D3.1 | Methodological Framework on Data Collection and Assessment

Deliverable:	Methodological Framework on Data Collection and Assessment
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Version:	Final Version
Quality review:	Stefano Proietti, Giorgia Galvini (ISINNOVA)
Date:	06/06/2023
Dissemination level:	Public (PU)
Grant Agreement N°:	101084200
Starting Date:	01-10-2022
Duration:	54 months
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Executive Summary

BIOMETHAVERSE aims at delivering a set of innovations in the biomethane sector capable of increasing the biomethane production, reducing costs, and coupling the electricity and gas grids to enable the transition towards renewable energy sources in all the energy sectors. The results of BIOMETHAVERSE are mainly economic/technological, but the deployment of the technologies developed will have an impact on society (green jobs, security of energy supply, energy poverty) and the environment (reduced GHG emissions, circularity).

In order to maximise the innovation performance and the contribution to the Green Deal objectives, but also to guarantee the replicability and transferability of optimised systems, as well as for cross-learning among demonstration plants, BIOMETHAVERSE will upscale and optimise the demonstrators to enable a state-of-the-art sustainability assessment covering the economic, social, and environmental aspects.

This deliverable sets the scene for the upscaling, optimisation, and sustainability assessment activities by defining the methodological approach to be adopted and a data collection strategy.

The techno-economic assessment will be performed by flowsheeting the demonstration plants with state of art tools (ASPEN). The system actually built during the project will form the basis for a scale-up and optimisation of the technologies developed to provide the detailed technical information needed to replicate the systems. The models built will also enable the optimisation of the infrastructure and the operation of the technologies developed.

The detailed inventories produced during the techno-economic assessment, up-scaling and optimisation will be assessed for their social and environmental sustainability (including GHG emission measurements at all demonstration sites) in order to evaluate their performance and also to ensure that the best performing configurations, in terms of environmental and social impacts, are identified.

The methodology of "LCSA - Life Cycle Sustainability Assessment" will be applied to the BIOMETHAVERSE project. LCSA is a well-known measurement tool applied to assess and quantify the impacts of any service, industrial system, or production process on all three dimensions of sustainability: social, environmental, and economic, also known as the Triple Bottom Line (TBL). For these three dimensions, well-known approaches are usually applied – i.e., Environmental Life Cycle Assessment (E-LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA).

These tools require transparent, high quality and detailed input data to be effective, therefore a timely, structured and efficient data collection strategy is envisaged.

With this deliverable, we are laying the foundations to the evaluation and optimisation of the technical, economic, social and environmental performances of the BIOMETHAVERSE innovations and ensure that they can contribute to the production of domestic renewable gases which would ensure security of gas supply at predictable and affordable prices and support the EU goals of energy independence and competitive sustainable growth, while creating local green jobs without significant harm to the environment.

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1. BIOMETHAVERSE in a nutshell

BIOMETHAVERSE (Demonstrating and Connecting Production Innovations in the **BIOMETHA**ne uni**VERSE**) aims to diversify the technology basis for biomethane production in Europe, increase its cost-effectiveness, contribute to the uptake of biomethane technologies, and support the priorities of the SET Plan Action 8.

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

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

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

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

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

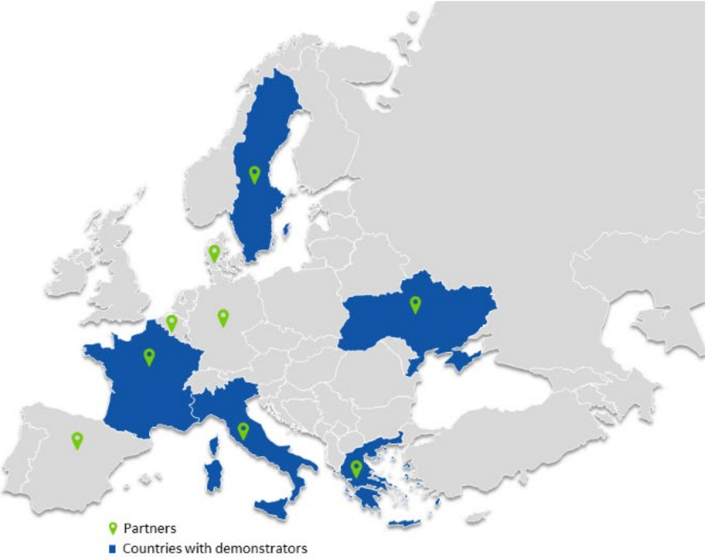

Figure 1- BIOMETHAVERSE countries and partners

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1.1. Deliverable content

This Deliverable 3.1 is the first deliverable of Work Package 3: Assessment and Optimisation of Innovative Biomethane Pathways.

The objectives of WP3 are twofold, i.e.: to perform a holistic, comprehensive sustainability assessment of the demonstrators as built within the project, and of their potential optimised and upscaled configurations; and to contribute to the optimisation of the BIOMETHAVERSE innovations design by providing eco-design guidelines and assessing the performance of alternative configurations to identify the most sustainable.

To this aim, WP3 will apply a state-of-the-art sustainability assessment methodology, covering the economic, social, and environmental pillars of sustainability, to avoid potential trade-offs among sustainability aspects. The developed methodology will be applied to the BIOMETHAVERSE innovations investigated in WP2 to identify the most promising configurations with an eco-design approach. The results of the sustainability assessment will enable drawing conclusions and recommendations on the future application of the demonstrator concepts (WP4).

This report is part of task 3.1: evaluation framework and data collection strategy that. Task 3.1 is led by ENEA, who is also responsible of this deliverable, and lasts from M1 to M8. Other participants include: ISINNOVA, EBA, CERTH, RISE, ENGIE, POLIMI, DBFZ.

Task 3.1 includes the definition of the methodological approach to be adopted, based on the most recent recommendations from international institutions, mainly ISO and the EC ILCD for the environmental LCA, the Renewable Energy Directive for the GHG accounting, the UNEP guidelines for the social LCA.

Based on the identified methodologies, it is expected that a clear and concise framework for data collection will be established by WP2 to streamline the data exchange and ensure the required completeness and consistency of the data collected. Task 3.1 is expected to cooperate with task 1.2 - data management plan to define a methodological framework for data management and management of other research outputs. The Data Management Plan has been submitted by ENEA at M6; therefore, it considers all the data management requirements from WP3. In order to fulfil, and demonstrate the activities expected in task 3.1, the deliverable is organized as follow.

Section 2 introduces the sustainability assessment methodology that will be applied to the BIOMETHAVERSE case studies. As well as the sustainability concept builds upon three pillars, the methodology adopted for the BIOMETHAVERSE project pilot plants assessment builds on the pillars of economic, environmental, and social sustainability.

Section 3 reports on the techno-economic methods used for the upscaling and optimization of the pilot plants to commercial scale size, in order to obtain a meaningful and reasonable estimate of the economic performance of optimised full-scale plants, as the economics of pilot plants would not be comparable with other, more mature, technologies.

Section 4 presents the methodology that will be adopted for the assessment of the environmental impacts and benefits of the technologies developed in the five pilot sites. Moreover, section 4.1 provides an overview of the methodology that will be used to measure methane leakage at the pilot sites.

Section 5 presents the methodology that will be used to assess the socio-economic repercussions related to the deployment of the BIOMETHAVERSE technologies for biomethane production.

Based on the identified methodologies, a clear and concise framework for data collection from WP2 is established in Section 6, to streamline the data exchange and ensure the required completeness and consistency in the data collected.

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2. Introduction

Several methods for the simultaneous assessment of different sustainability aspects are reported in the literature. The method "LCSA - Life Cycle Sustainability Assessment" is applied in the BIOMETHAVERSE project. LCSA is a well-known measurement tool applied to assess and quantify the impacts of any service, industrial system or production process on all three dimensions of sustainability: social, environmental and economic, also known as the Triple Bottom Line (TBL). For these three dimensions, well-known approaches are usually applied – i.e., Environmental Life Cycle Assessment (E-LCA), Life Cycle Costing (LCC) and Social Life cycle assessment (S-LCA), as illustrated in Figure 2.

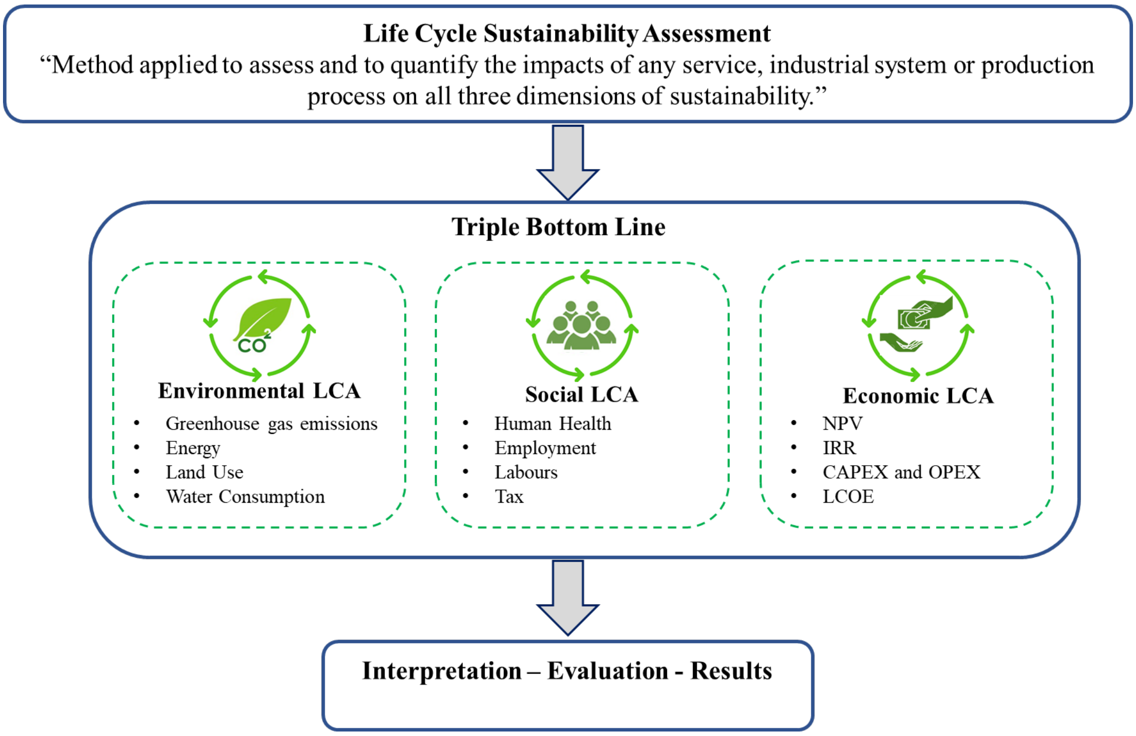

Figure 2 General representation of the methodology adopted for sustainability assessment

The LCSA methodological approach is based on the framework proposed by UNEP/SETAC Life Cycle Initiative [1], which "refers to the evaluation of all environmental, social and economic negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle" and “provides a map, a framework and a flash light for stakeholders involved in assessing the social and socio-economic impacts of products life cycle”.

In fact, decision-making with regard to the sustainability assessment of energy technologies is complex due to sometimes conflicting goals (e.g., low cost for end users, minimum environmental impact, security of supply, maximum social acceptance) and requires an integrated consideration of economic, environmental and social criteria. This approach ensures that burdens are not shifted between impact categories and along steps of the supply chain. In order to integrate circularity and criticality aspects into an overall LCSA framework (see e.g., ongoing activities of the ORIENTING project), a methodological discussion has recently started in the scientific community.

It is fundamental to establish the procedure by which the results from these three dimensions are combined in the context of drawing overall conclusions and recommendations.

In contrast to Klöpffer [2], who presented two main approaches - (i) an additive option (LCSA = E-LCA + LCC + SLCA), and (ii) an integrative option (LCSA = 'E-LCA new' including LCC and SLCA as additional impact categories in the LCA), the ORIENTING team examined a whole range of different integration

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approaches, divided into three groups (i.e., Group 1 = integration methods across sustainability domains / Group 2 = visualisation approaches / Group 3 = commonly used weighting methods in the environmental and/or social fields), and analysed according to relevant issues that need to be consistently assessed in an LCSA framework. In total 15 different integration approaches have been evaluated and assessed against 7 seven main items (i.e., weak vs strong sustainability / double-counting / benefits and burdens / relative vs absolute sustainability / communication purposes / uncertainty analysis / policy linkages).

Although a clear recommendation on how this integration step should be taken is still missing, the BIOMETHAVERSE Project will carry out an in-depth evaluation of what kind of integration will be done when the data collection phase is completed.

The E-LCA assessment provides a standardised and transparent method for making reliable statements about environmental impacts. Adopting the principles and guidelines of ISO 14040/14044 for the LCSA prevents mere shifts of undesirable effects between life cycle stages/dimensions/countries/in the dimensions/countries/in the future.

The benefits of combining E-LCA, LCC, and sLCA include cost savings due to simultaneous data collection, mitigating the risk of double counting, establishing comparability by referring to the same functional unit, and increasing motivation for sustainable action on the part of the stakeholders involved.

By producing three separate balances, the LCSA follows a reductionist logic, which, however, avoids the loss of information and subjectivity associated with the weighting process. On the other hand, the consideration of the whole system in its life cycle is essential, as an assessment of the system cannot be made on the basis of the individual system elements and their characteristics, as this would not take into account the mechanisms and relationships within the system and the latter would remain unconsidered.

The methodological difficulties arise at the interpretation stage, particularly in quantifying the effects and linking them meaningfully to the system and to a functional unit, or in interpreting the results especially as some indicators show a high degree of variance at the local level.

Notably, further research is needed on different aspects of LSCA, especially on the assessment of trade-offs within and between the sustainability dimensions. The provision of a coherent set of impact indicators and a methodology for aggregating and interpreting different types of data, together with the development of appropriate formats and standards for communication and dissemination of results would streamline the operationalisation of LCSA. In addition, the development of integrated application tools (software programs, databases) enabling the integrated assessment of the three dimensions of sustainability would further simplify and increase the consistency and comparability of LCSA studies. In conclusion, the LCSA is a relatively new methodological approach that is maturing rapidly, and it is hoped that by the time the methodology will be applied to the BIOMETHAVERSE technologies, the tools and methods will be more mature and easier to apply and use.

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3. Techno-economic assessment

In the framework of task 3.2 - demos flowsheeting and technoeconomic assessment, and task task3.4 - evaluation results and upscaling of demos; it is expected that the 5 demo installations built in WP2 will be reproduced by process flowsheet simulations by ENEA using a suitable model and a simulation code (such as Aspen Plus) then upscaled to commercial size.

According to the BIOMETHAVERSE project schedule, the modelling work and data collection start at M8, with the initial description of the innovations expected in the pilot units; this initial set of data will be continuously updated and completed with the innovation designs of the pilot units expected at M18, which will be used as reference case. Based on the understanding of the pilot unit designs and operating models, it will be possible to produce preliminary flowsheets, i.e., process flow diagrams, which represent the expected operating modes and performances of the pilot units, with corresponding mass and energy balances under steady state conditions. In this phase, relevant inputs from pilot plant developers and operators are expected to support the establishment of reliable and realistic flowsheets.

The results obtained during the experimental demonstration and provided by the pilot plant operators will be used to validate and to fine-tune the developed models and flowsheet analysis using the real case as a reference.

Once the above-mentioned validation phase is completed, the second development phase can begin: process scale-up, analysis and optimisation. Here, each unit of the pilot plant will be reviewed and its possible scale-up to commercial size will be analysed. The commercial size will be defined based on recommendations from partners and stakeholders. Any techno-economic constraints to scale-up will be assessed and solutions proposed, e.g., the possibility of using modular systems of equivalent (known) size to the pilot units.

Standard models or actual data could be eventually completed and integrated by detailed models from the literature or developed on purpose by ENEA.

Finally, up-scaled flowsheets will provide reliable mass and energy balances for further analysis and optimisation. Specifically, the scale-up process will allow the estimation of fixed capital expenditure (CAPEX); in addition, the identified plant operating sequences (also including possible shutdown or part-load scenarios), together with the input received from the plant operators', will allow the estimation of operating costs (OPEX). These results will be relevant project output and input for the following techno-economic assessment and sustainability studies.

The comprehensive and detailed demos flowsheets will be used as input for the techno-economic assessment, which will be based on well-established common dynamic economic indicators, i.e., the Net Present Value (NPV) and Internal Rate of Return (IRR), with the aim of performing the conventional Life Cycle Costing (LCC) evaluation. Discounting techniques are used to compare costs and benefits over different time periods. Costs at different points in the life cycle must be converted to a common point in time to reflect the time value of money. The reference point should be the start up or go live date of the system or asset being assessed. An interest rate based on an investor/stakeholder's perception of the time value of money perception is used to discount future expenditures to present values at a given reference point in time. [3] It may also be calculated using the Weighted Average Cost of Capital (WACC) approach if enough information is available from the stakeholder.

The economic indicator NPV represents the basic principle of modern investment analysis to examine the present value of all future cash flows. The purpose of NPV is to determine the value at the end of t interest periods of equal payments invested at an annual compound interest rate i at the end of each interest period t (usually one year). [4] These cash values (Pt Income-Costs Ct) are then summed up according to Eq. 1.

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$$C_{NPV} = -I_{t0} + \sum_{t=0}^{T} P_t - C_t(1+i)^{-t} + L(1+i)^{-t} \qquad \text{(Eq. 1)}$$

A variant of the NPV is the annuity method. The NPV is distributed in yearly equivalent series of cash flows over the entire lifetime of the product and is calculated by Eq. 2.

$$C_a = C_{NPV} * \frac{(1+i)^T * i}{(1+i)^T - 1} \qquad \text{(Eq. 2)}$$

Another relevant indicator that will be considered is the IRR, which is used to investigate the cost effectiveness of the potential investment. The investment alternative can be considered attractive if the calculated interest is higher than the expected Minimal Acceptable Rate of Return (MARR) or used depreciation rate respectively. If the calculated rate is lower the investment can be considered unattractive. The investor is indifferent in the case of equal interest rate. The method can be considered as supplement to the dynamic methods applied for LCC as annuity or NPV. IRR can be estimated by iterative approximation or more easily with rough arithmetical approximation methods as simple linear interpolation between a negative and positive NPV using Eq. 3.

$$-I_{t0} + \sum_{t=0}^{T} P_p(1+i)^{-t} - \sum_{t=0}^{T} C_p(1+i)^{-t} = 0 \qquad \text{(Eq. 3)}$$

Once calculated the indicators, LCC method can be applied for life cycle oriented (life cycle) evaluation of investment alternatives as part of techno-economic assessments. LCC analysis is also capable to fill the gap between the economic pillar within environmental and social pillars for the Life Cycle Sustainability Assessment (LCSA) In general, LCC can be applied anywhere and an has a "cradle-to-grave" perspective. There is no strict common standard for LCC approach but a common definition of it as follows: “process of economic analysis to assess the life cycle cost of a product/system over its life cycle or a portion thereof”. [5,6]

LCC studies are often carried out from a certain stakeholder perspective corresponding, for most cases, to the target audience, resulting in approaches that differ in scope and elements to consider. A few examples illustrate this:

- Consumers/users of a product are mainly interested in costs related to ownership (e.g., total cost of ownership, TCO), including costs for acquisition, use and disposal of a product, but ignoring, for example, details on the manufacturing costs;
- Producers/providers/manufacturers of the product (businesses) are typically interested in a thorough understanding of the manufacturing costs, including the supply of raw materials or intermediate products and potential product disposal costs, whilst usually not directly interested by costs incurred in the use phase;
- Policy makers/NGOs are likely to be more interested in the wider societal and environmental effects related to the same product, extending the scope to the entire life cycle, and also considering externalities (at least to some degree).

This variety in uses is also reflected in international standards for LCC (IEC-60300-3-3, 2017; ISO-15663, 2021; ISO-15686-5, 2017) and in the three main variants of LCC proposed by Hunkeler et al.

(2008) [7], i.e., conventional, environmental and societal LCC (abbreviated by cLCC, eLCC and sLCC, respectively). For a short characterization of these variants. the main distinguishing elements are the stakeholder perspective, consideration of externalities and alignment with environmental LCA (notably in terms of the functional unit, technical, spatial, and temporal system boundaries and distinguished life cycle stages). Whilst a producer is more likely to choose conventional or environmental LCC and a policy decision-maker is more likely to choose societal LCC, this choice is ultimately defined by the goal of the analysis.

In the context of the BIOMETHAVERSE Project, the conventional LCC to cover the economic dimension of sustainability will be performed. This means to take into account all expenses related to research and development (R&D) CRD, extraction of raw materials supply & manufacturing Cm, construction CI, which can be summarized as CAPEX; in addition, operation and maintenance CO&M or operational expenditures (OPEX and disposal or end of life respectively CEOL or end of life expenditures (EOLEX) are also included.

$$LCC = CAPEX + OPEX + EOLEX$$

In general, up-front capital is only a part of a products life cycle. It is therefore necessary to state the application conditions under which the demonstrator units in general will be operated. Operation conditions have a strong influence on e.g., necessary maintenance efforts, as well as potential replacement investments and thus on the total LCC.

Usually, in this application field, the cost is displayed as a ratio of the converted amount of energy content of the final product (biomethane or biogas) to the full LCC, resulting in a functional unit, which allows it to show the cost in form of energy €/kWh, monetary or derived variables, such as the net present value or amortization period. The cost sometime is referred to as Levelized Cost of Electricity.

$$LCOE = \frac{LCC_a}{n_a \cdot h}$$

Such an indicator allows to simply compare different alternatives delivering same services. However, the same calculation approach has to be followed to make alternatives comparable.

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4. Environmental Performances Assessment

The environmental impacts associated with the five demonstrator and upscaled plants will be quantified based on the mass and energy balances developed in Task 3.2 and 3.4. The framework for this activity is provided by Task 3.3 - environmental and social sustainability evaluation.

The analysis will follow the Environmental Life Cycle Assessment methodology (E-LCA) and encompass a cradle-to-grave perspective, with an attributional modelling approach, albeit the alternative fate of the feedstock (or land) will be included in the analysis, when relevant.

Although there are different definitions of consequential and attributional modelling, in our analysis we follow the approach proposed by the ILCD. In short, consequential modelling refers to an inventory modelling approach that also considers the scale effects. This type of modelling aims at internalising the market-mediated impacts caused by a change in the installed capacities of a system on the rest of the economic system. This modelling approach is suitable for capturing the impact of policies aimed at changing the installed capacities i.e., macroscale decisions. By contrast the attributional approach models the impacts of a specific amount of product without considering the impacts on other sectors of the economy, and it is therefore valid when installed capacities are not affected, either because it is a microscale decision, or because it is for accounting purposes. In our case, the functional unit will most likely be the production of 1 MJ of biomethane, while the reference flow (the reference to which all inputs and outputs are scaled) will be the construction and operation of a plant over its lifetime.

E-LCA is an analytical methodology for comprehensive environmental assessment of products and services (ISO, 2006a). It quantifies the potential environmental impacts from the raw material acquisition to the end-of-life disposal throughout a product's life cycle, which highlights environmental "hot-spots" and supports the identification of the potential opportunities to improve the environmental performance of the product or service (eco-design). E-LCA is internationally standardized with the ISO standard 14040 (ISO, 2006a; ISO, 2006b) and has several applications, with the most important of which is that by providing environmental metrics, designers can be informed about the environmental performance of the whole life cycle, compare, develop and improve products and services. In addition, LCA studies can be used for strategic planning, marketing and, at a higher level, for public policy making. The systematic procedure of an E-LCA consists of four phases:

- **The goal definition** phase identifies the purpose of the analysis, i.e., the question we want to answer. Therefore, the aims of the study are defined, namely the intended application, the reasons for carrying out the study and the intended audience. While the scope definition describes how the LCA practitioner plans to answer the question, therefore the main methodological choices are made in this step, in particular the exact definition of the functional unit, the identification of the system boundaries, the identification of the allocation procedures, the studied impact categories, the Life Cycle Impact Assessment (LCIA) models used, and the identification of data quality requirements. Particularly, the functional unit is the reference unit which is used to normalize all the inputs and outputs in order to make different systems comparable.
- **Life Cycle Inventory (LCI)**: this phase of an E-LCA involves the data collection and the calculation procedure for the quantification of inputs and outputs of the studied system. Inputs and outputs concern energy, raw material and other physical inputs, products and co-products and waste, emissions to air/water/soil, and other environmental aspects. This step therefore refers to the study and detailed analysis of the material and energy flows of the system considered with the aim of modelling the entire life cycle. One of the most critical aspects of this phase is the quality of inputs, which must be verified and validated in order to guarantee the data reliability and correct use. The Life Cycle inventory is the most time-consuming stage in the LCA study. It implies a detailed reconstruction of the material and energy exchanges between the foreground system (the system under analysis), the

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Technosphere (the rest of the economy, which provides inputs and dispose of residues) and the environment in terms of elementary flows. To translate the results of the inventory built with the technoeconomic assessment and the flowsheeting into elementary flows.

- **Life Cycle Impact Assessment (LCIA):** in the LCIA phase LCI results (the elementary flows) are associated to environmental impact categories and indicators. This is done through LCIA methods which firstly classify emissions into impact categories and secondly characterize them to common units so as to allow comparison (e.g., the flows of GHG emissions are associated to climate impacts through the related metrics) in the Life Cycle Interpretation phase, results from LCI and LCIA are interpreted in accordance with the stated goal and scope. This step includes completeness, sensitivity, and consistency checks. Uncertainty and accuracy of obtained results are also addressed in this step. In practice the analyst scrutinizes the results and discusses them, giving as accurate information as possible to the decision makers, stakeholders or manufacturers.

- **Life cycle interpretation**: according to the ISO 14044 standards, the interpretation phase should deliver results that are consistent with the defined goal and scope, and which reach conclusions, explain limitations, and provide recommendations. The interpretation phase is the key step which guarantees quality, consistency, and gives meaning to the work carried out. In practice, the life cycle interpretation is a systematic technique to identify, quantify, check, summarize and evaluate information from the results of the life cycle inventory and/or the life cycle impact assessment. The task to be carried out in the interpretation phase are: a) identification of significant issues; b) evaluation by checking the completeness, consistency and sensitivity of the results; c) drawing conclusions, describing the limitations and providing recommendations.

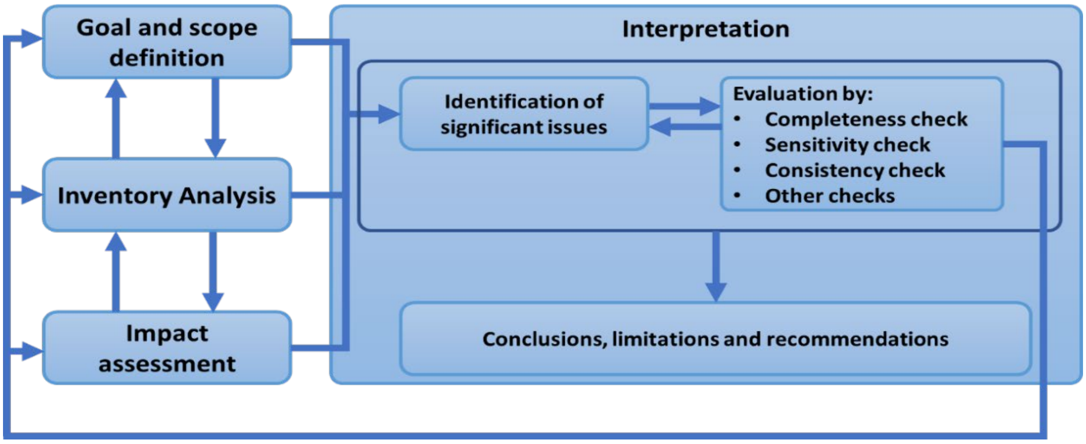

Figure 3- Life Cycle Assessment framework, adapted from ISO14040 (Agostini et al 2020)[8].

Impact categories selection

An important step in LCA is the selection of impact categories to be addressed and the related characterization models (i.e., the models needed to group and weight the elementary flows into a single parameter measuring an environmental impact) is an integral part of the goal and scope definition phase of an LCA, and further extends to the LCIA phase.

In the identification of the relevant impact categories, analysts should consider the consistency with the goal and scope definition: any choice made by the analysts has to support the defined goal and scope; that means for the indicator selection that when, for example, environmental sustainability assessment is the goal of a study, the practitioner cannot choose a limited set of indicators, or a single-indicator footprint approach (as often happens with GHG emissions), as this would be inconsistent with the sustainability objective of avoiding burden shifting among impact categories.[2]
Moreover, the correct approach implies considering the comprehensiveness of environmental issues

related to the product system being studied and the appropriateness of the characterization models in the context of the goal and scope of the study.

The environmental impact categories that will be addressed in BIOMETHAVERSE, as they are considered relevant to the specific technology of biomethane production, are the following and will be evaluated by applying the characterization models recommended by the European Commission for the Product Environmental Footprint programme in its most recent recommendations (Commission Recommendation on the use of the Environmental Footprint methods; 2021)[9] and, in case, according to the updated recommended methods (Table 1):

EF impact category	Impact category indicator	Unit	Characterisation model	Robustness
Climate change, total	Global warming potential (GWP100)	kg CO_2 eq	Bern model – Global warming potentials (GWP) over a 100-year time horizon (based on IPCC 2013) [10]	I
Ozone depletion	Ozone depletion potential (ODP)	kg CFC-11 $_{eq}$	EDIP model based on the ODPs of the World Meteorological Organisation (WMO) over an infinite time horizon (WMO 2014 + integrations) [11]	I
Human toxicity, cancer	Comparative toxic unit for humans (CTU_h)	CTUh	based on USEtox2.1 model (Fantke et al. 2017), adapted as in Saouter et al., 2018 [12]	III
Human toxicity, non-cancer	Comparative toxic unit for humans (CTU_h)	CTUh	based on USEtox2.1 model (Fantke et al. 2017), adapted as in Saouter et al., 2018 [12]	III
Particulate matter	Impact on human health	Disease incidence	PM model (Fantke et al., 2016 in UNEP 2016) [13]	I
Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U235 eq	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000) [14]	II
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC $_{eq}$	LOTOS-EUROS model (Van Zelm et al, 2008) as applied in ReCiPe 2008 [15]	II
Acidification	Accumulated exceedance (AE)	mol H+ $_{eq}$	Accumulated exceedance (Seppälä et al. 2006, Posch et al, 2008) [16]	II

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Eutrophication, terrestrial	Accumulated exceedance (AE)	mol N$_{eq}$	Accumulated exceedance (Seppälä et al. 2006, Posch et al, 2008) [16]	II
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P$_{eq}$	EUTREND model (Struijs et al, 2009) as applied in ReCiPe [17]	II
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N$_{eq}$	EUTREND model (Struijs et al, 2009) as applied in ReCiPe [17]	II
Ecotoxicity, freshwater	Comparative toxic unit for ecosystems (CTU$_e$)	CTUe	based on USEtox2.1 model (Fantke et al. 2017), adapted as in Saouter et al., 2018 [12]	III
Land use[1]	Soil quality index	Dimensionless (pt)	Soil quality index based on LANCA model (De Laurentiis et al. 2019) and on the LANCA CF version 2.5 (Horn and Maier, 2018) [18]	III
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 water eq of deprived water	Available Water Remaining (AWARE) model (Boulay et al., 2018; UNEP 2016) [19]	III
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb$_{eq}$	van Oers et al., 2002 as in CML 2002 method, v.4.8 [20]	III
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)[2]	MJ	van Oers et al., 2002 as in CML 2002 method, v.4.8 [20]	III

Table 1- PEF LCIA recommended methods by the European Commission.[9] The different colors refer to the different levels of robustness of the methods

According to the current recommended methods in the PEF approach, only the following impact categories have a method robust enough to draw meaningful conclusions:

- climate change,
- ozone depletion,
- particulate matter,

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[1] Refers to occupation and transformation

[2] In the EF flow list, and for the current recommendation, Uranium is included in the list of energy carriers, and it is measured in MJ.

- photochemical ozone depletion
- ionizing radiation – human health
- acidification
- eutrophication (marine, terrestrial and freshwater)

As no methods are considered robust enough to evaluate the abiotic depletion, both fossil and minerals, technical quantities will be used to assess the efficiency of the technologies, i.e., primary energy demand (both fossil and renewable).

Currently there are no recommended methods, or methods somehow accepted by the scientific community for the assessment of the circularity and raw material criticality of products. In BIOMETHAVERSE we will try to use the most relevant and mature method available for the assessment of the circularity of the technologies and their use of critical raw materials. Very likely the project Orienting (www.orienting.eu) will provide a selection and validation of the best approaches to assess material criticality and process circularity.

LCA of biogas and biomethane

LCA is widely applied in the field of biogas and biomethane production with the aim of environmental evaluation.[21–24] In a recent work, LCA has been also applied for the production of syngas and electricity from biomass.[25] This method can be used to compare the environmental impacts of single or multiple feedstock digestions in small or large-scale plants or understand the full impact of selected biogas utilization pathways, including upgrading to biomethane, and digestate management options. Moreover, LCA results can be used to inform bioenergy research and development efforts aimed at reducing adverse environmental impacts, to compare competing bioenergy technology options (e.g., energy crops), or to estimate the environmental implications of large-scale applications.

LCA studies of different biomethane pathways have been conducted in the scientific literature, providing an overview of their energy and environmental impacts, and identifying the key issues to be investigated to reduce these impacts. However, few studies rely on primary data (data measured directly at production sites) which is the focus of the BIOMETHAVERSE Project. Therefore, the further investigation and development activities on specific processes undertaken in the frame of the project are needed in order to acquire more knowledge in this field.

An interesting overview of LCA application to bioenergy, and how the methodological approach chosen, together with erroneous definitions of goal and scope, may mislead policy makers, is provided in Agostini et al. 2019 [8] where the 100 most cited papers on bioenergy LCA were critically reviewed and analysed to understand which are the mistakes to avoid in bioenergy LCA.

Strength and weaknesses

The last few decades have seen a marked rise in the application of life cycle assessments in virtually all countries around the world. This growing interest can be attributed to the powerful support the tool provides to decision makers. As with all complex assessment tools, the LCA methodology has its limitations as well as strengths.[2]

LCA is a cradle-to-grave analytical method that captures the overall environmental impacts of all the life cycle stages associated with a product, process, or human activity from raw material acquisition, through production and use phases, to waste management. This comprehensive view makes LCA a unique approach in the suite of environmental management tools available to decision makers. Without life cycle thinking, we risk focusing on the environmental issues that demand our immediate attention, and ignoring or devaluing issues that may occur either in another place or in another environmental impact. Such focused assessments can lead to decisions that are based on incomplete information. “Life cycle thinking,” as an idea was born in early nineties when governments and international organizations, together with the private sector, were called in Agenda 21 – Chapter 4 to “develop criteria and methodologies for the assessment of environmental impacts and resource requirements throughout the full life cycle of products and processes.” The ultimate purpose at that time was "assisting individuals and households to make environmentally sound purchasing decisions." Later, UNEP explained that "it is about going beyond the traditional focus on production sites and manufacturing processes so that the environmental, social, and economic impact of a product over its entire life cycle, including the consumption and end of use phase, is taken into account." At the end of the nineties, life cycle thinking, at least from an environmental perspective, became progressively more important for the international community [UNEP, 2021].[26]

Moreover, LCA highlights potential environmental trade-offs. The broad scope involved in conducting LCA makes users more aware of the complexities of integrated industrial systems and ecosystems, and the appropriate corresponding remedy for a given situation. LCA encompasses all the interacting activities, media, and impacts and the identification of potential trade-offs from one phase of the life cycle to another, from one region to another, or from one environmental problem to another that may occur as a result of a decision (that is, resulting from a change to a system or from choosing between systems).

The main limitation is that ISO series of standards provides us with a definition of LCA along with a general framework for conducting an assessment, but, on the other hand, they leave much to interpretation by the person conducting the assessment and it may be not always completely clear how the data were modelled in order to create the data found within them. The numerous, underlying assumptions, such as exclusions which were applied during data collection, are not typically revealed and can lead to not reliable results. For this reason, particular attention will be paid to the data collection strategy and to define scope and goals of each analysis accordingly.

Standards and guidelines

The ISO 14040 series standards are the core standards of LCA. These are the leading international standards on LCA. ISO 14040 is an overarching standard encompassing all four phases of LCA (ISO, 2006a). ISO 14041 deals with goal and scope definition and life cycle inventory methods. The ISO 14040 and 14044 standards provide an important framework for LCA. This framework, however, leaves the individual experts, practitioners, and data developers, with a range of important choices that can be individually interpreted, leading towards differences in consistency, reliability, and comparability of the results of the assessment. Equally, the methodological assumptions behind the life cycle data can differ widely, so that data from different sources can be not interoperable.

An other fundamental reference is the International Reference Life Cycle Data System (ILCD.)[27] It is an initiative developed by JRC and DG ENV since 2005, with the aim to provide guidance and standards for greater consistency and quality assurance in applying LCA. ILCD publications have been established through a series of extensive public and stakeholder consultations. The ILCD Handbook is accompanied by a set of publications in line with the international standards on LCA ISO 14040/44.

Finally, to provide the technology developers, stakeholders, and policy makers, a better understanding of the potential role and attractiveness of the technologies developed, the GHG emissions according to EU regulations will be calculated for the systems developed, in terms of gCO_2 equivalent per MJ of biomethane produced. This will imply both the calculation according to the Renewable Energy Directive (2018/2001/EU) methodology for calculating the GHG emissions of biofuels, or its update, or the Delegated regulation for a minimum threshold for GHG savings of recycled carbon fuels, when the energy content of the biomethane is from electricity.

4.1. Methane emissions measurements

As GHG emissions from plant operation (e.g., CH_4 and N_2O, which are potent GHG) are important and may jeopardise the GHG emission savings from biomethane production, as described in task 3.3, the BIOMETHAVERSE project will qualify and quantify the CH_4 and N_2O emissions of the demonstration units will be qualified and quantified using a methodology developed in the ERANet project EvEmBi. Each individual demonstration unit will be analysed using an IR camera to identify individual emission sources. The emissions from the identified source will then be quantified using housing of emission

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sources combined with mobile FID measurements and laboratory analysis of gas samples (the specific methane mass flow from each source is required, i.e., methane concentration and volume flow). The results of the measurements will be made available for the sustainability assessment and to advise the demonstration site operators where and how to reduce existing emissions.

The following is a brief and summarised description of the measurement methodology to be used for determining the emissions of the demonstration plants with the on-site approach is described in a short and summarized form. Further details can be found in the MetHarmo Guidelines [28].

With the on-site approach, as far as possible, all emission sources of the demonstration plant are detected individually, quantified with an adapted measurement methodology and finally summed up to the total methane emission. Since only a temporal portion of each emission source can be represented, emissions are assumed to occur constantly. Depending on the source type (point/area source, led/diffuse, time-dependent and/or operation-dependent), different methods must be used for quantification. The measurement methodology must be individually adapted to the different demonstration plants.

For emission measurements at locally unknown leaks, the first step is to detect the leaks. For this purpose, all gas-carrying plant components (fermenters, biogas pipelines, etc.) are examined. Three complementary measurement systems are used to identify leaks: an optical gas imaging camera system (OGI camera) from FLIR (GF 320), a portable methane-specific open-path laser from GROWCON (LaserMethane® mini Gen2), and a portable biogas monitor from Geotechnical Instruments Ltd (BIOGAS 5000).

The (OGI-camera) uses the specific property of volatile organic substances to absorb particularly high amounts of thermal radiation in certain wavelength ranges. Methane has different absorption maxima in the infrared (IR) spectrum. The camera uses the wavelength band of approx. 3.2 - 3.4 µm. The thermal radiation incident through the lens is restricted to this wavelength band by means of narrowband filters. When the radiation subsequently hits the detector, a photon flux is induced. A gas cloud between the background and the objective changes this energy flux, regardless of whether the gas temperature is higher or lower than the background temperature, because only a temperature difference is important. The detector consists of a cooled focal plane array, an array of light-sensitive detector elements that detect photon flux, based on the internal photoelectric effect. Using a special image superposition technique, the gas escaping from the leaks is visualized in the form of a cloud visible on the camera display.

Like the IR camera, the handheld methane laser is a remote measurement method for detecting biogas leaks. However, unlike the camera, it is an active IR measurement. An IR laser beam of a specific wavelength is emitted from the handheld unit, reflected off a surface and reflected back to the detector, which is also located in the handheld unit. Along this path, the intensity of the laser beam decreases exponentially as a function of the wavenumber (reciprocal wavelength of the laser light) according to Lambert-Beer's law. By selecting a suitable laser diode, the handheld instrument is selective for methane. From the measured absorption and the distance to the reflecting surface, the system calculates a path-integrated methane concentration, displayed in ppm m. If the display value is divided by the distance to the reflecting surface, the result is a path-averaged concentration in ppm.

A portable biogas monitor is used to determine the methane concentration at the immediate source location of a detected leak.

After locating the leaks, they can be enclosed and quantified via an "open wind tunnel". The measurement principle is similar to the use of open chambers for area sources [1]. Methane and nitrous oxide concentrations are measured discontinuously using evacuated vials for the sampling process with less than 10 hPa absolute pressure. For the analysis in the laboratory, an Agilent 7890A GC System is used with autosampler, flame ionization detector (FID) and electron capture detector (ECD).

An additional option is to quantify the leakage using an imaging gas camera with quantification capability (Q OGI). The camera from SENSIA (Mileva 33) quantifies CH_4 emission in mass or volume flow by AI-assisted analysis and displays the results in real time.

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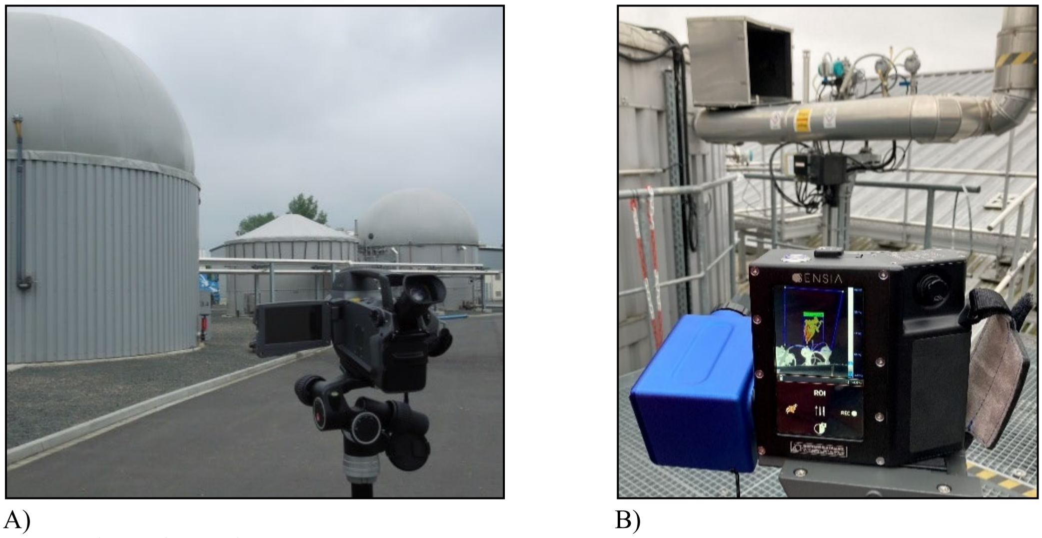
A) B)

Figure 4- A) FLIR (GF 320) Infrared OGI-gas camera in use for leak detection at the DBFZ research biogas plant; B) SENSIA (Mileva 33) Quantification of a simulated leak at the DBFZ research biogas plant with Infrared Q-OGI-gas camera (© DBFZ).

Figure 3: A) FLIR (GF 320) Infrared OGI-gas camera in use for leak detection at the DBFZ research biogas plant; B) SENSIA (Mileva 33) Quantification of a simulated leak at the DBFZ research biogas plant with Infrared Q-OGI-gas camera (© DBFZ).

How the actual measurements will ultimately look depends on the size and type of the respective demonstration plant. The time frame of the measurements also depends on the schedule of the individual demonstration plants. The measurements are carried out in close consultation with the respective institutions.

Since the pilot plants are integrated into an existing process, the aim is to measure the emissions of the entire plant complex as far as possible.

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5. Social Performances Assessment

In the framework of task 3.3 - environmental and social sustainability evaluation, it is planned the assessment of the socio-economic repercussions of the deployment of the technologies developed in BIOMETHAVERSE with a Social LCA Approach (S-LCA). S-LCA can be considered as an extension of the LCA framework. The goal of social LCA as a life cycle-based assessment is to identify social hotspots and to go into more detail along the life cycle of a product or a system. The method offers a starting point for improving the livelihoods of stakeholders and provide information for further research and detailed data collection. The method can be used alone or in combination with other methods, such as LCA and LCC in the frame of LCSA.

The aim of S-LCA is to analyse the potential impacts of the life cycle of a product/system on the well-being of stakeholders. Each phase of the life cycle can be allocated to a specific location (mine, factory, end user, recycling facility, recycling facility, etc.) with social and socioeconomic aspects impact on different stakeholders. S-LCA can cover different levels including:

- Full Life cycle of products and services (cradle-to-grave; from resource extraction to end-of-life);
- Supply chain (cradle-to-gate; exclude use phase and end-of-life);
- Parts of the Life Cycle (gate-to-gate or gate-to-grave).

Depending on the scope, only individual, particularly critical sections or stakeholder groups can be considered related to questions about corporate responsibility for the actors involved along the process chain and the social conditions and social impacts.

S-LCA is the most recently developed life cycle methodology in chronological order. It is designed to assess the social impacts arising from the life cycle of products or services and affecting different types of stakeholders, such as workers, local communities, value chain actors, consumers, societies, and children. Since its inception, it has been considered to assess social impacts in the same way LCA does it for the environmental ones; but while LCA is regulated by specific ISO norms (14040-44:2021)[29], S-LCA is still not consensually defined, and the most diverse methodologies have been proposed in literature. A specific ISO norm, the 14075 "Principles and framework for social life cycle assessment", is under development (in preparatory phase). Recently, UNEP (2020) updated the Guidelines for S-LCA, and the Methodological Sheets for subcategories in S-LCA (UNEP, 2021)[26], providing some guidance for S-LCA practitioners. An overview of the overall Assessment system from stakeholder to impact categories to inventory data is provided in Figure 5.

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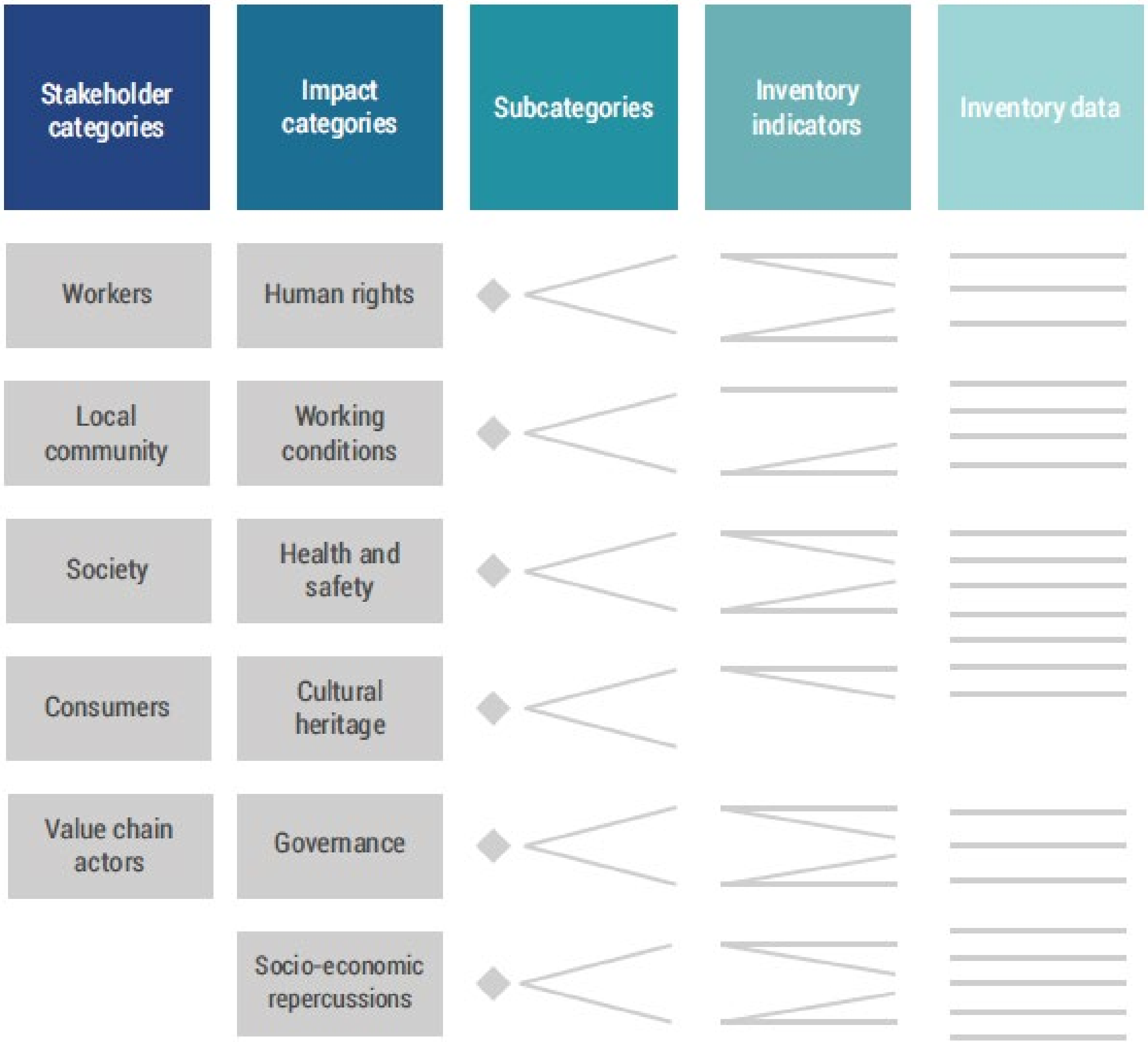

Figure 5- Assessment system from categories to inventory data (Source: UNEP 2021)

In general S-LCA looks at potential or actual Social and Socio-economic impacts (depending on its application) out of several stakeholder perspectives. These impacts are monitored alongside the entire life cycle or value chain of a product and have a strong relation to the seventeen SDGs that have been internationally accepted by governments, industries, and organizations.

Goal and scope: This is the key phase for S-LCA and includes the definition of the system boundaries, categories of impact, functional unit, cut-off criteria, foreground, and background processes, considering all possible phases of the system under study. The definition of named aspects should be carried out in concordance wit stakeholders' groups related to considered subcategories.

System boundaries: These boundaries determine the parts of an industrial pathway that will be considered in a S-LCA. It typically entails foreground processes (situated closer to the studied product, thus more likely to be directly studied; for which often specific data are collected) and background processes (further upstream or downstream, for which often generic data from databases are applied) in the product system.
Functional Unit: A proper definition of a functional unit is of high importance, as it characterizes the assessed product. In this case a biomethane production pathway of a demonstrator, with its major characteristics, its location for the use. This can be in analogy to LCC impact per converted kWh of the biomethane output.

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An inventory analysis: all relevant input and output flows, as well as relevant social inventory indicators, are identified. The data collected needs to be normalised and can then be linked together using activity variables. These are, e.g., hours of exposure for each life cycle phase and task (such as manual and intellectual working tasks, input supplying, transport, consumption, living in the proximity of plants, etc.), classifying the typology of exposure (manual or mechanical work, temperature, noise, etc.).

Social Life cycle impact assessment: This phase aims to connect and understand the potential social and socio-economic impacts related to the product under assessment. The construction of a psychosocial risk factor matrix, in which each exposure condition occurring in the scenarios is linked to a physical or psychosocial disease, as identified in the scientific literature. Assessing the social impact by quantifying the number of hours that stakeholders are exposed to specific conditions representing psychosocial risk factors. There are two main families of approaches, corresponding to different impact assessment procedures and each of them responding to different practical research aims: the Reference Scale Approach (Type I), and the Impact Pathway Approach (Type II). S-LCA Type I assesses the social performance of companies of organizations involved in the product system, by comparing their behaviour to a reference scenario (for example, specific legal regulations or norms). The comparison is made on the basis of specific primary or secondary data, information or stakeholder opinions, and therefore the assessment consists of describing a current state rather than accounting for the links between the activity and long-term impacts. Therefore, the characterization process is mainly based on interpretation.
S-LCA Type II evaluates social impacts through causal or correlation/regression-based relationships (impact pathways) between the product/service life cycle and possible social impacts in the short or long term. The characterisation process is based on an analytical and quantifiable identification of the consequences of the life cycle. According to UNEP (2020), the S-LCA Type II is epistemologically and methodologically more in line with environmental LCA, where inventory inputs are quantitatively linked with environmental impacts, and it is the one that will be pursed for the BIOMETHAVERSE project.

Interpretation of results: This is the last phase of a S-LCA. Here all obtained results are analysed following the ISO 14040/14044[29], including completeness check, consistency check, sensitivity and data quality check, a materiality assessment and final conclusions, limitations, and recommendations. Finally, insights useful for stakeholders (private or public ones) and academics have to be retrieved.

6. Data collection strategy

The quality of the LCSA is highly dependent on the quality and the level of detail of the input data. At present, the problem of data quality is still one of the critical issues of the LCSA methodology, due to both too much confidential data and a lack of primary data of innovative technologies and related materials and processes.

The quality of the data collected and used in the inventory phase determines the quality of the whole LCA study. In general, there are two types of data used in a LCSA study. Directly measured data are defined as primary data while those obtained from literature and databases are defined as secondary data. In general, the calculation of the environmental performance has to be based mainly on primary data, which refer to the reference year of the study and are specific to the system under consideration. In the absence of primary data, secondary data may be used. Whatever the origin of the data, it is essential that they are as representative as possible of the model being assessed.

The quality, validity and representativeness of the data must be checked already during the collection process, by means of mass and energy balances and comparative analyses on emission factors. In the event of anomalies in the data, alternative values must be sought that confirm the quality requirements established in the phase of defining the objectives and the field of application under study.

To this purpose a clear and concise framework for primary data collection is here setup, to streamline the data exchange and ensure the required completeness and consistency in the data collected regarding the three pillars of sustainability, i.e., economic, environmental and social.

The data collection step will be carried out through specific requests and questionnaires that will be addressed to demonstrators and research partners to collect all necessary information.

A key aspect of the LCA is the provision of meaningful information. To do this, the sustainability performance of a system needs to be contextualised and properly framed. In order to provide stakeholders with a reading key and to facilitate the interpretation of the results, it is essential that the results of the modelling are compared with technologies that provide the same level of service. In this respect, the technologies developed will be compared to natural gas provision and other biomethane production technologies.

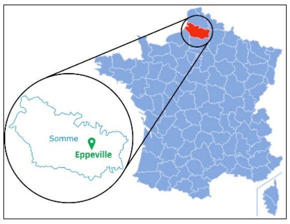
A further key point in the evaluation of the technology is the definition of the system boundaries. In order to ensure a level playing field for the comparison of the developed technologies, the system will be modelled with and without the developed technology in order to distinguish the added value of the specific technology.

6.1. FRENCH INNOVATIVE BIOMETHANE DEMONSTRATOR

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

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

6.1.1 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 $Nm^3\ h^{-1}$ 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 m^3 digestion volume with a hydraulic retention time higher than 50 days. The digestate is valorised through land-spreading (6,000 ha, 31 farms).

6.1.2 Technology description

Electro-methanogenesis (EMG) is known as a fast-developing process that can **produce biomethane directly from CO_2 and renewable electricity**. The basic principle of this technology is to **boost the 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 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.[3]

Two configurations will be evaluated:

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

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

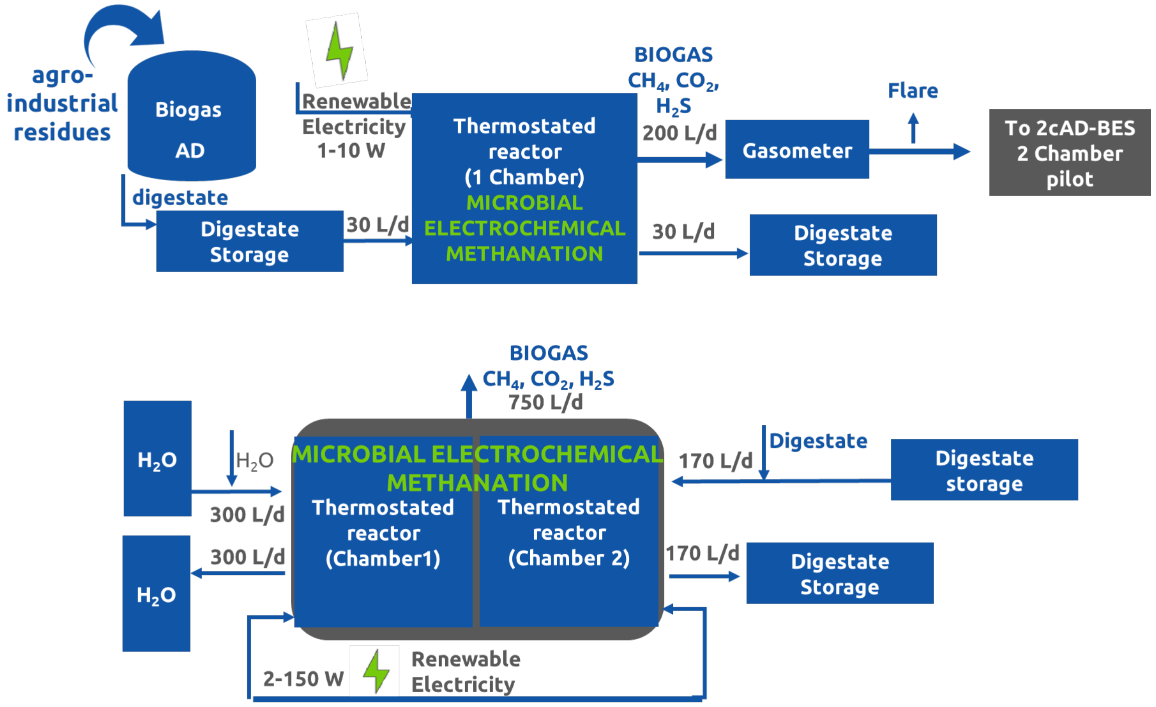


Figure 6- Block Flow Diagram for 1c-ADBES (single chamber reactor) and 2c-ADBES (double chamber reactor)

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[3] 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..

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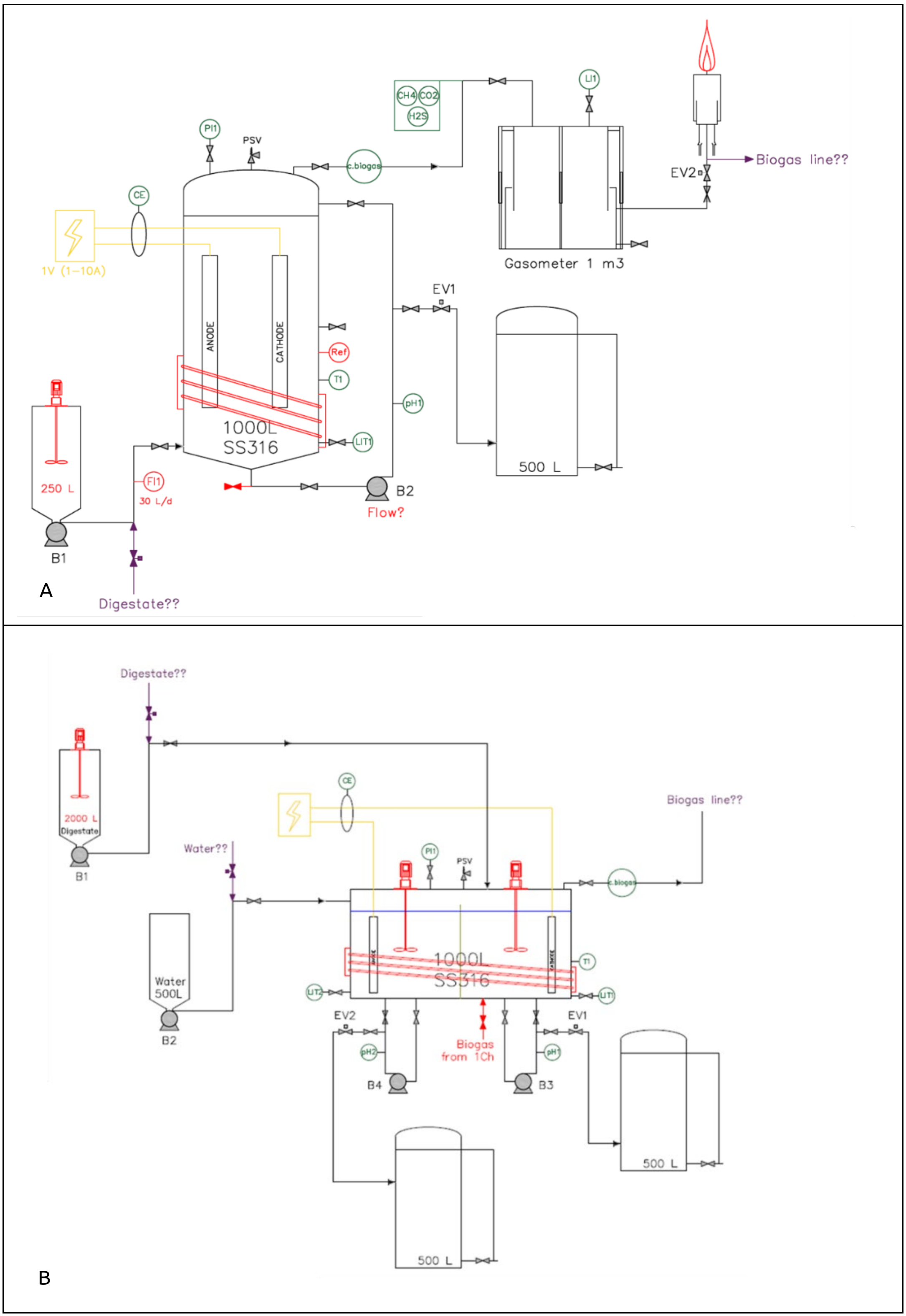

Figure 7- Process Flow Diagram for A. 1c-ADBES (single chamber reactor) B. 2c-ADBES (double chamber reactor) Data collection: timing

6.1.3 Data collection: timing

[M6: D2.1] The basic block diagram and the basic data for the pilot unit were provided in D2.1 'Demonstrators Implementation Activity Plans'.

[M18; D.2.2] 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, including:

- Design-point, off-design and/or stand-by operation conditions,
- Main reactions/biological process description and kinetics
- Input and output flows 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 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].

[M30; D2.4] Update of inventories based on the demonstrators' trials or improved design, including: cost estimates, capital costs (for each unit); maintenance cost (for each unit); labour costs and other costs (e.g. insurance, management and control system, estimation of the materials needed for civil works (e.g. concrete and steel), piping, auxiliaries, management and control devices.

6.1.4 Data collection: data requirements

The data requirement to enable a robust and comprehensive analysis of the sustainability of the technologies developed in the French demonstrator will be those required to model the electrobiochemical methanation plant at demo scale.
The biogas production will be considered within the system boundaries for what concerns the flowsheeting, therefore the full plant will be modelled, in both configurations, 1c and 2c.
The results will be compared to a biogas plant without electrobiomethanation. The French demo partners will support the definition and characterization of the reference plant, without the technology developed. Therefore, data requirement in the French demonstrator includes the following:

Technoeconomic assessment and social LCA:

- Overall description of the demo plant (1c, 2c and reference baseline) and detailed description of the plant units (including pre and post treatment, if needed, up to the delivery to the gas grid) in addition to the biogas plant.
- Quantify, by expert judgment, own calculation or market analysis, the following:
    - ✓ Capital costs (for each unit)
    - ✓ Maintenance cost (for each unit)
    - ✓ Insurance costs
    - ✓ Labour costs
    - ✓ Working hours by worker category
    - ✓ Land occupation, civil works costs
    - ✓ Management and control system
    - ✓ Cost of power
    - ✓ Cost of fuel, if needed.
    - ✓ Cost of chemicals, if needed.

Flowsheeting, optimization and upscaling inputs:

- General block diagram with interconnecting material and energy streams for the demo plants (1c 2c and reference).

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- Operation model for the key units, i.e., methanation reactors (pre and post treatment units if needed):
  - ✓ List of expected/obtained products/by-products
  - ✓ List of main reactions and side-reactions
  - ✓ Kinetic equations for main and side reactions
  - ✓ Expected/obtained conversion factors or effectiveness of reactions

- Design-point operation conditions for the different units of the demo plant:
  - ✓ Operation temperature (°C)
  - ✓ Operation pressure (bar)
  - ✓ Volume of reactor (litres)
  - ✓ Heat input/output (kW thermal)
  - ✓ Power input (kW electrical)

- For any off-design or stand-by operation conditions for the different units of the demo plant:
  - ✓ Operation temperature (°C)
  - ✓ Operation pressure (bar)
  - ✓ Volume of reactor (litres)
  - ✓ Heat input/output (kW thermal)
  - ✓ Power input (kW electrical)

- Specification of any additional consumption of:
  - ✓ Water
  - ✓ Fuels
  - ✓ Chemicals

- Specifications of outlet gas (methane-rich) stream:
  - ✓ Temperature (°C)
  - ✓ Pressure (bar)
  - ✓ Composition (% by volume of each component)

Environmental and Social LCA:

- For each processing unit:
  - ✓ Detailed **bill of materials:** a comprehensive list with the identification and quantification of all the materials constituting the equipment, with focus on critical raw materials. If primary data are not available (e.g., from invoices, designs, technical specifications) please provide an estimate of the main masses involved. Fundamental is also the estimate of the amount of concrete and steel used.
  - ✓ 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). These emissions include not only GHG (CH_4 and N_2O) but also other pollutants (NH_3, NOx and VOC). Data on water consumption and quality will be needed as well.
  - ✓ Estimation of the materials needed for auxiliary activities e.g., civil works (concrete and steel), piping, auxiliaries, management and control devices.
  - ✓ **Employment** related data: number of additional full-time jobs, expected wage (indicative in relation to national average)
  - ✓ Identification and description of **stakeholders involved**
  - ✓ Description of issues related to **social acceptance**, if any.

6.2. GREEK INNOVATIVE BIOMETHANE DEMONSTRATOR

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

- <u>Production pathways</u>: thermochemical

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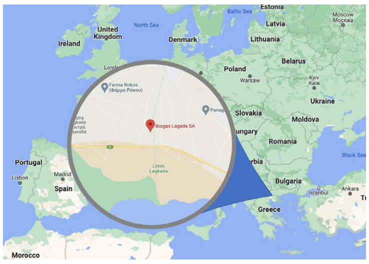
- Inputs: CO_2 + hydrogen

6.2.1 Brief description of the site



The Biogas Lagadas S.A. (BLAG) plant is located in **Kolchiko – Lagadas,** in **Central Macedonia Region**. The BLAG plant exploits around 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 m³ 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.

6.2.2 Technology description

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

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

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

The individual stages of the whole process include:

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

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

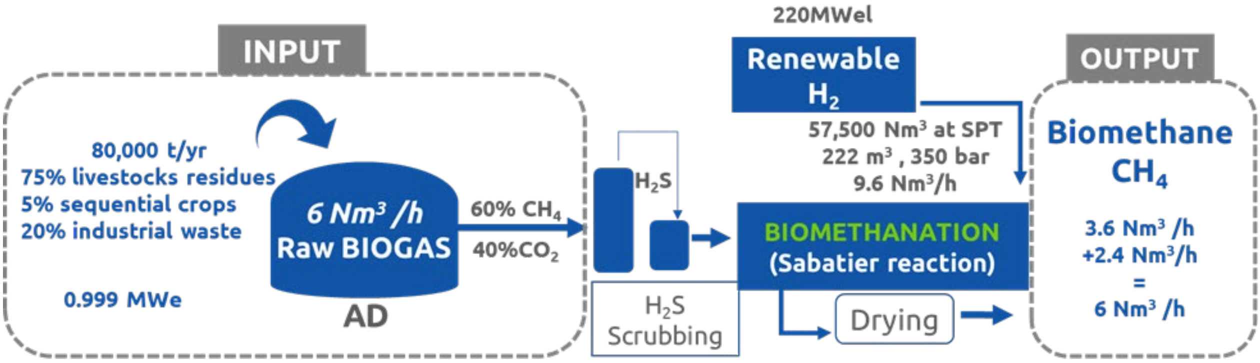


Figure 8- Block Flow Diagram for the ex-situ Thermochemical/catalytic methanation (ETM) process

6.2.3 Data collection: timing

[M6: D2.1] The basic block diagram and the basic data for the pilot unit were provided in D2.1 'Demonstrators Implementation Activity Plans'.

[M18; D.2.2] 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, including:

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- Design-point, off-design and/or stand-by operation conditions.
- Main reactions/biological process description and kinetics
- Input and output flows 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 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]

[M30; D2.4] Update of inventories based on the demonstrators' trials or improved design, including: cost estimates, capital costs (for each unit); maintenance cost (for each unit); labour costs and other costs (e.g., insurance, management and control system, estimation of the materials needed for civil works (e.g., concrete and steel), piping, auxiliaries, management and control devices.

6.2.4 Data collection: data requirements

The data requirement to enable a robust and comprehensive analysis of the sustainability of the technologies developed in the Greek demonstrator will be those required to model the thermochemical methanation plant at demo scale.

The biogas production will be considered as out of the system boundaries for what concerns the flowsheeting. A generic biogas plant will be considered instead of the Lagada plant, however, support for the identification of techno-economics of a generic plant is required from the Greek demo partners. The electrolyser will be modelled by ENEA.

The results will be compared to a biogas plant without methanation.

The data requirements therefore include the following data for the thermochemical methanation plant:

Technoeconomic assessment and social LCA:

- Overall description of the demo plant and detailed description of the plant units (including pre and post treatment, if needed, up to the delivery to the gas grid) in addition to the biogas plant.
- Quantify, by expert judgment, own calculation or market analysis, the following:
  - ✓ Capital costs (for each unit)
  - ✓ Maintenance cost (for each unit)
  - ✓ Insurance costs
  - ✓ Labour costs
  - ✓ Working hours by worker category
  - ✓ Land occupation, civil works costs
  - ✓ Management and control system
  - ✓ Cost of power
  - ✓ Cost of fuel, if needed.
  - ✓ Cost of chemicals, if needed.

Flowsheeting, optimization and upscaling inputs:

- General block diagram with interconnecting streams for the demo plant
- Specifications of biogas feed stream:
  - ✓ Temperature (°C)
  - ✓ Pressure (bar)
  - ✓ Composition (% by volume of each component)
  - ✓ Flow rate expected in the demo plant (kg/h)
  - ✓ Flow rate expected in the scaled-up unit (kg/h)
  - ✓ Flow rate profiles on hourly basis over the year

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- Operation model for the key units, i.e., methanation reactors (pre and post treatment units if needed):
  - ✓ List of expected/obtained products/by-products
  - ✓ List of main reactions and side-reactions
  - ✓ Kinetic equations for main and side reactions
  - ✓ Expected/obtained conversion factors or effectiveness of reactions

- Design-point operation conditions for the different units of the demo plant:
  - ✓ Hydrogen feed flow rate (kg/h)
  - ✓ Operation temperature (°C)
  - ✓ Operation pressure (bar)
  - ✓ Volume of reactor (liters)
  - ✓ Heat input/output (kW thermal)
  - ✓ Power input (kW electrical)

- For any off-design or stand-by operation conditions for the different units of the demo plant:
  - ✓ Hydrogen feed flow rate (kg/h)
  - ✓ Operation temperature (°C)
  - ✓ Operation pressure (bar)
  - ✓ Volume of reactor (liters)
  - ✓ Heat input/output (kW thermal)
  - ✓ Power input (kW electrical)

- Specification of any additional consumption of:
  - ✓ Water
  - ✓ Fuels
  - ✓ Chemicals

- Specifications of outlet gas (methane-rich) stream:
  - ✓ Temperature (°C)
  - ✓ Pressure (bar)
  - ✓ Composition (% by volume of each component)

Environmental and Social LCA:

- For each processing unit:

  - ✓ Detailed **bill of materials:** a comprehensive list with the identification and quantification of all the materials constituting the equipment, with focus on critical raw materials. If primary data are not available (e.g., from invoices, designs, technical specifications) please provide an estimate of the main masses involved. Fundamental is also the estimate of the amount of concrete and steel used.
  - ✓ Identification and quantification of **structural emissions to the atmosphere**, if any (methane and other pollutants, e.g., from off-gases, overpressure valves, auxiliaries). These emissions include not only GHG (CH4 and N2O) but also other pollutants (NH3, NOx and VOC)
  - ✓ Estimation of the materials needed for auxiliary activities e.g., civil works (concrete and steel), piping, auxiliaries, management and control devices.
  - ✓ **Employment** related data: number of additional full time jobs, expected wage (indicative in relation to national average)
  - ✓ Identification and description of **stakeholders involved**
  - ✓ Description of issues related to **social acceptance**, if any.

6.3. ITALIAN INNOVATIVE BIOMETHANE DEMONSTRATOR

DEMONSTRATION: Ex Situ Biological Methanation (EBM)

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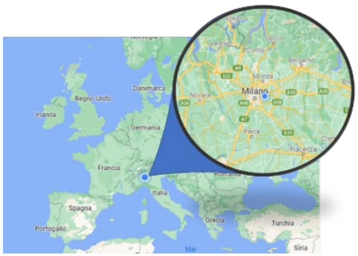
- Production pathway: biological
- Input: CO2 +hydrogen

6.3.1 Brief description of the site



Gruppo CAP, as integrated water service manager for the Metropolitan City of Milan area **(Lombardy Region)** operates 40 wastewater treatment plants of different sizes and capacities over a 1,500 km2 area. Among those, anaerobic digestion is already widely implemented as 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.

6.3.2 Technology description

CAP, in collaboration with partners Politecnico di Milano, SIAD and CIC, will implement an **integrated demo plant, to achieve a more sustainable biomethane production, in a holistic approach that includes biogas upgrade side by side with several approaches to increase biogas production**.
The demonstration plant will be implemented to one of the 2 parallel AD lines, the second one will be kept as such to have a direct comparison of the overall biomethane yield improvement and production cost reduction achievable by applying the integrated technologies. It will be **composed by four units**:
(1) **sewage sludge ozonolysis**, which will serve as pre-treatment to enhance the feedstock digestibility and thus the biogas yield, (2) **ex-situ biological upgrading**, to convert carbon dioxide in methane and boost the yield, (3) **microalgae cultivation** on the liquid fraction of digestate and (4) **co-digestion of pre-treated sludge, microalgae, and selected substrates**.

The purpose of sludge treatment using ozone is to increase the anaerobic biodegradability of the substrate and its capacity to produce biogas while **reducing the digestate to be disposed of**. In the scientific literature, several experiences are reporting the application of this technology on a laboratory and pilot scale. These experiences generally describe significantly positive effects on anaerobic digestion. However, pilot-scale experiments are extremely rare. **Biological ex-situ upgrade operates at mild conditions and represent a promising and rapidly evolving technology**, in terms of reactor configurations and process volumetric intensity. Key aspects are the **gas transfer efficiency** and the **dynamic response to variable and even null H_2 load**. The *ex-situ* upgrade prototype will run biological hydrogenotrophic conversion of biogas to biomethane by Archaea present as suspended biomass and as biofilm, the latter attached on hollow fibers tubular gas transfer membranes.
In this innovative configuration, H_2 and biogas are supplied by two devices: to the biofilm by diffusion through the lumen of the membrane and, to the suspended biomass, by gas sparging. This configuration combines the scheme of a previously tested *ex-situ* reactor (V = 500 L) with the gas transfer membrane biofilm reactor, a technology already known and applied at full scale in other sectors.

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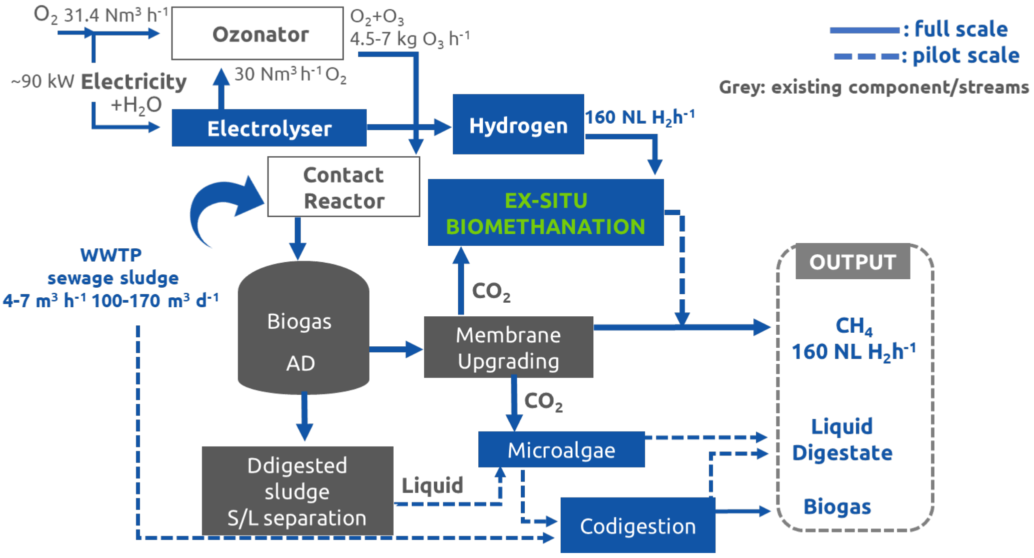

Figure 9- Block Flow Diagram for innovative production pathway (EBM)

6.3.3 Data collection: timing

[M6: D2.1] The basic block diagram and the basic data for the pilot unit were provided in D2.1 'Demonstrators Implementation Activity Plans'.

[M18; D.2.2] 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, including:

- Design-point, off-design and/or stand-by operation conditions
- Main reactions/biological process description and kinetics
- Input and output flows 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 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].

[M30; D2.4] Update of inventories based on the demonstrators' trials or improved design, including: cost estimates, capital costs (for each unit); maintenance cost (for each unit); labour costs and other costs (e.g. insurance, management and control system, estimation of the materials needed for civil works (e.g. concrete and steel), piping, auxiliaries, management and control devices.

6.3.4 Data collection: data requirements

The Italian demo plant involves the development of several technologies. All the technologies involved, biomethanation, electrolysis, membrane separation, ozonolysis, algae cultivation and co-digestion, will have to be characterized in a dynamic manner to enable the optimization and upscaling. In particular the identification of the best operation strategy will be a key task and will involve the definition of numerous plants configuration and operation scenarios taking into account the kinetics, the mass and energy flows and the costs.

The results will be compared to a conventional plant of sewage sludge anaerobic digestion without the technologies developed. The data on the conventional plant will be provided by the Italian demo partners as well.

The data requirement to enable a robust and comprehensive analysis of the sustainability of the technologies developed in in the Italian demonstrator include the following for each technology:

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Technoeconomic assessment and social LCA:

- Overall description of the demo plant and detailed description of the plant units (including pre and post treatment, storages, and whatever is needed up to the delivery to the gas grid).
- Quantify, by expert judgment, own calculation or market analysis, the following:
  - ✓ Capital costs (for each unit)
  - ✓ Maintenance cost (for each unit)
  - ✓ Insurance costs
  - ✓ Labour costs
  - ✓ Working hours by worker category
  - ✓ Land occupation, civil works costs
  - ✓ Management and control system
  - ✓ Cost of power
  - ✓ Cost of fuel, if needed.
  - ✓ Cost of chemicals, if needed.

Flowsheeting, optimization and upscaling inputs:

- General block diagram with interconnecting material and energy streams for the demo plants and support to the definition of potential configurations.
- Operation model for the key units, i.e., biomethanation reactors, ozonolysis, algae cultivation, co-digestion; electolyser, membranes (including pre and post treatment units if needed):
  - ✓ List of expected/obtained products/by-products
  - ✓ List of main reactions and side-reactions
  - ✓ Kinetic equations for main and side reactions
  - ✓ Expected/obtained conversion factors or effectiveness of reactions.
- Design-point operation conditions for the different units of the demo plant:
  - ✓ Operation temperature (°C)
  - ✓ Operation pressure (bar)
  - ✓ Volume of reactor (liters)
  - ✓ Heat input/output (kW thermal)
  - ✓ Power input (kW electrical)
- For any off-design or stand-by operation conditions for the different units of the demo plant:
  - ✓ Operation temperature (°C)
  - ✓ Operation pressure (bar)
  - ✓ Volume of reactor (liters)
  - ✓ Heat input/output (kW thermal)
  - ✓ Power input (kW electrical)
- Specification of any additional consumption of:
  - ✓ Water
  - ✓ Fuels
  - ✓ Chemicals
- Specifications of outlet gas (methane-rich) stream:
  - ✓ Temperature (°C)
  - ✓ Pressure (bar)
  - ✓ Composition (% by volume of each component)

Environmental and Social LCA:

- For each processing unit:

  - ✓ Detailed **bill of materials:** a comprehensive list with the identification and quantification of all the materials constituting the equipment, with focus on critical raw materials. If

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primary data are not available (e.g., from invoices, designs, technical specifications) please provide an estimate of the main masses involved. Fundamental is also the estimate of the amount of concrete and steel used.

- ✓ 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). These emissions include not only GHG (CH_4 and N_2O) but also other pollutants (NH_3, NOx and VOC). Impact on **water consumption and quality** will be investigated as well. Therefore, data on water consumption, quality and nutrients will be needed for both the conventional plant and the BIOMETHAVERSE innovative plant.
- ✓ Estimation of the materials needed for auxiliary activities e.g., civil works (concrete and steel), piping, auxiliaries, management and control devices.
- ✓ **Employment** related data: number of additional full-time jobs, expected wage (indicative in relation to national average)
- ✓ Identification and description of **stakeholders involved.**
- ✓ Description of issues related to **social acceptance**, if any.

6.4. SWEDISH INNOVATIVE BIOMETHANE DEMONSTRATOR

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

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

6.4.1 Brief description of the site

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

The produced syngas is used as a green energy input for steel powder manufacturing by an adjacent industry.

6.4.2 Technology description

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

The syngas meets a selectively adapted mixed culture biofilm on carriers and a continuous flow of nutrient rich solution. 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 conversion of all CO_2 to methane.

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

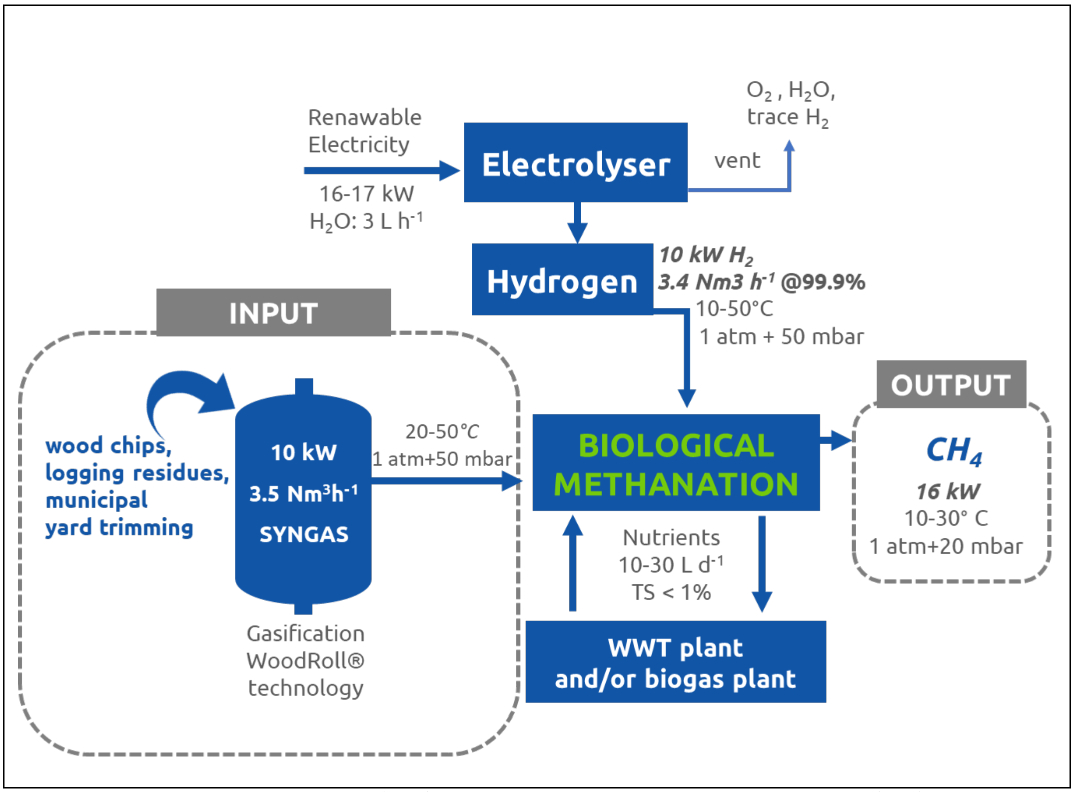

Figure 10- Block Flow Diagrams (BFD) of the ex-Situ Syngas Biological methanation (ESB) process

6.4.3 Data collection: timing

[M6: D2.1] The basic block diagram and the basic data for the pilot unit were provided in D2.1 'Demonstrators Implementation Activity Plans'. The design should be available at M5.

[M18; D.2.2] 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, including:

- Design-point, off-design and/or stand-by operation conditions,
- Main reactions/biological process description and kinetics
- Input and output flows 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 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].

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[M30; D2.4] Update of inventories based on the demonstrators' trials or improved design, including: cost estimates, capital costs (for each unit); maintenance cost (for each unit); labour costs and other costs (e.g., insurance, management and control system, estimation of the materials needed for civil works (e.g., concrete and steel), piping, auxiliaries, management and control devices.

6.4.4 Data collection: data requirements

The data requirement to enable a robust and comprehensive analysis of the sustainability of the technologies developed in the Swedish demonstrator will be those required to model the syngas biomethanation plant at demo scale.

The syngas production will be considered as out of the system boundaries for what concerns the flowsheeting. A generic biogas plant will be considered instead of the gasification plant, however, support for the identification of techno-economics of a generic plant is required from the Swedish demo partners. The electrolyser will be modelled by ENEA, however if actual data are available, they may be an added value.

The results will be compared to the syngas plant without biomethanation.

The data requirement to enable a robust and comprehensive analysis of the sustainability of the technologies developed in in the Swedish demonstrator include the following:

Technoeconomic assessment and social LCA:

- Overall description of the demo plant and detailed description of the plant units (including pre and post treatment, if needed, up to the delivery to the steel plant) in addition to the gasification plant.
- Quantify, by expert judgment, own calculation or market analysis, the following:
  - ✓ Capital costs (for each unit)
  - ✓ Maintenance cost (for each unit)
  - ✓ Insurance costs
  - ✓ Labour costs
  - ✓ Working hours by worker category
  - ✓ Land occupation, civil works costs
  - ✓ Management and control system
  - ✓ Cost of power
  - ✓ Cost of fuel, if needed
  - ✓ Cost of chemicals, if needed

Flowsheeting, optimization and upscaling inputs:

- General block diagram with interconnecting material and energy streams for the demo plants
- Operation model for the key units, i.e., methanation reactors (pre and post treatment units if needed):
  - ✓ List of expected/obtained products/by-products
  - ✓ List of main reactions and side-reactions
  - ✓ Kinetic equations for main and side reactions
  - ✓ Expected/obtained conversion factors or effectiveness of reactions
- Design-point operation conditions for the different units of the demo plant:
  - ✓ Operation temperature (°C)
  - ✓ Operation pressure (bar)
  - ✓ Volume of reactor (litres)
  - ✓ Heat input/output (kW thermal)
  - ✓ Power input (kW electrical)
- For any off-design or stand-by operation conditions for the different units of the demo plant:
  - ✓ Operation temperature (°C)
  - ✓ Operation pressure (bar)
  - ✓ Volume of reactor (litres)

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  - ✓ Heat input/output (kW thermal)
  - ✓ Power input (kW electrical)

- Specification of any additional consumption of:
  - ✓ Water
  - ✓ Fuels
  - ✓ Chemicals
  - ✓ Nutrients

- Specifications of outlet gas (methane-rich) stream:
  - ✓ Temperature (°C)
  - ✓ Pressure (bar)
  - ✓ Composition (% by volume of each component)

Environmental and Social LCA:

- For each processing unit:
  - ✓ Detailed **bill of materials:** a comprehensive list with the identification and quantification of all the materials constituting the equipment, with focus on critical raw materials. If primary data are not available (e.g., from invoices, designs, technical specifications) please provide an estimate of the main masses involved. Fundamental is also the estimate of the amount of concrete and steel used.
  - ✓ 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). These emissions include not only GHG (CH_4 and N_2O) but also other pollutants (NH_3, NOx and VOC) if any.
  - ✓ Estimation of the materials needed for auxiliary activities, e.g., civil works (concrete and steel), piping, auxiliaries, management and control devices.
  - ✓ **Employment** related data: number of additional full-time jobs, expected wage (indicative in relation to national average)
  - ✓ Identification and description of **stakeholders involved**
  - ✓ Description of issues related to **social acceptance**, if any.

6.5. UKRAINE INNOVATIVE BIOMETHANE DEMONSTRATOR

DEMONSTRATION: In-Situ Biological methanation (IBM)

- Production pathway: biological
- Input: CO_2 +hydrogen

6.5.1 Brief description of the site

The biogas plant in **Ladyzhin**, **Vinnytsia region,** has an installed electric capacity of 12 MW, producing biogas from 330 t d^{-1} of chicken manure and other agricultural residues, producing 85,000,000 kW of electricity per year. Plant configuration consists of twelve reactors (9 main digesters and 3 post digesters) with 90,000 m^3 volume each. Also, the complex has its own biogas pipeline that transfers biogas to the cogeneration unit located near the slaughter complex, in order to use heat to supply steam to the latter.

6.5.2 Technology description

During anaerobic digestion, different microorganisms convert organic residues into biogas. The process occurs in four different phases of which the last phase is methanogenesis. Two metabolic

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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.

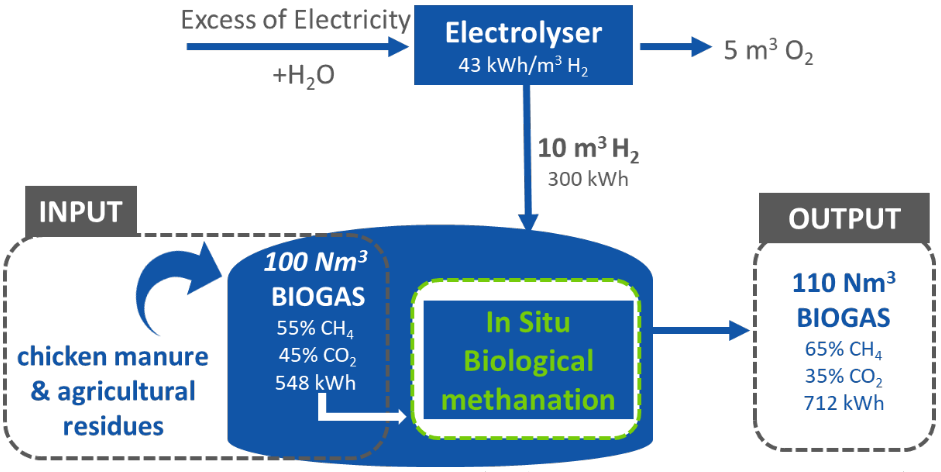

Figure 11- Block Flow Diagrams (BFD) of the in-Situ Biological methanation (IBM) process

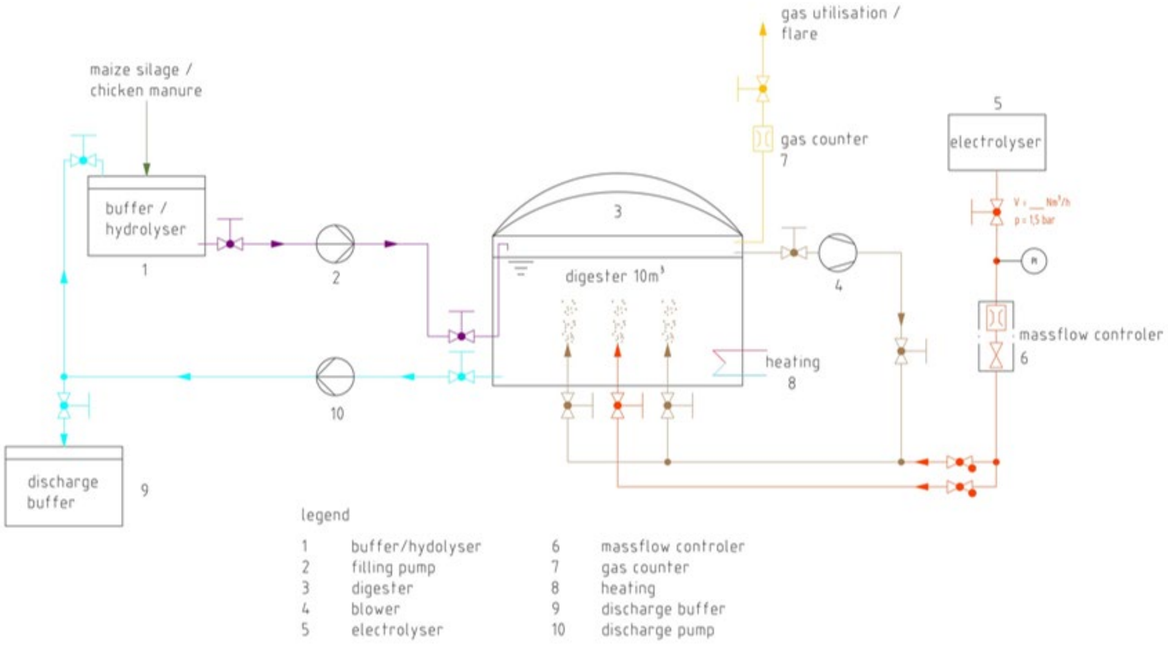

Figure 12- In-Situ Biological methanation (IBM): Process Flow Diagram.

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6.5.3 Data collection: timing

[M6: D2.1] The basic block diagram and the basic data for the pilot unit were provided in D2.1 'Demonstrators Implementation Activity Plans'.

[M18; D.2.2] 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, including:

- Design-point, off-design and/or stand-by operation conditions,
- Main reactions/biological process description and kinetics
- Input and output flows 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 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].

[M30; D2.4] Update of inventories based on the demonstrators' trials or improved design, including: cost estimates, capital costs (for each unit); maintenance cost (for each unit); labour costs and other costs (e.g. insurance, management and control system, estimation of the materials needed for civil works (e.g. concrete and steel), piping, auxiliaries, management and control devices.

6.5.4 Data collection: data requirements

The data requirement to enable a robust and comprehensive analysis of the sustainability of the technologies developed in the Ukrainian demonstrator will be those required to model the in-situ biomethanation plant at demo scale.
The anaerobic digester will be considered within the system boundaries for what concerns the flowsheeting. The electrolyser will be modelled by ENEA, however, if actual data are available, they would be an added value.

The results will be compared to a biogas plant without H2 provision, i.e., without in-situ biomethanation. The data requirement to enable a robust and comprehensive analysis of the sustainability of the technologies developed in the Ukrainian demonstrator include the following, for both the plant with and without in-situ biomethanation:

Technoeconomic assessment and social LCA:

- Overall description of the demo plant and detailed description of the plant units (including pre and post treatment, if needed, up to the delivery to the gas grid or its combustion in a CHP).
- Quantify, by expert judgment, own calculation or market analysis, the following:
    - ✓ Capital costs (for each unit)
    - ✓ Maintenance cost (for each unit)
    - ✓ Insurance costs
    - ✓ Labour costs
    - ✓ Working hours by worker category
    - ✓ Land occupation, civil works costs
    - ✓ Management and control system
    - ✓ Cost of power
    - ✓ Cost of fuel, if needed.
    - ✓ Cost of chemicals, if needed.

Flowsheeting, optimization and upscaling inputs:

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- General block diagram with interconnecting material and energy streams for the demo plant and reference plant.
- Operation model for the key units, i.e., anaerobic digester (pre and post treatment units if needed):
  - ✓ List of expected/obtained products/by-products
  - ✓ List of main reactions and side-reactions
  - ✓ Kinetic equations for main and side reactions
  - ✓ Expected/obtained conversion factors or effectiveness of reactions
- Design-point operation conditions for the different units of the demo plant:
  - ✓ Operation temperature (°C)
  - ✓ Operation pressure (bar)
  - ✓ Volume of reactor (liters)
  - ✓ Heat input/output (kW thermal)
  - ✓ Power input (kW electrical)
- For any off-design or stand-by operation conditions for the different units of the demo plant:
  - ✓ Operation temperature (°C)
  - ✓ Operation pressure (bar)
  - ✓ Volume of reactor (liters)
  - ✓ Heat input/output (kW thermal)
  - ✓ Power input (kW electrical)
- Specification of any additional consumption of:
  - ✓ Water
  - ✓ Fuels
  - ✓ Chemicals
- Specifications of outlet gas (methane-rich) stream:
  - ✓ Temperature (°C)
  - ✓ Pressure (bar)
  - ✓ Composition (% by volume of each component)

Environmental and Social LCA:

- For each processing unit:

  - ✓ Detailed **bill of materials:** a comprehensive list with the identification and quantification of all the materials constituting the equipment, with focus on critical raw materials. If primary data are not available (e.g., from invoices, designs, technical specifications) please provide an estimate of the main masses involved. Fundamental is also the estimate of the amount of concrete and steel used.
  - ✓ 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). These emissions include not only GHG (CH_4 and N_2O) but also other pollutants (NH_3, NOx and VOC)
  - ✓ Estimation of the materials needed for auxiliary activities e.g., civil works (concrete and steel), piping, auxiliaries, management and control devices.
  - ✓ **Employment** related data: number of additional full-time jobs, expected wage (indicative in relation to national average)
  - ✓ Identification and description of **stakeholders involved**
  - ✓ Description of issues related to **social acceptance**, if any.

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7. Bibliography

1. UNEP/SETAC Life Cycle Initiative. https://wedocs.unep.org/handle/20.500.11822/32747.

2. Klöpffer, W. & Grahl, B. *Life Cycle Assessment (LCA): A Guide to Best Practice*. (Wiley, 2014).

3. Review, D. Literature review of life cycle costing (LCC) and life cycle assessment (LCA). (2006).

4. Dhillon, B. S. *Life cycle costing for engineers*. (Routledge Taylor & Framcis Group, 2009).

5. Ximenes, A., Barreneche, C., Fernández, A. I. & Cabeza, L. F. Life cycle costing as a bottom line for the life cycle sustainability assessment in the solar energy sector : A review. *Sol. Energy* **192**, 238–262 (2019).

6. IEC 60300-3-3: 2017. Dependability management - Part 3-3: Application guide - Life cycle costing. https://webstore.iec.ch/publication/31206 (2017).

7. Hunkeler, D., Lichtenvort, K. & Rebitzer, G. *Environmental Life Cycle Costing*. (Taylor & Francis Group, 2008). doi:https://doi.org/10.1201/9781420054736.

8. Agostini, A., Giuntoli, J., Marelli, L. & Amaducci, S. Flaws in the interpretation phase of bioenergy LCA fuel the debate and mislead policymakers. *Int. J. Life Cycle Assess.* **25**, (2020).

9. European Commission. Joint Research Centre. Institute for Energy and Transport. Recommendation on the use of Environmental Footprint methods. https://environment.ec.europa.eu/publications/recommendation-use-environmental-footprint-methods_en (2021).

10. Working Group I: IPCC. CLIMATE CHANGE 2013 The Physical Science Basis. https://www.ipcc.ch/site/assets/uploads/2018/03/WG1AR5_SummaryVolume_FINAL.pdf (2013).

11. World Meteorological Organization. WMO Statement on the status of the global climate in 2013. https://library.wmo.int/index.php?lvl=notice_display&id=15957#.ZGJR03ZByBI (2014).

12. Saouter, E. R. S. *et al.* Hazard / Risk Assessment IMPROVING SUBSTANCE INFORMATION IN USETOX , PART 1 : DISCUSSION ON DATA AND APPROACHES FOR ESTIMATING FRESHWATER ECOTOXICITY EFFECT FACTORS. **36**, 3450–3462 (2017).

13. Fantke, P. *et al.* Health impacts of fine particulate matter. in *Global Guidance for Life Cycle Impact Assessment Indicators: Volume 1. UNEP/SETAC Life Cycle Initiative* 76–99 (2016).

14. Frischknecht, R., Braunschweig, A., Hofstetter, P., Suter, P. Modelling human health effects of radioactive releases in Life Cycle Impact Assessment. *Environ. Impact Assess. Rev.* **20**, 159–189 (2000).

15. Zelm, R. Van *et al.* European characterization factors for human health damage of PM 10 and ozone in life cycle impact assessment. **42**, 441–453 (2008).

16. Posch, M., Seppälä, J., Hettelingh, J. & Johansson, M. The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. 477–486 (2008) doi:10.1007/s11367-008-0025-9.

17. Struijs, J., Beusen, A., van Jaarsveld, H., Huijbregts, M. A. J. Aquatic Eutrophication. Chapter 6. in *A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation factors* (2009).

18. HORN, R. & MAIER, S. Updated Characterization Factors (Version 2.5). https://www.bookshop.fraunhofer.de/buch/LANCA/244600. (2018).

19. BOULAY Anne-Marie; BARE Jane; BENINI Lorenzo; BERGER Markus; LATHUILLIÈRE Michael J.; MANZARDO Alessandro; MOTOSHITA Masaharu; MARGNI Manuele; NÚÑEZ Montserrat;

Co-funded by the European Union

PASTOR Amandine; RIDOUTT Bradley; OKI Taikan; WORBE Sebastien; PFISTER StephanBOULAY Anne-Mari. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). *2018* https://publications.jrc.ec.europa.eu/repository/handle/JRC100097.

20. L. van Oers, A. de Koning, J. B. G. & G. H. Abiotic resource depletion in LCA Abiotic resource depletion in LCA. (2002).
21. Poeschl, M., Ward, S. & Owende, P. Environmental impacts of biogas deployment e Part II : life cycle assessment of multiple production and utilization pathways. *J. Clean. Prod.* **24**, 184–201 (2012).
22. Poeschl, M., Ward, S. & Owende, P. Prospects for expanded utilization of biogas in Germany. *Renew. Sustain. Energy Rev.* **14**, 1782–1797 (2010).
23. Poeschl, M., Ward, S. & Owende, P. Environmental impacts of biogas deployment e Part I : life cycle inventory for evaluation of production process emissions to air. *J. Clean. Prod.* **24**, 168–183 (2012).
24. Styles, D., Dominguez, E. M. & Chadwick, D. Science of the Total Environment Environmental balance of the UK biogas sector : An evaluation by consequential life cycle assessment. *Sci. Total Environ.* **560–561**, 241–253 (2016).
25. Bargiacchi, E., Candelaresi, D., Valente, A., Spazzafumo, G. & Frigo, S. Life Cycle Assessment of Substitute Natural Gas production from biomass and electrolytic hydrogen. *Int. J. Hydrogen Energy* **46**, 35974–35984 (2021).
26. Federal, B. & Planning, P. *GUIDELINES FOR SOCIAL LIFE CYCLE*.
27. European Commission. Joint Research Centre. Institute for Energy and Transport. ILCD International Life Cycle Data system. https://eplca.jrc.ec.europa.eu/ilcd.html.
28. Clauß, T. *et al. Recommendations for reliable methane emission rate quantification at biogas plants*. (2019).
29. Weidema, B., Lca, I. J. & Doi, O. Letters to the Editor ISO 14044 also Applies to Social LCA Letters to the Editor ISO 14044 also Applies to Social LCA. **10**, 86899 (2005).

Co-funded by the European Union