substrate**. MHP and EE successfully performed the first *in-situ* methanation tests using a 50 L lab reactor equipped with the described gas mixing system and **additional provision of H_2 into the gas mixing loop**.

The lab reactor comes with a TRL 4, as several validation experiments with regard to H_2 flow rate and concentration in the gas phase, process stability and process management using a different kinds of substrates must be performed.

7.5.1. Ambition and progress beyond the state of the art

First of all, it is necessary to evaluate different process parameters, e.g., H_2 flow rate and methanation rate concerning process stability and develop process control approach for *in-situ* methanation.
Here, **DBFZ will perform several lab tests** in the described 50 L reactor set up, amongst others, to examine the process under different controlled conditions and develop process control strategies that will be implemented and validated in the lab reactors of MHP and later transferred to the demonstration reactor.
At the end of the project, TRL will be 6-7 due to the demonstration of *in-situ* methanation in >10 m^3 scale at the site of the MHP biogas plant in Ladyzhyn.
The demonstrator will be equipped with a gas circulation system like the mixing system in the biogas plants of MHP. **H_2 is injected into the gas loop of the mixing system, whereas the H_2 concentration in the gas phase is monitored and adjusted to levels previously determined under lab conditions**. During the demonstration phase, **H_2 will be provided from a hydrogen tank**, once established in full scale an electrolyser for intermittent and power-demand-oriented hydrogen production will be used for H_2 production. The overall aim is to increase both the overall methane yield per given amount of feedstock, as well as the methane content of the final biogas produced. **The methane concentration in the biogas is foreseen to increase from 55% to 85%** by the injection of H_2. Hereby the carbon efficiency of the AD process is improved and biomethane production is increased using a **comparable technically simple approach** that is easy to implement in biogas plants equipped with a gas mixing system.

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[15] Voelklein, M. A.; Rusmanis, D.; Murphy, J. D. Biological methanation: Strategies for in-situ and ex-situ upgrading in anaerobicdigestion. Applied Energy 2019, 235, 1061–1071; DOI 10.1016/j.apenergy.2018.11.006.

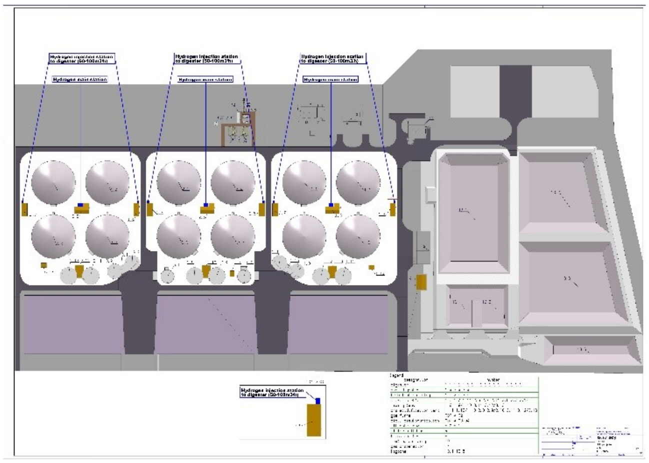

Figure 21 - Concept for full integration of in-situ methanation at the biogas plant in Ladyzhin

7.6. Challenges

Important **technical and safety aspects** need to be considered during *in-situ* methanation. Process parameters, such as the concentration of volatile fatty acids and pH, the quality and quantity of biogas, the presence of residual H_2 in the biogas, the optimal H_2 flow rate, the optimal gas recirculation rate and the mixing ratio of hydrogen/raw gas, as well as potential erosion on the existing gas mixing system due to H_2 and potential diffusion of hydrogen through the roof membranes of AD reactors will be evaluated in the project.

7.7. Economic viability and business outlook

The **electrolyser can be run intermittently to exploit the low power costs of excess intermittent renewables**, and therefore contribute to power peak-shaving. The project will provide numbers on the overall economy of the process based on data collected at industrially relevant conditions. As the **final methane concentration will already be higher, the final costs for biogas upgrading will be lower**. The **total cost for biomethane production can be reduced from the current 31.2 €/MWh to 27.1 €/MWh** with an **increase in biomethane production of about 40%.**
Thanks to the project activities, the goal of the research is to achieve a TRL6-7 (Figure 22).

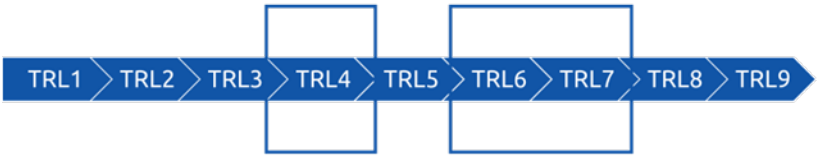

Figure 22 - TRL for in-situ Biological Methanation (IBM) Innovative technological pathway

In order to calculate the economic viability of the IBM process, two scenarios' cases are considered with respect to retrofitting existing AD plants with IBM and preliminary estimations are shown in Table 33:

- **Scenario A:** Retrofit of an AD plant with an existing gas mix system.

- **Scenario B:** Retrofit of an AD plant with mechanical agitators (gas mixing systems need to be installed additionally).

These two scenarios should represent well over 95% of all existing AD Plants worldwide. For the following conservative assessment of an initial business case, assumptions were made (e.g. prices for green hydrogen and price of biomethane). Furthermore, the efficiency of IBM can be only estimated at this time on a technical/full scale, as this is currently under research. The business perspective is constantly updated with the data obtained in BIOMETHAVERSE.

Biomethane production (without IBM) out of 443 m^3 h^{-1} biogas at 55% CH_4 is 244 m^3 h^{-1}. It is expected that ~10% additional biogas production by IBM will be achieved along with a 10 % increase of the CH_4 concentration to 65 % (v/v). This, in turn, will lead to the production of 487 m^3 h^{-1} with 65% (v/v) CH_4 concentration, resulting in 317 m^3h^{-1} biomethane. The net increase due to the implementation of IBM results is 73 m^3 h^{-1} biomethane or 731 kWh h^{-1} or 6,402,684 kWh y^{-1}, respectively. Finally, a biomethane price of 0.14 €/kWh results in a revenue of 896,375 € y^{-1}.

Conservative approaches were deliberately chosen for the calculation of economic viability. Nevertheless, high profitability of the process results. To the extent that the assumed IBM performance parameters can be confirmed in the context of BIOMETHAVERSE, there is great economic potential for IBM.

7.8. Timeline-Implementation Schedule-Chronogram for implementation

The innovative production pathway (IBM) will be developed through the application of different approaches and will be divided into specific activities/tasks that will contribute to improving the conversion in biomethane production and its cost-effectiveness.

These activities/tasks will be:

- **Activity 1: Demonstration of IBM in 50 L lab-scale reactors**
- **Activity 2: Construction and installation of IBM demo reactor (> 10m3) at a biogas plant**
- **Activity 3: Demonstration of IBM**
- **Activity 4: Providing a concept for the implementation of IBM at biogas plants.**

A Gantt chart for planning the project with all the tasks is listed and all activities are presented in Figure 23. All activities/tasks are described in detail in Tables 28-29-30-31.

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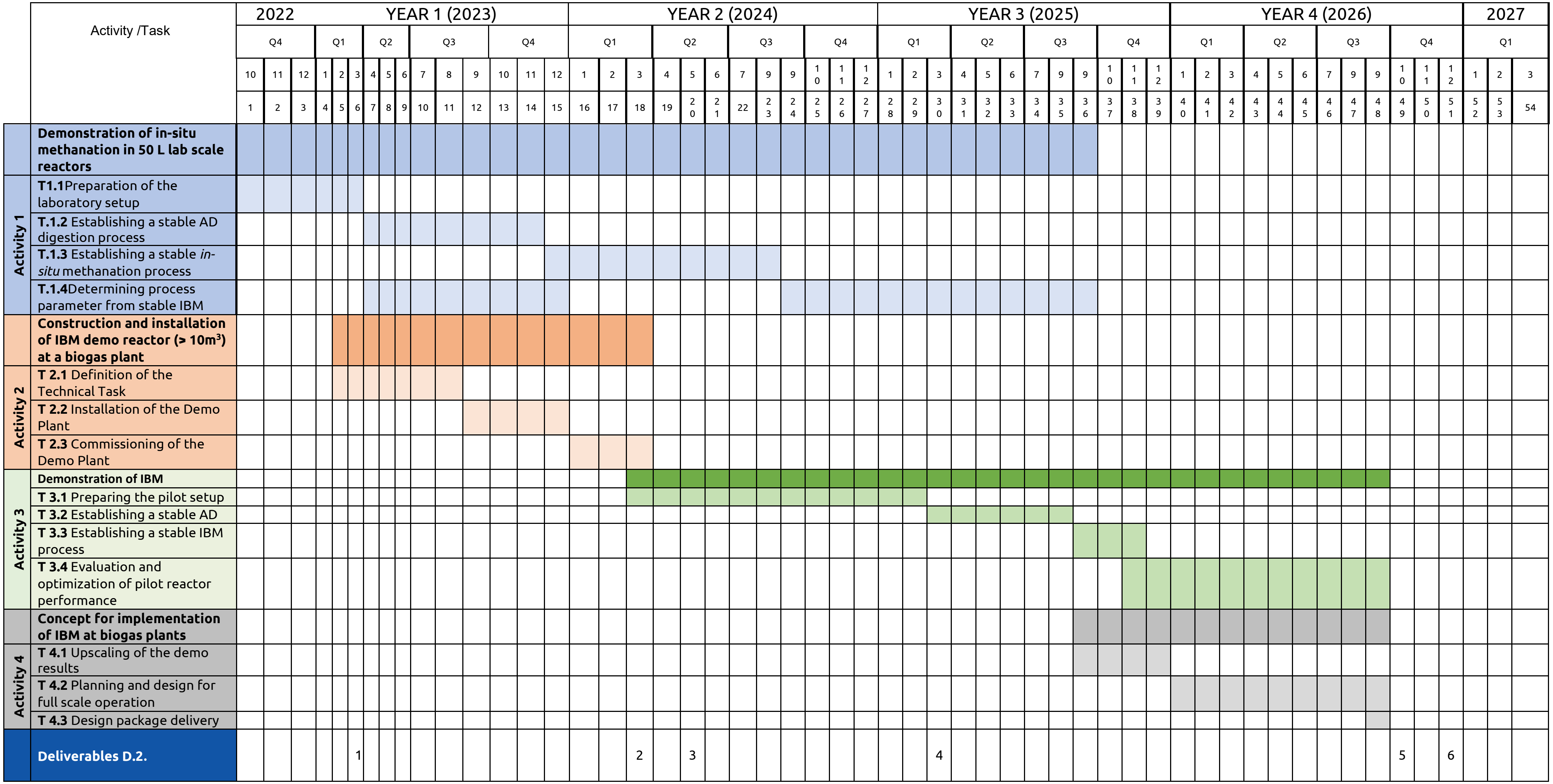

Activity /Task		2022			YEAR 1 (2023)												YEAR 2 (2024)												YEAR 3 (2025)												YEAR 4 (2026)												2027		
		Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1		
		10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3	4	5	6	7	9	9	10	11	12	1	2	3
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
	Demonstration of in-situ methanation in 50 L lab scale reactors	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■																		
Activity 1	**T1.1**Preparation of the laboratory setup	■	■	■	■	■	■																																																
	T.1.2 Establishing a stable AD digestion process							■	■	■	■	■	■	■	■																																								
	T.1.3 Establishing a stable *in-situ* methanation process															■	■	■	■	■	■	■	■	■																															
	T.1.4 Determining process parameter from stable IBM							■	■	■	■	■	■	■	■	■									■	■	■	■	■	■	■	■	■	■	■	■	■																		
	Construction and installation of IBM demo reactor (> 10m^3) at a biogas plant					■	■	■	■	■	■	■	■	■	■	■	■	■	■																																				
Activity 2	**T 2.1** Definition of the Technical Task					■	■	■	■	■	■	■																																											
	T 2.2 Installation of the Demo Plant												■	■	■	■																																							
	T 2.3 Commissioning of the Demo Plant																■	■	■																																				
	Demonstration of IBM																		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						
Activity 3	**T 3.1** Preparing the pilot setup																		■	■	■	■	■	■	■	■	■	■	■	■																									
	T 3.2 Establishing a stable AD																													■	■	■	■	■	■																			
	T 3.3 Establishing a stable IBM process																																			■	■	■																
	T 3.4 Evaluation and optimization of pilot reactor performance																																					■	■	■	■	■	■	■	■	■	■	■						
	Concept for implementation of IBM at biogas plants																																			■	■	■	■	■	■	■	■	■	■	■	■	■						
Activity 4	**T 4.1** Upscaling of the demo results																																			■	■	■	■															
	T 4.2 Planning and design for full scale operation																																							■	■	■	■	■	■	■	■	■						
	T 4.3 Design package delivery																																															■						
	Deliverables D.2.						1												2		3										4																			5		6			

Figure 23 - Gantt chart showing overview of timeline and schedule of the phases and the activities for IBM innovative production pathway

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7.8.1. Activity 1: Demonstration of in-situ methanation in 50 L lab-scale reactors

Task 1.1 Preparing the laboratory setup

The aim of the task is to construct and set up 50 L AD reactors for IBM at the laboratories of DBFZ (2 reactors) and MHP (2 reactors). Besides building and preparing the reactors, this task includes the purchase of components for, e.g., gas sparging systems and temperature maintenance and control as well as reactor periphery for hydrogen addition and gas circulation (e.g. gas pumps and mass flow controller). Furthermore, substrates for the following AD experiments will be defined and organized and necessary personnel will be hired.

Task 1.2 Establishing a stable anaerobic digestion process

Before active implementation of IBM in the lab reactors, it is necessary to establish a stable AD process using chicken manure, cow manure, straw and maize silage and derive basic process parameters such as gas quality and quantity, pH of the digestate as well as volatile fatty acid (VFA) concentration, total solid (TS) and volatile solid concentration (VS), ammonia nitrogen concentration (NH4-N), trace element demand and composition of the microbial consortia. These parameters need to be derived from steady state operation of the reactors (> operation for more than three hydraulic retention times) and will be used as control data for later comparison with data from IBM (see Task 1.4). Chicken manure and straw were chosen as the main substrates, besides cow manure and maize silage as both occur in high quantity in Ukraine or the biogas plant in Ladyzhyn, respectively.

Task 1.3 Establishing a stable IBM process

The aim of this task is to switch from a standard AD process to IBM by the addition of hydrogen to the reactor in order to reduce the carbon dioxide in the biogas to CH4 by hydrogenotrophic Archaea. The aim of the task is a transition from classic AD to IBM without disturbing the syntrophic relationship between acetogenic bacteria and hydrogenotrophic archaea by a slow increase of hydrogen flow rates. Another focus of the task is to monitor the potential occurrence of homo-acetogenesis, i.e., the production of acetate from CO2 and hydrogen by homo-acetogenic bacteria as a possible side reaction of hydrogen addition. Homo-acetogenesis leads to an overall increase in biogas production but not an increase in the methane concentration in the biogas. Therefore, we will monitor gas quality and quantity as well as the composition of the microbial consortia amongst others.

Task 1.4 Determining process parameter

In this task, process optimal parameters of IBM, such as organic loading rate (OLR), H2 flow rate, gas quality and quantity, VFA quality and quantity induced by the addition of H2, will be determined in order to provide data for the operation of the demo plant in Ladyzhyn. This includes the screening of the microbial consortia and their stability over time of reactor operation. Furthermore, data from Task 1.2 will be compared with the process parameters of IBM in order to derive data for a preliminary evaluation of the energy efficiency and economy of the process.

The time planning and the summary of task for Activity 1 are shown in Table 28.

Table 29 - Summary of tasks, schedule and responsible for Activity 1 - Demonstration of in-situ methanation in 50 L lab scale reactors

Activity 1: Demonstration of *in-situ* methanation in 50 L lab scale reactors				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Demonstration of *in-situ* methanation in 50 L lab scale reactors	• T1.1 Preparation of the laboratory setup	2022-10-01	2023-03-31	DBFZ MHP
	• T1.2 Establishing a stable AD digestion process	2023-04-01	2023-11-30	DBFZ MHP
	• T1.2 Establishing a stable *in-situ* methanation process	2023-12-01	2023-05-31	DBFZ MHP
	• T1.3 Determining process parameter from stable IBM	2024-09-01	2025-09-30	DBFZ MHP

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7.8.2. Activity 2: Construction and installation of IBM demo reactor (> 10m^3) at a biogas plant

Task 2.1 Planning and design of the demo plant

The formulation of a technical task is based on the one hand, on the objective defined for this research project and, on the other hand, on the results from the operation of the laboratory systems with a volume of 50 L. The technical task will be worked out by EE and then discussed and agreed with the project partners DBFZ and MHP. Based on the technical task, EE will develop a concept design consisting of the following items:

- Process flow diagram
- Plant layout
- Verbal short description of the plant

In the next step, EE will develop a detailed technical design, which will include the following key documents:

- Mass flow Diagram for the Demo Plant (Sankey Diagram)
- P+I diagram of the plant
- Piping diagram
- Parts list of the plant
- Measuring point and drive list
- Control system description

The documents are discussed with the project partners and then made available to MHP in the form of a design package.

Task 2.2 Installation of the Demo Plant

The Plant will be built on the basis of an operating biogas complex and integrated into the general system. By the end of 2023, based on the results of joint laboratory research, the concept and project for the implementation of the Demo Plant will be developed. Construction and commissioning will be completed in 2024 (Task 2.3), and operation will begin in 2024 (Task 3). After the development of the concept and project, the suppliers of materials and equipment will be determined.

Task 2.3 Commissioning of the Demo Plant

The commissioning of the demo plant takes place after the completion of the installation process and after acceptance of the plant by representatives of the project partners. After approval, all functions of the system and the control system are first tested in a dry test and then in a water test. The following criteria must be checked:

- Tightness of the system components (water tightness, gas tightness)
- Hydraulic functionality
- Dynamics of the gas circulation
- Function of the individual system components
- Test of the system in manual operation
- Test of the system in automatic mode
- Parameterization and function of the measurement technology
- Parameterization of the control system
- Functional test of the measurement data recording 24 h endurance test

The system is then released for pilot operation with substrates.
The next step is to fill the system with regular operating materials and commission it.
The biological system can be inoculated from the contents of the 50-L scale fermenters that are available from three project partners (MHP, DBFZ and EE).

The time planning and the summary of tasks for Activity 2 are shown in Table 29.

Table 30 - Summary of tasks, schedule and responsible for Activity 2- Construction and installation of in-situ methanation demo reactor (> 10m^3) at a biogas plant

Activity 2: Construction and installation of IBM demo reactor				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Construction and installation of *in-situ* methanation demo reactor (> 10m^3) at a biogas plant	• T2.1 Definition of the Technical Task	2023-02-01	2023-08-31	EE
	• T2.2 Installation of the Demo Plant	2023-09-01	2023-12-31	EE MHP
	• T2.3 Commissioning of the Demo Plant	2024-01-01	2024-03-31	EE MHP

7.8.3. Activity 3: Demonstration of IBM

Task 3.1 Preparing the pilot setup

Construction of a pilot plant with a volume of 10 m^3 on the territory of the “Biogas Laldyzhin” biogas complex. For this, it is necessary to purchase equipment and materials, both for the reactor itself and for the mixing system, gas accounting, temperature control and hydrogen dosing system. A separate task is to solve the problem of the hydrogen source and its supply to the system. The final mass balance will be calculated based on the results of laboratory tests.

Task 3.2 Establishing a stable AD process

Before starting the dosing of hydrogen into the system, it is necessary to obtain a stable classical anaerobic process of methanogenesis. For this purpose, the developed formulation and feeding regimes strategy (temperature, mixing, loading by organic matter) will be used during laboratory tests. The process will be controlled by the following parameters: daily volume of biogas produced, biogas composition, FOS/TAC ratio, the concentration of volatile fatty acids (VFA), ammonium nitrogen (NH_4-N), dry matter and organic dry matter. If during 2-3 periods of digestion in stationary mode the indicators are in the same range without significant deviations, the process will be considered stable, and the indicators will be used to evaluate the efficiency of biomethanation.

Task 3.3 Establishing a stable IBM process

The purpose of this task is to increase the yield of biogas and methane concentration in it from 55% to 85% due to the injection of hydrogen into the reactor environment. Since an increase in the concentration of hydrogen in the system will cause the development of a hydrogenotrophic consortium of methanogens, as a result of which the concentration of carbon dioxide in biogas should decrease, the key points of control will be the composition of biogas and its daily volume. To ensure the effective assimilation of hydrogen into the system after the injection, the laboratory experience of hydrogen management will be used which includes determining the appropriate method of supply and mixing mode.

Task 3.4 Evaluation and optimization of pilot reactor performance

To evaluate the effectiveness of IBM the consumption of hydrogen will be evaluated by determining its concentration in the final biogas and the ratio of the supplied amount of hydrogen to the amount not consumed by hydrogenotrophic methanogens. In order to assess the stability and viability of the cultivated microflora, the concentration of VFA and their profile will be monitored, In order to assess the reduction of the ecological capacity, the effectiveness of reducing CO_2 emissions due to its transformation into biomethane will be investigated.

The time planning and the summary of task for Activity 3 are shown in Table 31.

Table 31 – Summary of tasks, schedule and responsible for Activity 3- Demonstration of in-situ methanation

Activity 3- Demonstration of *in-situ* methanation				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Demonstration of *in-situ* methanation	• T3.1 Preparing the pilot setup	2024-03-01	2025-02-28	MHP EE
	• T3.2 Establishing a stable AD	2025-03-01	2025-08-31	MHP EE
	• T3.3 Establishing a stable IBM process	2025-09-01	2025-11-30	MHP EE
	• T3.4 Evaluation and optimization of pilot reactor performance	2025-11-01	2026-09-30	MHP EE

7.8.4. Activity 4: Concept for implementation of IBM at biogas plants

Task 4.1 Upscaling of the demo results

Now that the phases of establishing and optimizing IBM can be considered successfully completed, planning for a large-scale plant can begin. In addition to the construction of new biogas plants, in which the new technology is to be implemented from the beginning, the focus is also on increasing the effectiveness of existing plants for economic reasons. Here, an increase in efficiency of 10 – 30 % can be achieved with low investment and the same plant input.

For this reason, the project partners agreed to select the existing Ladyzhyn biogas plant, which is operated by the project partner MHP and has a capacity of 12 MW el. For the planning of the large-scale plant. The plant is also suitable because a gas mixing system is already installed here and thus the CAPEX and OPEX are expected to be particularly low.

The basis for this will be the mass balances of the demo plant and the experience gained with this plant. The IBM system will first be installed in one of the 12 digesters of the biogas plant and later transferred to one of the three blocks (each with 4 digesters). The technical task will be worked out by EE and then discussed and agreed upon with the project partners DBFZ and MHP.

Task 4.2 Planning and design for full-scale operation

The as-built design of the Ladyzhyn biogas plant represents the basis for the development of the concept for in-situ methanization at the plant. Therefore, a thorough inventory of the plant must first take place, considering all changes/extensions to the plant concept. Special attention must be paid to the development and adaptation of the safety and ATEX documentation.

The following document needs to be thoroughly revised to provide the permitting authorities and the operator with a basis for the future operation of the facility:

- Mass flow Diagram for the Demo Plant (Sankey Diagram)
- Process flow diagram
- Plant layout
- verbal short description of the plant
- P+I diagram of the plant
- piping diagram
- ATEX Plan and description
- Health and Safety Assessment

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- Parts list of the plant
- Measuring point and drive list
- Control system description

Task 4.3 Design package delivery
The handover of the design package will take place in the form of an audit. The project partner MHP, representatives of the approval authorities, the operating staff and EE will be present. The project will be presented in detail and all documentation will be handed over. Afterwards, a joint schedule will be drawn up and discussed with the operator of the plant.

The time planning and the summary of tasks for Activity 4 are shown in Table 32.

Table 32 - Summary of tasks, schedule and responsible for the Activity 4 – Concept for implementation of IBM at biogas plants

Activity 4- **Concept for implementation of IBM at biogas plants**				
Phase/Goal	**Actions/steps description**	**Time (date to start)**	**Time (due date)**	**Responsible**
Providing a concept for implementation of IBM at biogas plants	• T4.1 Upscaling of the demo results	2025-09-01	2025-12-31	EE
	• T4.2 Planning and design for full scale operation	2026-01-01	2026-09-30	EE MHP
	• T4.3 Design package delivery	2026-09-01	2026-09-30	EE

The following list represents an overview on Deliverables that will be prepared during Activities 1-4

- D2.2 Report on Design of the Pilot Plants (M18)
- D2.3 Summary on the Design of the Pilot Plants (M20)
- D2.4 Intermediate Implementation Report (M30)
- D2.5 Final Implementation Report (with Blueprints of the Pilot Plants) (M49)
- D2.6 Blueprints Showcasing the Final Results of the Demonstration Activities (M51)

Details on the content of the individual deliverables will be provided in Deliverable 3.1 by the project partner ENEA and will furthermore be specified during the project (M8).

7.9. Milestones

The demonstration of IBM includes the two Milestones MS5 and MS8 (see table 37 below). For MS5 "Demonstration of *in-situ* methanation in 50 L lab scale reactors", process parameters from a stable reactor operation at DBFZ and MHP will be provided. This milestone includes information on the following process parameters:

- Substrate composition, organic loading rate and hydraulic retention time of the anaerobic digestion process
- Hydrogen flow rate, and frequency of hydrogen addition
- Volatile fatty acid pattern of the process
- Gas composition (H_2, CO_2, CH_4, H_2S)
- Data on microbial community composition and changes of the microbial community compared to the start of the process (only if already available)

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- Required process additives including their dosing (e.g. trace metals or $FeOH_2$ to reduce H_2S concentration in the biogas)

The aim of MS8 "Demonstration of *in-situ* methanation at MHP demo site" is to show successful upscaling of the IBM process to > 10m^3 scale and includes a comparison of the process parameters to the lab scale results (MS5) (Table 33).

Table 33 - Milestones of IBM

Milestone N°	Key Milestone name	Month of completion	Major Tasks
MS5	Demonstration of *in-situ* methanation in 50 L lab-scale reactors	M25	Production of biomethane in stable AD process.
MS8	Demonstration of *in-situ* methanation at MHP demo site	M42	

7.10. Risks

According to the existing knowledge and literature data on IBM, two major technical risks have been identified for the project (Table 34).

The first risk (R17) is at the microbiological process level. Due to diverse microbiological processes and physical conditions, the CH_4 concentration in the biogas may not be raised up to 80% by H_2 addition to the fermenter. Adding H_2 to AD processes can result in increased activity of hydrogenotrophic methanogenesis and increased CH_4 production (desired reaction). Due to thermodynamic restrictions, increased H_2 partial pressure can also result in reduced activity of acetogenic bacteria of the biogas process that produce acetate and H_2, (e.g. from organic compounds, resulting in process disturbances of the whole AD process).

Furthermore, the addition of H_2 can lead to an increased activity of homo-acetogenic bacteria, i.e. increased acetate production from CO_2 and H_2, that finally results in higher activity of acetoclastic methanogenesis from acetate and therefore, to a stoichiometric biogas composition of 50 % CH_4 and 50 % CO_2 at an overall increased biogas production. To mitigate these risks, we will perform in-depth process analytics during the 50 L lab-scale experiments to assure low H_2 concentrations in the gas phase, and to monitor the composition and concentration of VFA and the development of the microbial community over time. We have already taken this risk into account in our preliminary business perspective in chapter 6.1.8., (i.e. using a methane concentration of 65 % at an overall increased biogas production due to homo-acetogenesis).

The second risk (R18) is of physical and technical nature and addresses an insufficient H_2 provision using the proposed (and already existing) gas mixing system. Hydrogen has very low solubility in water but needs to be provided in dissolved form to the methanogens. This is a general weakness of biological methanation (ex-situ and *in-situ*). If the used gas mixing system does not allow a sufficient IBM process, the system needs to be adapted in order to increase the solubility of H_2 in the system, e.g. by increasing specific bubble surface area (decreased bubble size). Application of increased pressure is not an option for IBM as it is planned to integrate the concept into existing biogas plants that, very often, are equipped with flexible membrane roofs.

In addition to the technical risks associated with the development of IBM described above, there exist uncertainties in the implementation of the activities of the demo leader MHP due to the current war conditions in Ukraine. However, MHP will do whatever is necessary to fulfil its tasks and duties in the project to the best of its ability. The sub-project partners EE and DBFZ support MHP within its capabilities.

Table 34 - Risk probability/ impact on the IBM Innovative technological pathway and potential risk mitigation strategies

Risk	Probability	Impact	Mitigation measures
R17: *In-situ* methanation biogas with less than 80% methane.	High	High	In-depth analysis of the process (including molecular biological analysis of the microbial community) and adaption of process parameters or substrates.
R18: Unfeasible hydrogen provision via gas mixing system during *in-situ* methanation.	Low	High	Adaptation of the gas mixing system in lab scale and demo reactors to solve the problem.

7.11. Exploitation

From its experience with *in-situ* methanation EE assists to install lab-scale reactors at MHP and DBFZ. These reactors will be used for detailed lab-scale process evaluation and development.
DBFZ will transfer all knowledge on lab-scale *in-situ* methanation to MHP to be validated in their own lab-scale reactors. Based on the results, a demonstrator for *in-situ* methanation will be installed at the MHP biogas plant (together with EE). Furthermore, EE will provide a concept for the implementation of IBM at biogas plants.
In summary, UABIO will ensure appropriate exploitation from a policy perspective while MHP and EE will ensure it from a commercial perspective.

Using the IBM implementation concept MHP (together with EE) will apply it to biogas plants under its operation. MHP, as one of the world's leaders in poultry farming, operates biogas plants in Ukraine (most of them already equipped with a gas mixing system that allows fast implementation of in situ biomethanation) with an overall installed electrical capacity of > 12 MW (24 MW planned). This plant portfolio provides the first basis for the commercialization of the in situ biomethanation technology and serves as a nucleus to spread the technology in the huge Ukrainian agricultural sector and beyond. Retrofitting of biogas plants in remaining European countries, as well as integration of distribution, sales, and customer support for in situ methanation systems in the European market, will be provided mainly by EE.

In a second step, the concept will be provided to other biogas plant operators. Necessary adaptations of existing regulations for injection of biomethane in the Ukrainian gas distribution network due to IBM will be accompanied by UABIO. In particular, UABIO will promote and share the project results at policy consulting activities, e.g., in advisory committees or policy expert discussions and therefore provide a profound basis for the adaption of Ukrainian legislation to support biomethane production and marketing strategies in the country. In particular, it with allow supporting the process of the biomethane registry development, implementation, and synchronization with similar registries in Europe, and defining long-term actions, including national biogas production target for 2035 and a long-term national incentive package. The targets and actions agreed together would create confidence in the industry's growth potential for the current players and for newcomers.
Furthermore, UABIO will report on the results and outcome of the sub-project using its wide network during the project and beyond. This ensures the transfer of project results to stakeholders from industry, policy and research.

7.12. Block Flow Diagram

The Block Flow Diagrams (BFD) and Process flow diagram of the IBM process are presented in Figure 24.

Co-funded by the European Union

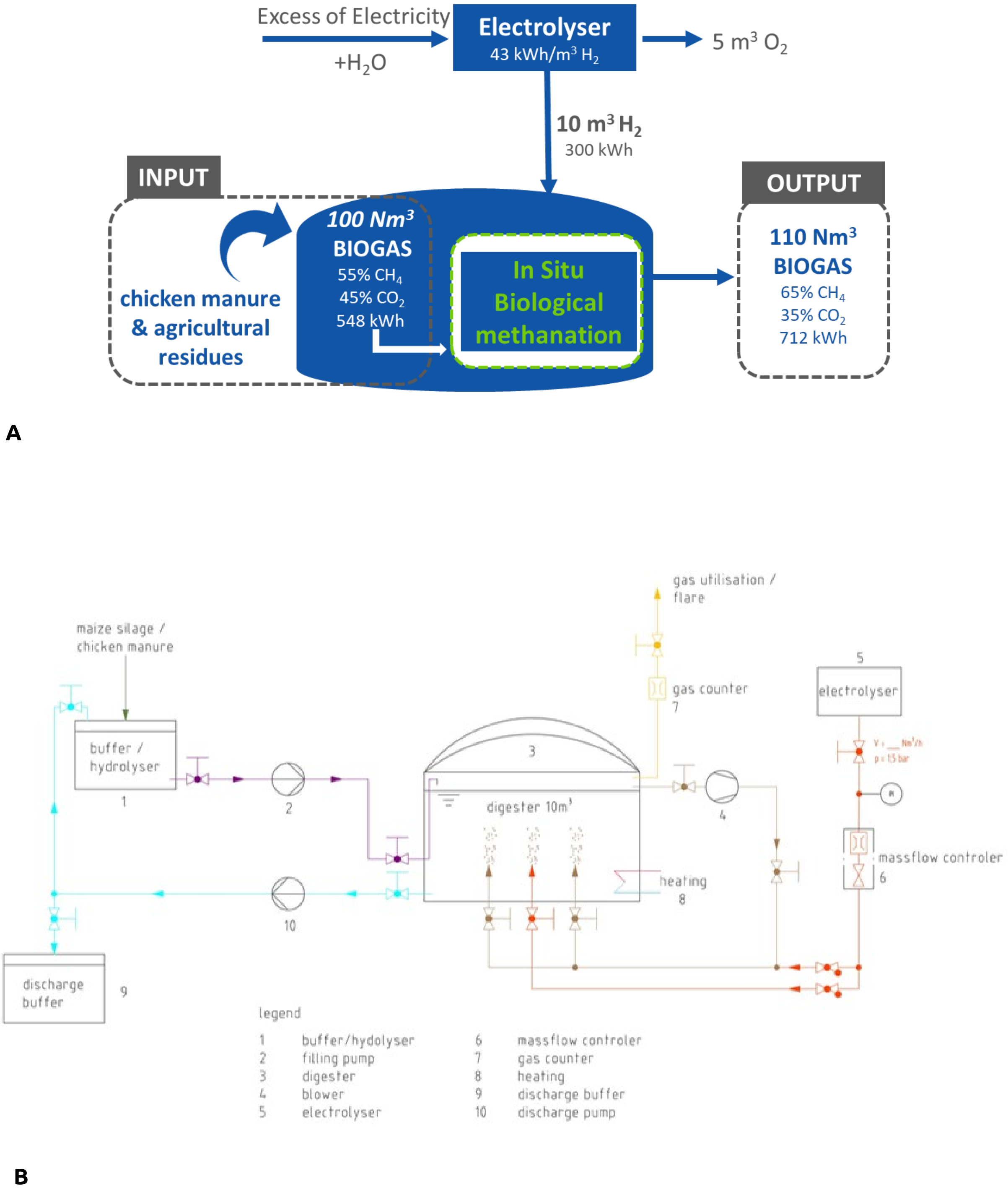

Figure 24 - In-Situ Biological methanation (IBM) A. Block flow diagram and B. Process Flow Diagram