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European Master in Biological and Chemical Engineering for a Sustainable Bioeconomy

# Master Thesis Report

submitted to obtain the degrees of:

- Master in Biology AgroSciences (BAS) of the University of Reims Champagne-Ardenne
- Master of Science in Engineering of Tallinn University of Technology
- Master in Bioengineering: Chemistry and Bioindustries of the University of Liège

## Literature review of biomethane production, with a preliminary life-cycle assessment and techno-economic analysis of an innovative biomethane production process (European Union – HYFUELUP Project)


Presented by: **RODRIGO, Naresh Peter Basil**


Defended the: **19 / 06 / 2023**

Supervised by: **LOPES Tiago**

At: **National Laboratory of Energy and Geology (LNEG) – Portugal**


Estrada da Portela, Bairro do Zambujal
Apartado 7586 – Alfragide, 2610-999 AMADORA, Portugal
Tel: +351 210 924 600/1 & Fax: +351 217 163 806
www.lneg.pt


From: **06 / 02 / 2023** to **19 / 06 / 2023**

**Bioceb supervisors:**

S3 Supervisor: **RICHEL, Aurore** – University of Liège – Gembloux AgroBioTech (Belgium)

S2 Supervisor: **SMOLANDER, Olli-Pekka** – Tallinn University of Technology (Estonia)

Confidentiality: **Yes**

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# Abstract

The transition to sustainable biomethane production is gaining momentum as a viable alternative for decarbonizing the transportation industry in particular long-distance road-freight and maritime transportation. The European Union HYFUELUP project aims to demonstrate an innovative pathway for biomethane production via the integration of sorption-enhanced gasification (SEG), fluidized bed methanation and electrolysis. The National Laboratory of Energy and Geology (LNEG) in Portugal, where this thesis was completed, is responsible for the life-cycle assessment (LCA) and techno-economic analysis (TEA) of the HYFUELUP project. This thesis aims to provide a comprehensive review of biomethane production and gasification technologies, emphasizing the need to shift from the conventional anaerobic digestion process to gasification. Moreover, to support this analysis, existing LCA and TEA data using similar technologies were reviewed aiming to provide a basis for comparison and guide data collection for the HYFUELUP project. The use of biomethane as a sustainable energy alternative can enhance energy security, significantly reduce emissions in the transport sector and reduce dependence on external providers. Gasification technologies such as SEG and methanation holds great potential for future biomethane production however substantial support from governments and companies will be needed for scaling up these processes and making them economically feasible.

Three studies from the literature were chosen for TEA analysis and three studies for LCA analysis. The TEA data examined in this thesis revealed various factors influencing capital and operating costs where study A – which closely resembled the HYFUELUP project – showed the highest overall costs. Electrolysis was identified as a major cost driver, and the overall costs were expected to increase with larger functional units. The LCA data was converted via normalization factors to allow for a more accurate comparison between studies, where study A had the higher global warming potential possibly due to the fact that the system boundaries were larger than the other studies investigated. Experimental data in the literature is still lacking, where further research is needed for a more comprehensive analysis of TEA and LCA of this integrated biomethane production process. A preliminary life cycle inventory and techno-economic cost estimation are also presented based on the existing literature. By considering the findings from this thesis, and the ongoing work of the HYFUELUP project, it is evident that biomethane has potential for decarbonizing the transport sector and emissions reduction. Future efforts should focus on the need for implementing regulations and policies to drive the widespread adoption of biomethane technologies.



**KEYWORDS:** Biomethane, HYFUELUP, Techno-Economic Analysis, Life Cycle Assessment, Gasification, Master Thesis

# List of Abbreviations

1. AD – Anaerobic Digestion
2. AP – Acidification Potential
3. CAPEX – Capital Expenditure
4. CHP – Combined Heat and Power
5. CNG – Compressed Natural Gas
6. GHG – Greenhouse Gas
7. GWP – Global Warming Potential
8. HYFUELUP – Hybrid Biomethane Production from Integrated Biomass Conversion
9. IPCC – Intergovernmental Panel on Climate Change
10. LCA – Life Cycle Assessment
11. LCI – Life Cycle Inventory
12. LNEG – National Laboratory of Energy & Geology – Lisbon, Portugal
13. OPEX – Operating Expenditure
14. Oxy-SEG – Oxidized Sorption Enhanced Gasification
15. PEM – Polymer Electrolyte Membrane
16. POFP – Photochemical Ozone Formation Potential
17. RNG – Renewable Natural Gas (Biomethane)
18. SEG – Sorption Enhanced Gasification
19. SER – Sorption Enhanced Reforming
20. SOE – Solid Oxide Electrolysis
21. SRF – Short Rotation Forestry
22. TEA – Techno-economic Analysis
23. TTW – Tank-to-wheel
24. WTT – Well-to-tank
25. WTW – Well-to-wheel

# Introduction

## *Biogas*

Greenhouse gases (GHGs) have increased global temperatures throughout the years causing negative impacts on the environment. Climate change and global warming are only some consequences of this growing issue. Fossil fuel combustion is one of the largest contributors to GHG emissions, while coal-fired power plants act as the largest source of carbon dioxide emissions. (Parvez et al., 2021).

It is essential that society transitions into more sustainable energy alternatives in order to make positive impacts on the planet. One possible alternative is the use of biogas. Biogas is a mixture of methane, carbon dioxide, and small quantities of other gases produced normally via a technique called anaerobic digestion of biomass (such as organic matter) in an oxygen-free environment (IEA, 2020). Biogas can be produced in different ways and depends on the type of feedstock used thus it's production pathway. Its applications are plentiful having the ability to be used in transportation, electricity generation, heating, or as an energy source in the cooking industry.

Some of the main technologies for the production of biogas are as follows (IEA, 2020)

- Biodigesters – microorganisms break down organic matter which is diluted in water in airtight systems such as tanks or containers.
- Landfill gas recovery systems – decomposition of municipal solid waste (MSW) in landfill sites under oxygen-free conditions
- Wastewater treatment plants – recover organic matter, solids, and nutrients (e.g. nitrogen and phosphorous) from sewage sludge, where further treatment in an anerobic digester can form biogas.

Biogas is the end product of a biological mediated process which is normally anaerobic digestion (AD) whereby different microorganisms decompose organic matter following numerous metabolic pathways (Kougias & Angelidaki, 2018). Presently, the biogas sector is rapidly emerging whereby novel technologies and processes are becoming apparent to produce this upcoming bioenergy source. Hence, these biogas plants are targeting the circular economy concepts shedding light on the recycling of nutrients and reducing greenhouse gas impacts and emissions.

With little to no processing, biogas can be burned on-site to heat up buildings, power boilers or even the digester itself (Tanigawa, 2017). If biogas is produced via a digestion process, a digestate is a nutrient-rich solid or liquid material which is left-over. This digestate contains the nutrients which are

recycled which were present in the original organic material which can have different applications such as for soil building or composting.

***Biomethane***

Biogas has varying amounts of methane in its composition which averages from around 45-75% volume (IEA, 2020) while the remaining is carbon dioxide. Biomethane (also referred to as "renewable natural gas") is a near-pure source of methane produced either via "upgrading" biogas (IEA, 2020) whereby removing carbon dioxide or other contaminants which are evident in the "raw" biogas, or through solid-biomass gasification followed by methanation.

- **Upgrading biogas** – accounts for around 90% of total biomethane production worldwide today (IEA, 2020). Technology such as water scrubbing, and membrane separation can be used for upgrading biogas and separating the contaminant gases.
- **Thermal gasification of solid-biomass followed by methanation** – biomass is broken down at high temperatures and pressures in a low-oxygen environment where this biomass is converted into a syngas. This syngas has a composition of carbon monoxide, hydrogen, and methane. Afterwards, methanation will occur with the aid of a catalyst to promote a reaction between hydrogen and carbon monoxide/carbon dioxide to produce methane (IEA, 2020).

*Figure 1* shows different production pathways for biogas and biomethane, whereby only biomethane is normally suitable for applications in the transportation sector.

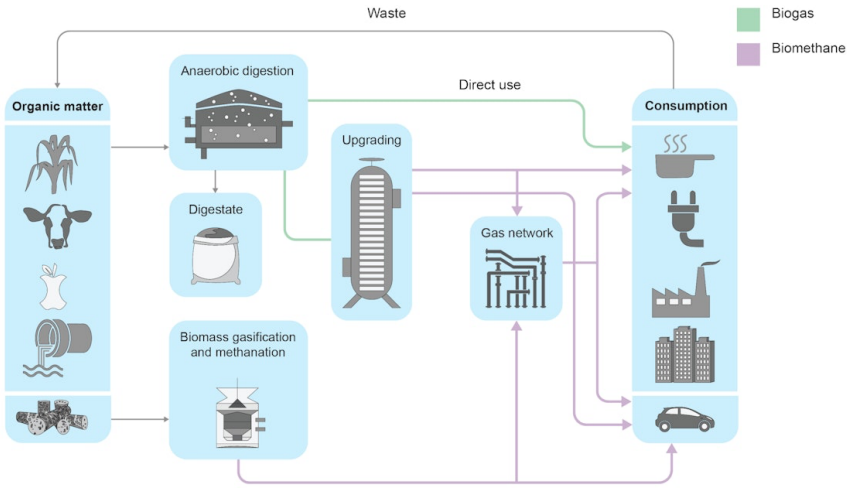



*Figure 1 - Production pathways for biogas and biomethane taken from (IEA, 2020)*

The green arrow shows the applications of biogas where it can be produced from organic matter through anaerobic digestion for direct use in cooking, electricity, building and power industries. It can also be used in upgrading to biomethane. The purple arrows show the production pathway for

biomethane whereby the feedstock is biomass. This biomass can then undergo biomass gasification and methanation which can be directly used in the transport sector. Moreover, this biomethane can also go through the gas network to have applications in cooking, electricity, building and power industries. There is also evidence of circularity in this process whereby the waste from consumption can be used as organic matter for the production of biogas.

***Importance / advantages of biomethane***

Biogas and biomethane are both types of renewable gases which can help reduce emissions across the whole value chain. Having the option to use biogas and biomethane are essential to speed up the reduction of greenhouse gases in sectors across the board including transport, building, and electricity industries.

There are different advantages of using biomethane when replacing fossil fuels.

- **Properties of Biomethane –** it can be easily stored and produced at a constant rate which can help balance the energy supply from intermittent energy sources of renewable origin e.g., solar or wind (EBA, 2023).

- **Energy security –** Biomethane can be traded and produced locally in Europe, whereby this ensures the EU's energy security of supply which prevents the dependence of biomethane using external providers. This is important because Russian natural gas made up a big share of energy imports to the EU in previous years as shown in *figure 2.*

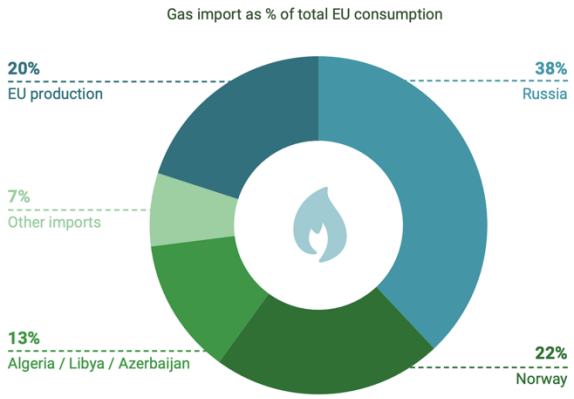



*Figure 2 - Dependency on natural gas imports in the EU 2020 taken from (Alberici et al., 2023)*

From this figure it is evident that Russia had the majority of natural gas imports at 38%, however due to the Russian invasion in Ukraine in 2022, the European commission published an REPowerEU plan to make Europe independent from fossil fuels in Russia before 2030 (Alberici et al., 2023).

- **Organic waste processing** – biomethane production from organic waste feedstocks can provide services of processing waste and generation of energy. This has positive impacts on the reduction of treatment costs of waste producers hence improving the overall economics of the operation (Alberici et al., 2023). Moreover, this advantage plays a role in closing the circular economy loop whereby recycling the organic wastes turning them into value-added products such as renewable energy.

- **Preventing greenhouse gas emissions –** biogas and biomethane can prevent emissions across its whole value chain. For example, this renewable energy alternative can replace normal fossil fuels as energy sources. Biogas produced via anaerobic digestion produces a digestate which can be used as a biofertilizer helping return the organic carbon back into the soil while also reducing the demand for carbon-intensive production of normal mineral fertilisers (EBA, 2023).

- **Clean transport –** around 25% of total emissions in EU comes from transport (Buysse & Miller, 2021; EBA, 2023), hence biomethane would be an effective and positive way to reduce greenhouse gas emissions. Biomethane can be used as a biofuel in the form of a CNG (compressed natural gas) or LNG (liquified natural gas) substitute termed bio-CNG or bio-LNG. Another advantage, is depending on the feedstock used to produce the biomethane, it could even have negative emissions implicating that carbon dioxide can be removed from the atmosphere (EBA, 2023). Moreover, liquified biomethane can be used in more challenging modes of transport such as maritime and heavy-duty road transportation. These are both challenging to electrify so biomethane is a good alternative for these types of transport.

- **Closing the carbon loop** – carbon dioxide is a by-product when purifying biogas into biomethane and can be valorized either in the food industry or used for enhancing photosynthesis in greenhouses. As mentioned before, the digestate formed from anaerobic digestion also contains carbon which can be used as an organic fertilizer, thus putting carbon back into the soil. Which completes the carbon cycle loop via utilizing the carbon dioxide after biomethane production hence removing carbon from the atmosphere.

***Hybrid Biomethane Production from Integrated Biomass Conversion (HYFUELUP) – EU Project***

The Hybrid Biomethane Production from Integrated Biomass Conversion (HYFUELUP) project is a new EU-funded project launched in November 2022 which will demonstrate an innovative pathway for biomethane production at scale. It is based on the integration of sorption-enhanced gasification, methanation via catalytic fluidized-bed and high temperature electrolysis (HYFUELUP, 2022) with the aim of contributing to the objectives of the REPowerEU plan. The REPowerEU is a plan for saving energy, producing clean energy, and diversifying the EU's energy supplies. The biomethane produced from the HYFUELUP project will be liquified after the gasification and methanation processes for the applications in decarbonizing long-distance road freight and maritime transportation.

This project will also see advances in technologies normally used in biomethane production. *Table 1* shows the differences between normal biomethane production and what HYFUELUP will be doing in their project.

*Table 1 - Conventional biomethane production vs HYFUELUP technology* (HYFUELUP, 2022)

| **Conventional Biomethane Production** | **Biomethane produced via HYFUELUP** |
|---|---|
| Most production occurs via biogas upgrading | Diverse technological concept via advanced gasification |
| Sustainable biomass production fragmented | Expanded lignocellulosic crop supply for biomethane |
| Gasification of lignocellulosic biomass | Diverse feedstocks using low-grade wastes |
| Rigid and complex process operation | Flexible operation with fewer steps |
| $CO_2$ separated/not converted into $CH_4$ | *In-situ* $CO_2$ sorption/capture: enhanced carbon efficiency |
| $CO/CO_2$ methanation in separate steps | Hybrid/adaptable operation mode in the same reactor |
| Renewable energy fluctuations not considered | Flexible $H_2$ addition following availability and needs |
| Biomethane offtake after the end of the project | Complete deployment value chain demonstrated |

*The general objectives of the HYFUELUP project are (HYFUELUP, 2022):*

1. To demonstrate an innovative pathway for the efficient and cost-effective biomethane production at scale based on the integration of thermochemical technologies with renewable hydrogen.

2. To demonstrate a complete deployment value chain, including biomethane offtake and distribution, for contributing to the penetration of biomethane in the transport and energy systems.

*The specific objectives, to achieve the goals of this project are (HYFUELUP, 2022):*

1. To assess the integration of low-grade and other sustainable materials in biomethane production for diversification purposes and identify regional supply chains for the use of these feedstocks
2. To demonstrate and optimize a flexible gasification process using sorption-enhanced gasification (SEG) with low grade feedstocks
3. To derive an efficient gas cleaning concept for tar reforming and sulphur removal from the producer gas from SEG
4. To test and validate the catalytic methanation of syngas from SEG of low-grade feedstocks
5. To test and validate the flexible addition of renewable hydrogen in methanation and enhance biomethane production
6. To demonstrate a deployable and enhanced technological solution to produce biomethane, based on SEG coupled to a fluidized bed methanation reactor
7. To develop business plans for decentralized biomethane liquefaction
8. To validate the increased sustainability of the project's approach (circularity for energy and materials) and the particular social, economic, and environmental implications linked to the concept

***Aims of this thesis***

This thesis will aim to shed light on the importance of biomethane production and the technologies and innovations involved. More specifically, the technologies and advances seen in the HYFUELUP project. This thesis will also examine preliminary techno-economic analyses, life-cycle assessment, and environmental analyses of the technology involved.

Since the HYFUELUP project is in its early stages (created in November 2022),

*The aims of this thesis are:*

1. To conduct an in-depth review of the literature concerning biomethane production processes and gasification technologies

2. To identify innovations in the literature of the technology used by HYFUELUP for example using: sorption-enhanced gasification, fluidized-bed methanation, and using sustainable biomass feedstocks

3. To analyze the market potential and penetrability of the technology used by HYFUELUP using preliminary techno-economic assessment and life-cycle assessment data found in the literature and/or in HYFUELUP's preliminary experiments (if available)

# Methodology

Since this thesis is a non-laboratory (literature review) based piece of work, the methodologies here will be how the literature was collected.

The research for the state-of-art and preliminary life cycle and techno-economic assessment data collection used in this thesis was taken from scientific research articles, publications, journals, and other sources. *Table 2* shows how the literature was collected in this report.

*Table 2 - Literature Collection Methodology*

| Database | Search terms | Hits | Inclusion/exclusion criteria |
|---|---|---|---|
| Google Scholar | "biomethane" AND "gasification" | 10,600 | Must be directly relevant to biomethane production |
| Google Scholar | "biomethane" AND "fluidized bed methanation" | 6,100 | Must be directly relevant to biomethane production |
| Google Scholar | "biomethane" AND "sorption-enhanced gasification" | 16,100 | Must be directly relevant to biomethane production |
| Google Scholar | "biomethane" AND "techno-economic assessment" | 14,600 | Must be directly relevant to biomethane production |
| Google Scholar | "biomethane" AND "life cycle assessment" | 16,100 | Must be directly relevant to biomethane production |

## Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a framework used to evaluate the environmental impact associated with a product, process, or service throughout its entire life cycle; whereby it helps to identify areas of improvement to reduce the negative impact making the system more sustainable. LCA can be divided over four stages: 1) goal and scope, 2) life cycle inventory (LCI), 3) life cycle impact assessment (LCIA) and 4) interpretation.

### *1) Goal & Scope*

The goal and scope step of an LCA makes sure your LCA is performed consistently (Golsteijn, 2022). This step is important for giving a reason for why an LCA has to be executed and defining the product and its life cycle with an overview of the system boundaries. System boundaries are an important factor to consider as it describes what should be considered during the assessment, and what can be

neglected. In most situations there can be three types of LCA's: "cradle-to-gate," "cradle-to-grave" and "cradle-to-cradle." Whereby cradle-to-gate LCA considers the environmental impacts of a product from its creation to the manufacturing stage, up to when it leaves the factory gate ready for distribution. A cradle-to-grave approach considers the entire life-cycle of a product from the extraction of its raw materials to the manufacturing, use, and disposal phase (Campisano, 2023). Finally, the cradle-to-cradle approach aims to create a "closed-loop" system where waste is minimized, and the materials used are re-used and recycled.

In the HYFUELUP project, since the "product" is biomethane – a (bio) fuel, the LCA of fuel can be considered from the perspective of "well-to-wheel" (WTW), which can be subdivided into "well-to-tank" (WTT) and "tank-to-wheel" (TTW). Figure 3 shows the different LCA terms in a schematic.

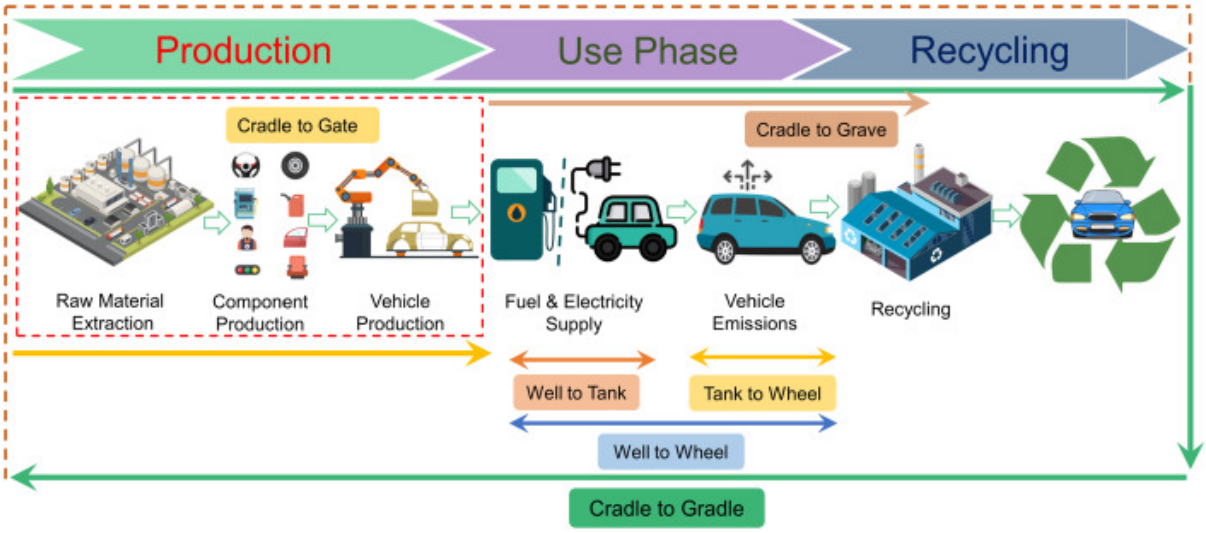



*Figure 3 - LCA terminology of fuels and vehicles taken from (Xia & Li, 2022)*

WTT focuses on the entire production process of the fuel which includes the extraction of raw materials, to delivering the fuel to the tank, including extraction, transportation, and refining. WTT also considers the energy and emissions associated with this production process hence the emissions of GHGs or other pollutants.

TTW considers the environmental impact of the fuel combustion and vehicle propulsion, hence is limited to the use phase of the vehicle. In comparison, WTW considers the full life cycle of the fuel from its extraction to its use in a vehicle. Hence, WTW considers not only the fuel combustion emissions but also the emissions from the production of the vehicle.

### *2) Life cycle inventory analysis (LCI)*

The life cycle inventory involves the collection and quantification of data on the inputs and outputs of the processes involved in the life cycle of a product, service, or fuel in this case. This LCI provides an inventory of the material and energy flows associated with the product and is the basis for assessing

the environmental impacts (Campisano, 2023). Inputs can be raw materials and energy for example, and outputs could be the emissions of pollutants and waste streams of the product.

### *3) Life cycle impact assessment (LCIA)*

In the LCIA, classification of the environmental impacts collected and modelled from the LCI can be translated into environmental themes (Golsteijn, 2022) formally known as "impact categories" such as global warming potential, ozone depletion, acidification, and eutrophication for example. LCIA utilizes different models and tools to aid in evaluating these impacts via the use of databases, software's or LCIA methods such as SimaPro or Ecoinvent.

### *4) Interpretation*

The final stage of an LCA study is the interpretation phase where the results from the inventory and impact assessments are combined to identify limitations, environmental hotspots, and draw conclusions and make recommendations (Campisano, 2023). The interpretation stage should have consistencies with the ultimate goal and scope of the study, whereby considering the results are relative and not predicting actual risks or impacts.

## Techno-Economic Assessment (TEA)

Techno-economic analysis or techno-economic assessment (TEA) is a method used to analyze the economic performance of processes in different industries. TEAs are important for evaluating whether a process or technology will be feasible for upscaling or industrialization. A TEA can be conducted via a holistic analyses taking into consideration different aspects of the process for example: process design, process modelling, equipment sizing, capital cost estimation, operating cost estimation, and cash flow analysis (Chai et al., 2022).

Manufacturing costs can be separated into two categories: capital expenses (CAPEX) and operating expenses (OPEX). CAPEX includes one-time (non-recurring costs) such as equipment, building, construction and facility costs. In a TEA these one-time facility costs are amortized (gradually paid off) over the asset's use lifetime in relation to a specific production volume (Energy.Gov, 2023). OPEX on the other hand, are recurring costs such as materials, labor and energy. These recurring costs can be fixed or variable. For example, fixed OPEX such as labor stays the same with production output. However, variable OPEX for example materials, are directly related to the production volume.

Net present value (NPV) is an important tool used in TEA, which is a financial metric that calculates the value of an investment. NPV calculates the present value of future cash flows, and when its compared with the initial outflows a project is acceptable if NPV is positive (Wicaksono et al., 2019).

A positive NPV means the project will generate profit, and a negative NPV is an indicator of the project expected to lose money.  Another important financial metric in TEA is internal rate of return (IRR) which measures the profitability of a project or investment considering the time value of money. IRR is a percentage rate equating the present value of future cash inflows with the present value (Wicaksono et al., 2019). The IRR is the rate at which the project's NPV is equal to 0.

NPV and IRR were not analyzed in this report due to the lack of experimental data from the HYFUELUP project, however it is worth mentioning that HYFUELUP should consider NPV and IRR in their TEA.

## State-of-art of biomethane production processes

The HYFUELUP project team have identified three major challenges the European Union should target to increasing the European renewable gas capacity and establishing biomethane as a successful decarbonization strategy.

*Challenge 1: Need to diversify the available technologies for biomethane production removing the focus from anaerobic digestion at a wider scale*

Biomethane is widely produced using the technologies known as anaerobic digestion (AD). Anaerobic digestion is a biochemical process, where complex organic matter is decomposed in an anoxic (oxygen-absent) environment via different anaerobic microorganisms (Li et al., 2017). Thus, this type of technology doesn't require a high amount of energy such as heat and electricity. However, the biogas produced from anaerobic digestion can contain a large portion of carbon dioxide (around 35-45%), thus in order to use biogas as a fuel it would need to be upgraded for removal of the carbon dioxide gaining a purer biomethane gas.

Anaerobic digestion occurs through multiple steps with complex interactions between different microorganisms and can be divided into four different stages: 1. Hydrolysis, 2. Acidogenesis, 3. Acetogenesis and 4. Methanogenesis (Uddin & Wright, 2022). These four stages can be seen in *figure 4*.

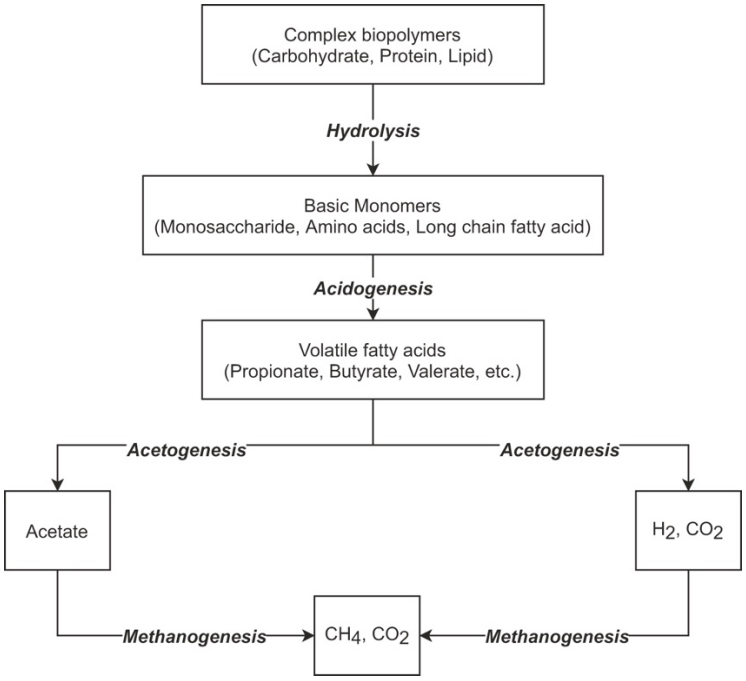



*Figure 4 - Anaerobic digestion for biomethane production taken from (Uddin & Wright, 2022)*

This anaerobic digestion process as seen in *figure 4* happens via four stages where complex organic compounds are first hydrolyzed via enzymatic reactions to basic monomers. These monomers include monosaccharides (e.g., glucose), amino acids and long chain fatty acids (LCFAs). These are subsequently converted via acidogenesis to volatile fatty acids (VFAs), hydrogen and acetic acid (Rabii et al., 2019). In the next stage, acetogenesis occurs whereby the acetogenic bacteria convert these VFAs into hydrogen and carbon dioxide. Lastly, within methanogenesis the methanogens convert the hydrogen, carbon dioxide and acetate into methane and carbon dioxide. After anaerobic digestion is complete, there will be leftovers of residual solids and organic matter known as digestate. This digestate can be separated into liquid and solid streams where the digestate can act as a suitable alternative for fertilisers in soil applications due to its nutrition value containing nitrogen and phosphorous which are beneficial nutrients for plant growth.

Currently, the most used option to produce biomethane is to upgrade the biogas produced after anaerobic digestion. However, this technology of anaerobic digestion contains some limitations including:

- **Feedstock availability and variability –** anaerobic digestion requires a continuous supply of organic waste feedstock for effective operation. Since feedstocks can have a wide variability in physical and chemical properties this could be a challenge for the technology (Uddin & Wright, 2022). Some of the physical characteristics include feedstock size and moisture content which has to be compatible with the anaerobic digester, as differences in moisture content for example could impact digester feeding and bacterial growth within the system. Lignocellulosic biomass contains the fractions cellulose, hemicellulose and lignin; where biomass with higher lignin contents makes it more recalcitrant consequently slowing down the hydrolysis stage. Moreover, since lignocellulosic feedstocks are highly recalcitrant their conversion via anaerobic digestion requires different pre-treatments (e.g. biological, chemical, mechanical and thermal) which can be complex and costly to implement.

- **Low process efficiency –** during anaerobic digestion, there are four different types of bacteria which breaks down the organic material in four stages. Each type of bacteria requires specific process conditions (e.g. temperature, pH, C/N ratio) to work well. There can be times where during one of the stages, disruptions occur due to the syntrophic relations among bacteria thus promoting a cascading effect on the rest of the stages (Uddin & Wright, 2022).

- **Process inhibition –** during digestion there can also occur a high accumulation of different intermediate products such as ammonia ($NH_3$), volatile fatty acids (VFA), long-chain fatty

acids (LCFA) etc. Ammonia is mainly produced when the feedstock is rich in nitrogen such as food waste. In the right amounts, ammonia is fine in order for microorganisms to gain its nutrients, however if this passes a certain level, the ammonia can damage the VFA which consumes methanogens thus reducing methane production (Uddin & Wright, 2022). Moreover, another inhibitory trigger for methanogens is via the accumulation of LCFAs, and this happens from lipid-rich substrates during the hydrolysis step.

- **Lower product quality –** biogas is the main product of anaerobic digestion however the presence of carbon dioxide being more than 40% can be an issue. This majority of carbon dioxide can reduce the biogas' specific energy content, flame speed and increase transportation costs (Uddin & Wright, 2022). Another co-product in the anaerobic digestion process is the unconverted substrate – digestate. This digestate can have end-use applications such as a replacement for chemical fertilisers in the soil industry because of its nutrition value. However, since the digestate normally has a high moisture level, this often requires a solid-liquid separation posttreatment process which is normally energy and cost intensive.

- **Hydrogen sulfide presence –** in addition to methane and carbon dioxide, biogas contains trace amounts of hydrogen sulfide. This depends on the sulfur content of the feedstock used in anaerobic digestion. Thus, hydrogen sulfide in biogas is a problematic impurity which can inhibit methanogenesis causing the corrosion of equipment's if not removed (Vu et al., 2022). Hence, leading to higher maintenance costs.

From all of the above, it is evident to widen the scope of possible feedstocks for biomethane production and effective deployment of biomethane at scale, gasification technology should be further implemented. Gasification technologies will be further explained from page 26.

*Challenge 2: Need to use sustainable biomass and biogenic waste feedstocks and improve supply chains*

HYFUELUP is proposing different sustainable biomass and biogenic waste feedstocks in order to improve the supply chain of biomethane production. One of these options is the use of the dried digestate sludge as a gasification feedstock to ensure a reliable and affordable supply of feedstock. The anaerobic digestion industry is growing across Europe where the sludge digestate found at the end of this process has increased. Hence, this sludge digestate has an opportunity for further use. Another feedstock which can be utilized for the increase in biomethane production can be the use of lignocellulosic wastes. European lignocellulosic wastes amounted to around 56.3 Mt in 2018 which represented a 8% increase since 2014 (HYFUELUP, 2022). Another option is the use of intermediate

catch or cover crops which are grown before or after the main crops that produce “non-food cellulosic material” without causing limitations of land demand or food competition.

This section will briefly describe the three different sustainable biomass & biogenic waste feedstock options for biomethane production.

**Option 1: Dried digestate sludge / Treatment of digestate from wastewater treatment (WTT)**

A study found in the literature, experimented on the biogas-derived digestate using air gasification with high ash content in a downdraft fixed bed gasifier (G. Chen et al., 2017). The raw material that was used was a mixture of manure and straw for biogas production, where the digestate produced was drained via a liquid-solid separator and subsequently air-dried. The experiment was performed at varying temperatures from 600 to 800°C, with an air equivalence ratio of 0.25 to 0.30 (G. Chen et al., 2017).

One limitation of digestate is the large amount of ash content, hence can cause differing problems within the gasification process such as ash slagging. This slag can accumulate on surfaces of gasification equipment which can cause blockages, reducing gasification efficiency hence is an important factor to consider. Chen et al found using an air gasification temperature of 800°C and an equivalence ratio of 0.25-0.30 no ash slagging was observed and can easily be powdered.

The gasification temperature at 800°C showed the highest gas yield improving the gasification process and gas quality. Whereas the equivalence ratio increasing from 0.25 to 0.28 improved the gasification process with the gas volumes of hydrogen, carbon monoxide, and methane increasing (G. Chen et al., 2017). They concluded that the byproducts from this reaction – biochar and ash, could be applied as a land fertilizer whereby gasification could be a good method to utilize the digestate produced via anaerobic digestion of biomass.

Another study done experimented on digestate from a pilot biorefinery in Poland, using both pyrolysis and gasification (Wiśniewski et al., 2015). The authors characterized the digestate’s chemical composition finding it rich in organic matter, nitrogen and phosphorous. They conducted different experiments using different process conditions on pyrolysis and gasification. Pyrolysis was carried out at 500°C, and subsequently gasification was performed at 850°C both done in a batch reactor.

The authors found that during pyrolysis, reduction of residual moisture occurs where volatile fractions are evaporated and the carbon in the digestate is converted to molecule of higher molecular weight (Wiśniewski et al., 2015). Moreover, the sulphur, nitrogen and chloride levels also significantly

decreased. In contrast, gasification was more effective than pyrolysis in producing syngas which had a higher calorific value than the gas produced by pyrolysis. Overall, the study suggested that pyrolysis and gasification are effective ways to valorise the digestate and produce renewable energy.

**Option 2: Lignocellulosic (wastes) biomass**

Lignocellulosic biomass is an abundant renewable resource which can be used for biogas production and is available in many countries worldwide (Solarte-Toro et al., 2018). This raw material can be considered as a potential source of fermentable sugars e.g. glucose, xylose, mannose and arabinose which can be degraded anaerobically. Gas produced by the anaerobic digestion of lignocellulosic materials is rich in methane (Solarte-Toro et al., 2018).

Although lignocellulosic biomass can serve as a good alternative biomass contender, the lignin in lignocellulosic biomass encapsulates hemicellulose and cellulose into a hydrophobic structure making the biomass highly recalcitrant needing suitable pretreatments. The structure of lignocellulosic biomass can be seen in *figure 5*.

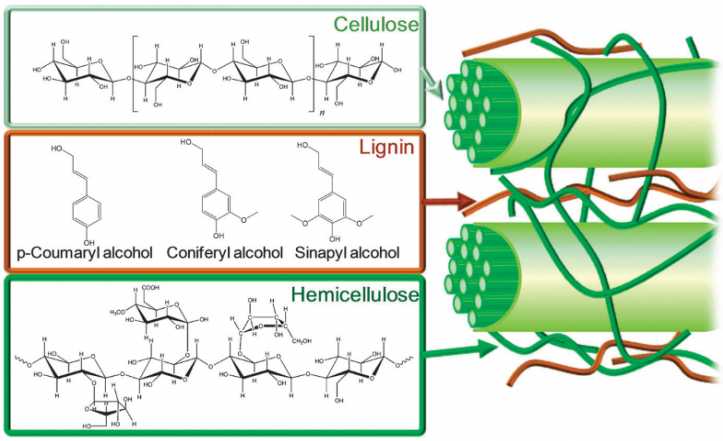



*Figure 5 - Structure of lignocellulosic biomass taken from (Alonso et al., 2012)*

In general, the content of cellulose, hemicellulose and lignin in lignocellulosic biomass consists in the range of 30-60%, 20-40% and 15-25% respectively (Hosseini Koupaie et al., 2019). *Table 3* shows some of the common lignocellulosic biomass compositions used in energy production.

*Table 3 - Lignocellulosic biomass composition – data taken from (Hosseini Koupaie et al., 2019)*

| Source | Biomass type | Cellulose (%) | Hemicellulose (%) | Lignin (%) |
|---|---|---|---|---|
| Municipal | Paper | 85-99 | 0 | 0-15 |
| Agricultural | Bagasse | 38.2 | 27.1 | 20.2 |
| | Barley Straw | 31-34 | 24-29 | 14-15 |
| | Cattle Manure | 20 | 1.6-4.7 | 1.4-3.3 |

| | | | | |
|---|---|---|---|---|
| | Rice Straw | 32 | 24 | 13-18 |
| | Rye Straw | 38 | 36.9 | 17.6 |
| | Sugarcane | 25 | 17 | 12 |
| | Wheat Straw | 29-35 | 26-32 | 16-21 |
| Forestry | Grasses | 25-40 | 35-50 | 10-30 |
| | Hardwood Stems | 40-55 | 24-40 | 18-25 |
| | Softwood Stems | 45-50 | 25-35 | 25-35 |

Pretreatments help aid in the breakdown of the recalcitrant nature of lignocellulosic biomass and has varying effects depending on the type of pretreatment selected and type of lignocellulosic biomass. The most applied pretreatments for the enhancement of digestibility of lignocellulosic biomass are dilute acid hydrolysis, steam explosion, alkaline hydrolysis, size reduction and liquid hot water because of their high potential to be scaled up at an industrial level (Solarte-Toro et al., 2018).

One study investigated the use of oil palm rachis – a lignocellulosic residue produced in Colombia – for biogas and syngas production simulated to be used by both anaerobic digestion and gasification processes (Solarte-Toro et al., 2018). Gasification was simulated using two stages, where the first stage was reducing the particle size of the lignocellulosic biomass using a crusher model and the second using an air-blown downdraft gasifier. For the anaerobic digestion simulation, biogas production was done via liquid hot water pretreatment and a water scrubbing cleaning method. After this, they simulated a cogeneration plant with a gas turbine using fuel gases formed by the anaerobic digestion and gasification processes for the production of power and fuel. They found that the net energy value of the gasification process was higher than that of the anaerobic digestion process (Solarte-Toro et al., 2018). Moreover, they also found that the gasification process required less equipment than the anaerobic digestion process.

**Option 3: Use of intermediate catch or cover crops e.g. sorghum / winter cereals**

Intermediate catch – also known as cover crops are defined as close-growing crops which provides soil protection, seeding protection, and soil improvement between periods of normal crop production (Quintarelli et al., 2022). These crops are planted between two main crop seasons having significant benefits such as reducing soil erosion, controlling weeds, and improving overall soil health. The main purpose of intermediate catch or cover crops is to protect and improve the soil during the period when the soil would otherwise be left bare and exposed to erosion, nutrient leaching and weed growth.

There are also some disadvantages or negative effects cover crops could have. For example, cover crops could engage in pre-emptive competition with cash crops (high-value crop grown primarily for sale which are in demand in local or international markets) for nutrients and water (Launay et al., 2022). Moreover, cover crops could also be hosts to pathogens which can put succeeding crops at higher risk of diseases thus leading to lower yields. Hence, plans should be in place to select a cover crop species that won't be a host to pathogens for the subsequent crop.

One study done investigated the use of rye as a cover crop for biogas production (Igos et al., 2016). This study done aimed to assess the environmental and economic impacts of planting rye as a winter cover crop (after maize) in addition to its use as a co-substrate in an anerobic digestion plant for biogas production. Based on the results of the life-cycle assessment they conducted, the use of rye as a winter cover crop generated environmental benefits on a local scale; including reduced nitrate leaching, optimized land use, and avoidance of using herbicides (Igos et al., 2016). However, there was negative effects as well including lower rye productivity and biogas potential compared to maize. Moreover, there were increased indirect environmental impacts (i.e. resource depletion) because of higher fuel and material consumption when producing 1 MJ of bioenergy. Overall, the use of rye planting in winter can generate additional revenue for farmers however there can be some uncertainties including price volatility, seasonal weather conditions and influences of these cover crops on the summer crop yield (Igos et al., 2016).

From this information it is evident that the use of cover crops can be a viable option for the use in the HYFUELUP project as a sustainable biomass feedstock with additional positive environmental and social impacts. Including improvements in soil health, water storage, nutrient leaching avoidance and increases in farmer's income.

*Challenge 3: Market penetration of biomethane production technologies*

Finally, the third challenge in tackling biomethane production is the ability to penetrate the market of biomethane production technologies. This needs to increase while also reducing associated production costs in order to be sustainable. Currently, anaerobic digestion is the most regarded technological solution for biomethane production, however from the bottle-necks explained in challenge 1 with its scale-up limitations, alternative technologies such as gasification needs to be more dominant in the industry.

From *figure 6* and *figure 7* we can see the biomethane market potentials in 2030 and 2050 comparing anerobic digestion and gasification technologies taken from the Guidehouse – a gas for climate report (Alberici et al., 2022).

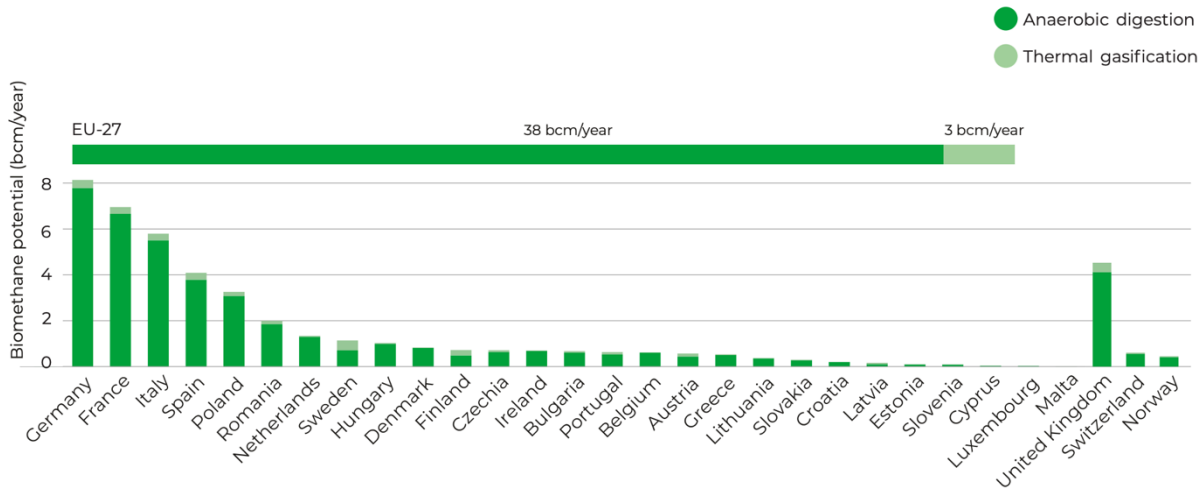



*Figure 6 - Biomethane potential in 2030 in the EU*

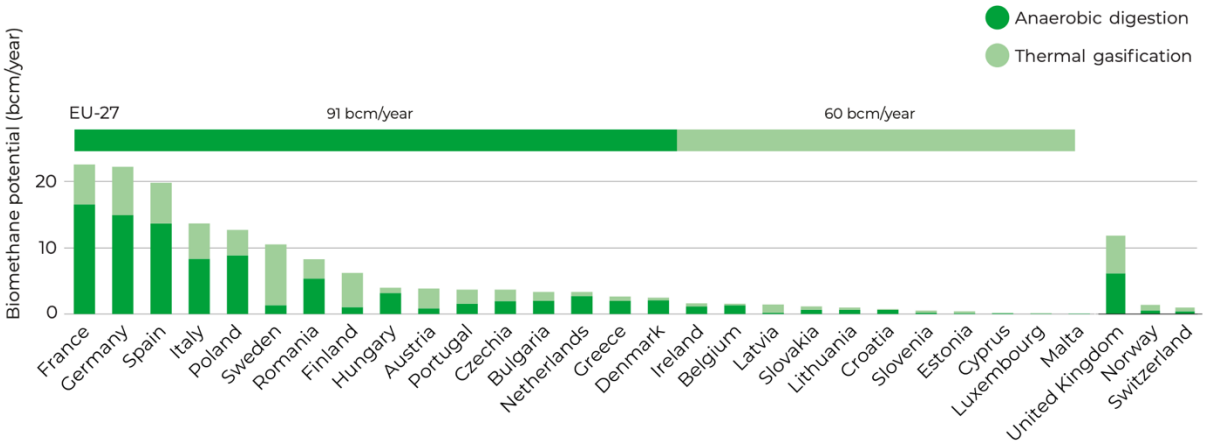



*Figure 7 - Biomethane potential in 2050 in the EU*

It is evident that in the short-term by 2030 anaerobic digestion will still be the dominant technology for biomethane production with gasification becoming more intensive by 2050. The biomethane potential will be around 41 billion cubic meters (bcm) in 2030 and increase almost three and a half times to 151 bcm by 2050 in the EU-27 countries. The 2030 data is around 93% based using anaerobic digestion technology where gasification will be more prominent to 41% by 2050 as technology evolves (Alberici et al., 2022). France, Germany, Spain, Italy, Sweden, and the United Kingdom are currently the top countries within the EU for biomethane potential.

The increase in gas prices since late 2021, due to the ongoing Russia-Ukraine crisis have made it vital to increase the pace of EU energy generation while reducing fossil fuels. According to the EU Biomethane Action Plan (European Union, 2022) they have advised a number of suggestions on how biomethane production can be penetrated into the market in the years to come. These include a number of different actions that should take place seen in *table 4*.

*Table 4 - Biomethane Targets for market penetration, targets taken from (European Union, 2022)*

| **Action** | **Content** |
|---|---|
| Create a biogas & biomethane industrial partnership/forum for the promotion of biomethane's sustainable production and application | • Support the achievement of the EU target for biomethane production<br>• Create a platform for stakeholder engagement along the value chain for biomethane production<br>• Identify policy gaps / barriers for the production of biomethane within the EU |
| Providing incentives for the production of biomethane | • Reduce costs for economic operators which are currently preventing the scaling up of biomethane<br>• Consider investments into upcoming and new technology for biomethane production like the technology used in HYFUELUP |
| Assess challenges or bottlenecks for the cost-effective deployment of biomethane | • National regulatory authorities should examine potential investment challenges for the increase in biomethane uptake and production<br>• Transmission system operators (TSO's) and distribution system operators (DSO's) should assess the potential cost of biomethane injection, coordinate and plan successful biomethane integration |
| Identify Research & Development & Innovation (RND&I) gaps | • Focus should be given on improvements to technological efficiency and cost-effectiveness of supporting innovative technologies for the production of sustainable biomethane e.g. on solutions that won't impede EU food / feed production<br>• Identify regions where biomethane production can be sustainably increased from sustainable biomass production / cover cropping to help accelerate regional bioeconomy development |

*The demand for biomethane in the market*

Biomethane has potential demand due to its capability in different applications. It is important to note that even though biomethane can be directly applied into the gas network, the entire replacement of methane (natural gas) with biomethane is impossible (Sulewski et al., 2023). Since one reason is the

structure of methane is different to that of biomethane. The demand of biomethane is growing not only in the transportation sector but in other industries such as heating, electricity, or fertilisers.

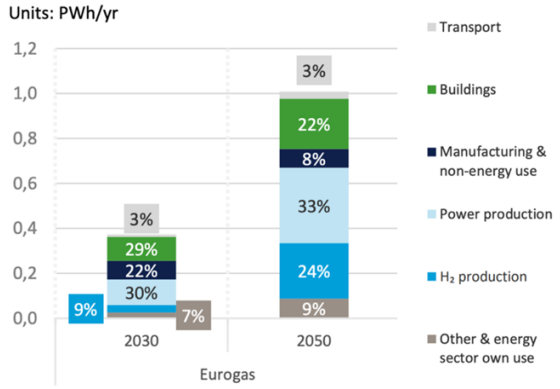



*Figure 8 - Biomethane demand in 2030 & 2050 taken from (Waner et al., 2020)*

Figure 8 shows the future demand of biomethane according to the DNV GL report (Waner et al., 2020), where biomethane demand will double in demand from 2030 to 2050. It is evident that from the statistics found from Eurogas, the manufacturing industry is estimated to transition to hydrogen instead of methane which is why there is a decrease in this sector. We can see that all sectors use biomethane due to its ability to blend with the natural gas grid so it's demand will still be prevalent in the future.

It is worth noting, the demand for biomethane in the EU will be determined in the upcoming years via the EU's plan to diversify its gas supply sources (Sulewski et al., 2023). This is due to previously the EU's dependence on Russia for its natural gas supply. International trade could also be a possible avenue for biomethane market development where transport between countries via high-pressure pipelines or transport in liquified form through shipping (Sulewski et al., 2023). Scaling-up of biomethane production to 35 bcm by 2030 can help support the EU in achieving its climate goals and energy security.

One example of this is via the EU-funded project REGATRACE (Renewable Gas Trade Center in Europe), which aims to create an efficient trade system based on issuing and trading biomethane/renewable gases Guarantees of Origin (GoO) (REGATRACE, 2022). This project will set up a GoO system for biomethane / renewable gases and national GoO issuing bodies through integration of different technologies, support for biomethane market uptake and sustainable feedstock mobilization strategies.

To summarize, in order for the EU to achieve its political targets and decarbonize its energy systems from fossil fuels, a secure and reliable common market for biomethane and other renewable gases is vital.

## State-of-art of gasification processes

From the above information it is evident that the HYFUELUP team is aiming to steer away from the common – anaerobic digestion technology and biogas upgrading in producing biomethane. Instead to expand the array of possible feedstocks for biomethane production and deploy biomethane at scale, gasification technologies will have to be applied.

*Biomass gasification*

Biomass gasification or thermal gasification is the process of converting woody biomass such as lignocellulose's as feedstock with an applied high temperature of around 700-800°C, and high pressure in a low-oxygen environment (European Technology & Innovation Platform, 2020) into a gas. This results in a combination of gases such as methane, hydrogen and carbon monoxide – commonly referred to as syngas.

A second step is necessary after gasification for the cleaning of the syngas. This can be done via methanation where the syngas is cleaned producing a pure biomethane removing any acidic or corrosive components. This process also requires the use of a catalyst for the promotion of the reaction between the hydrogen and carbon monoxide or carbon dioxide in order to produce methane (IEA, 2020). The remainder carbon dioxide or water is thus removed at the end of this process.

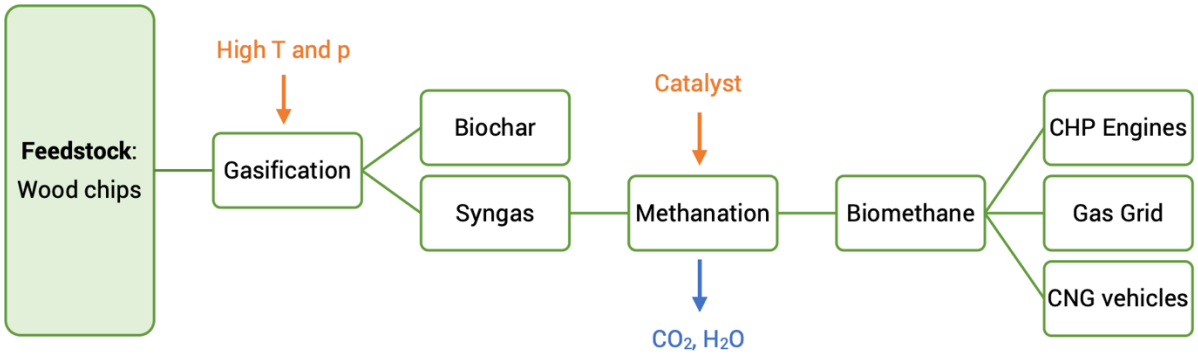



*Figure 9 - Process of biomass gasification and methanation taken from (European Technology & Innovation Platform, 2020)*

From *figure 9* it is evident how the process of producing biomethane works. Where a feedstock (such as wood chips) undergoes gasification at high temperatures and pressures which in turn produced syngas and biochar. The syngas phase then undergoes methanation with the aid of a catalyst producing carbon dioxide and water in addition to biomethane. The biomethane can then be applied to the gas grid, combined heat and power (CHP) engines and compressed natural gas (CNG) vehicles.

In biomass gasification, it is important to note that there are different reactors which obtain different gaseous products of different concentrations. Some gasifiers/reactors include: fixed-bed, fluidized-bed and entrained flow reactor.

The first type of reactor is known as a fixed-bed gasifier which is one of the simpler reactors in gasification as seen in *figure 10.*

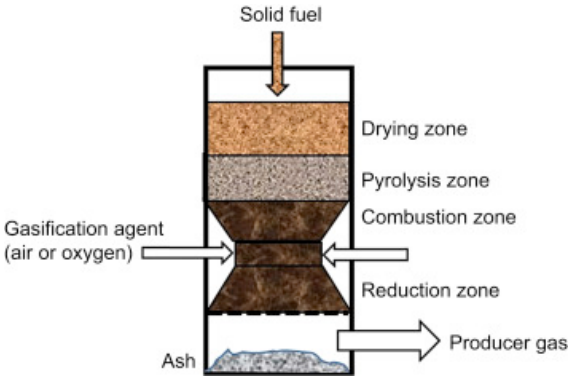



*Figure 10 - Fixed-bed Gasifier*

The biomass is fed from the top of the reactor and is decomposed via different processes such as drying, pyrolysis, reduction, and combustion (Ren et al., 2020). A gasification agent then enters the gasifier at a different side.

Another type of reactor is the fluidized-bed reactor also known as "bubbling" and "circulating," whereby fluidization helps to provide a uniform temperature distribution aiding in the increase of carbon conversion efficiency and production of gas with a high heating value (Mirmoshtaghi, 2016). In a fluidized-bed reactor a moving bed of fine-grained material is where the biomass is introduced, and air enters through the bottom. The bed temperature is normally between 800-950°C, whereby the biomass is gasified in the present of a gasification agent in the hot bed which also produces char with gaseous contents (Moilanen & Nasrullah, 2011). *Figure 11* shows the differences between a bubbling fluidized bed and circulating fluidized bed gasifier.

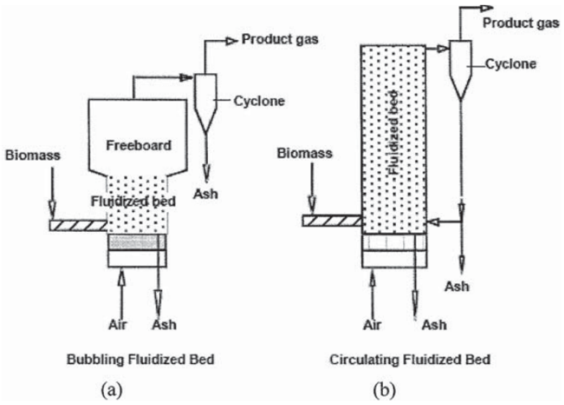



*Figure 11 - Fluidized bed gasification taken from (Moilanen & Nasrullah, 2011)*

Another type of gasifier is the entrained flow gasifier. In this gasifier, the fuel and gasifying agent in addition to steam are introduced from the top (Moilanen & Nasrullah, 2011) which can be seen in *figure 12.*

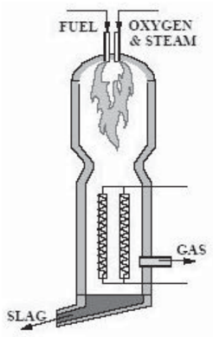



*Figure 12 - Entrained gas flow taken from (Moilanen & Nasrullah, 2011)*

This gasifier usually has higher capacities than the other types of gasifiers available, whereby this gasifier is conventionally used for fossil fuels (e.g., coal) or refinery wastes. Due to its need for a very fine particle size, this is a limitation for gasification of biomass.

*Table 5* shows a summary of the three different types of gasifiers outlining their advantages and limitations.

*Table 5 - Advantages & Limitations of Gasifier Types – info from (Ren et al., 2020)*

| **Gasifier** | **Advantages** | **Limitations** |
|---|---|---|
| **Fixed Bed** | High thermal efficiency | Tar found in syngas |
| | Capability of handling ranges of biomass | Difficult to start and control temperature |
| | Large-scale feasibility | Catalysts could be easily poisoned and deactivated |
| | Simple construction | Installation of mobile grates is needed |
| **Fluidized Bed** | High carbon conversion and thermal loads | Ash content causes loss of carbon |
| | Excellent for temperature control and handling biomass whose properties differ | Large investment and maintenance costs |
| | Large-scale feasibility | Complex technology, and hard to control |
| | Lower residence times | Dragging of ash and dust |
| **Entrained Flow** | High carbon conversion and reduced tar content | Oxidants in abundancy are needed |

| | | |
|---|---|---|
| | Lower reactor residence time and simple to control process parameters | Fine particle size and preparation of biomass is vital |
| | Large-scale feasibility | Heat recovery is needed for efficiency improvements |
| | Flexibility of materials and consistent react temperature during gasification | Large investment and maintenance costs |

***Sorption-enhanced gasification (SEG)***

One of the HYFUELUP's solutions is to use a specific type of gasification known as: sorption-enhanced gasification (SEG). SEG is a process in which a carbonaceous feedstock is gasified and carbon dioxide is simultaneously removed (in-situ) via the use of a sorbent (Pfeifer, 2013).

Hence, SEG is largely dependent on the by the sorbent properties such as the type and activity. There are many different sorbents, however limestone ($CaCO_3$) has been widely used due to the excellent carbon dioxide capture capacity and relatively low price point (Parvez et al., 2021). Moreover, the reactor temperature needs to be set a specific point for optimal carbon dioxide capture while also maintaining the $CaO/CaCO_3$ equilibrium.

*Figure 13* shows a depiction of how SEG works.

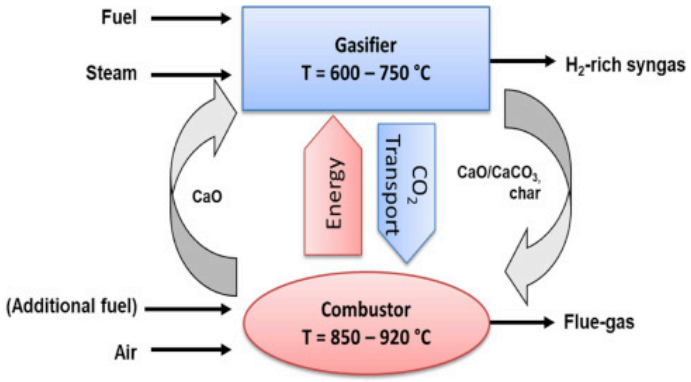



*Figure 13 - Principle of Sorption-Enhanced Gasification (SEG) taken from (Parvez et al., 2021)*

The gasifier and combustor are the two fluidized bed reactors in this process whereby the bed material is circulated between them. The sorbent (in this case CaO) found in the gasifier, captures the carbon dioxide which is formed during the gasification process and form $CaCO_3$ (Parvez et al., 2021). The gasifier is at around 600-750°C where the combustor is at a higher temperature of 850-920°C. A hydrogen-rich syngas is obtained in this process due to the gasifying agent of steam, and the removal

of carbon dioxide via the sorbent which together leads to increased hydrogen generated. Moreover, the unconverted char and the bed material is transferred from the gasifier to the combustor where it is then burned which gives the heat needed for part of the reaction. While this is happening, in the gasifier, the carbon dioxide absorbed by the CaO is released into the flue gas via the calcination, whereby this flue gas emitted from the combustor has large amounts of carbon dioxide.

In addition to SEG, a specialised form is known as oxygen-feed SEG (Oxy-SEG) as shown in *figure 14*.

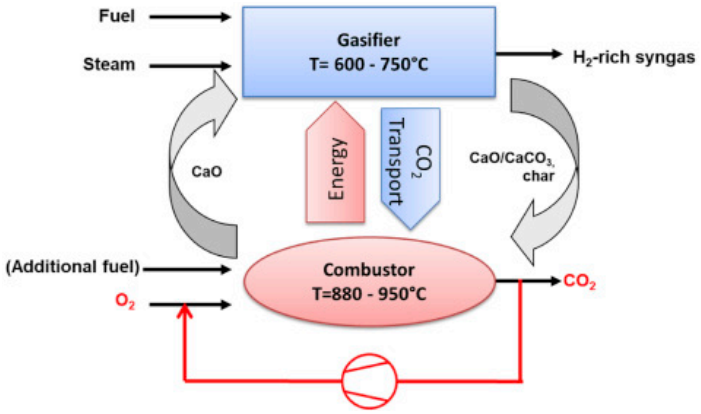



*Figure 14 - Principle of Oxygen-feed SEG (Oxy-SEG) taken from (Parvez et al., 2021)*

Oxy-SEG is a type of SEG whereby the combustor is operated in an oxy-fuel fired mode, whereby recirculated flue gas and pure oxygen acts as an oxidizer (Parvez et al., 2021). This in turn produces an almost pure carbon dioxide stream from the combustor. The calcination requires a higher temperature of around 880-950°C in the combustor due to the fact that the SEG derived flue gas consists of a high quantity of carbon dioxide.

### *Comparison of Fluidized Bed Steam Gasification, SEG and Oxy-SEG*

The principles of SEG and Oxy-SEG are based on fluidized bed gasification where the differences can be seen in *Table 6.*

*Table 6 - Differences between fluidized bed gasification & SEG & Oxy-SEG taken from (Parvez et al., 2021)*

| **Parameters** | **Fluidized bed gasification** | **SEG** | **Oxy-SEG** |
|---|---|---|---|
| Gasification agent | Steam | Steam | Steam |
| Oxidizer | Air | Air | $O_2$ |
| Fluidized bed material | Olivine | Limestone | Limestone |
| Gasifier Temperature | 800 - 850 °C | 600 – 750 °C | 600 – 750 °C |
| Combustor Temperature | 900 – 950 °C | 850 – 920 °C | 880 – 950 °C |

| | | | |
|---|---|---|---|
| $H_2$ in syngas (vol %) | < 50 | > 70 | > 70 |
| $CO_2$ in flue gas (vol %) | < 10 | < 30 | > 90 |

It is evident from this table that for all three types of gasification, the gasifying agent is steam. The oxidizer is air, except for Oxy-SEG which requires oxygen. The bed material for fluidized bed gasification is olivine whereas for both types of SEG it uses limestone. Limestone is a good bed material for SEG processes due to its high level of carbon dioxide capture, where another advantage is it's a cheap and readily available material (Parvez et al., 2021).

Moreover, the gasifier temperature is much higher at 800-850°C in conventional fluidized bed gasification compared with SEG and Oxy-SEG at a range of 600-750°C. This is also similar with the combustor temperature where in this case Oxy-SEG requires a very slightly higher temperature compared with SEG. The hydrogen content in syngas is notably lower in fluidized bed gasification at less than 50% compared to SEG and Oxy-SEG which produces more than 70%. Finally, the carbon dioxide content in the flue gas is lowest in fluidized bed gasification with SEG having a slightly higher percentage. However, since Oxy-SEG needs pure oxygen as the oxidizing agent in the combustor, this results in a pure carbon dioxide stream. This carbon dioxide could thus be used for carbon capture, utilization, and storage. It is important to note that extra capital expenditure (CAPEX) and operating expenditure (OPEX) are required for Oxy-SEG due to the need of an air seperation unit (ASU) for the production of pure oxygen.

***Catalysed fluidized bed methanation***

Gasification is only one part of the process whereby the syngas produced from gasification needs to be transformed into biomethane. This can be done through a process known as methanation, more specifically – catalysed fluidized bed methanation – a process which HYFUELUP is investigating.

After biomass gasification, the gaseous mixture – syngas is produced. This syngas usually contains carbon monoxide (CO), carbon dioxide, hydrogen, and small amounts of other gases. Methanation is the process and is often used to "upgrade" the syngas by converting the carbon monoxide and carbon dioxide into methane and water as shown in the equations in *figure 15*.

$$CO + 3H_2 \rightleftharpoons CH_4 + H_2O$$

$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O$$

*Figure 15 - Methanation Reactions*

Both of these reactions are reversible exothermic reactions and is important to design catalysts for these reactions to reach maximal conversion rates at around 350°C (Ren et al., 2020). One example of a good catalyst for syngas and methane production is $Ni/Al_2O_3$ which has been shown to have high activity during gasification of biomass and methanation of syngas (Ren et al., 2020).

One study investigated the methanation of hydrogen-rich syngas from dual fluidized bed gasification and sorption enhanced reforming using an optimized catalyst (Bartik et al., 2022). Since the methanation reactions are highly exothermic thus needing for large amounts of heat to be removed, fluidized beds were used due to their high heat and mass transfer capabilities. *Figure 16* shows the diagram flow of the process they used in their investigation.

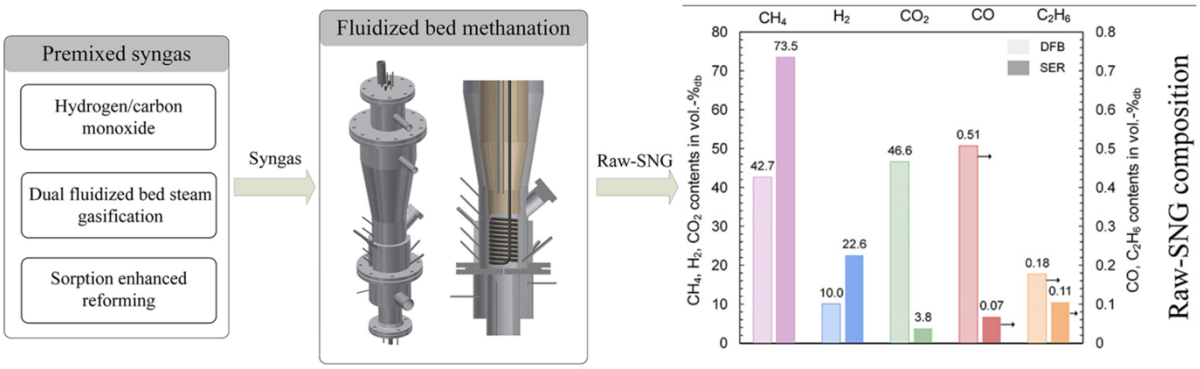



*Figure 16 - Syngas Methanation with SNG composition taken from (Bartik et al., 2022)*

This study investigated the syngas from dual fluidized bed gasification, and a combination with syngas from sorption enhanced reforming (SER). They found the methane concentration after the methanation reaction to have increased from around 43 to 74 vol % through the methanation of hydrogen-rich syngas via sorption enhanced reforming (Bartik et al., 2022). In addition, the yield of methane also doubled from around 48 to 95% whereby the gas conversions of hydrogen, carbon monoxide and carbon dioxide improved. Sorption enhanced reforming is an alternative mode of the dual fluidized bed gasification process, where influences in the stoichiometric ratios of hydrogen to carbon monoxide and carbon dioxide can be adapted to the downstream process (Bartik et al., 2022). Hence in this study, the syngas from SER was very flexible in its composition which was a benefit in the process of methanation. They concluded that the SER syngas methanation yielded higher methane levels, was more advantageous in composition for grid injection, and concurrently improving hydrogen, carbon monoxide and carbon dioxide conversions in comparison with the dual fluidized bed methanation process.

***Market potential***

There is a growing market potential for gasification of fossil, biomass and waste resources where this technology was valued at $479 billion in 2019 and is projected to increase to $901 billion by 2028 (European Biogas Association, 2021). Moreover, biomass waste is expected to increase in the future where it will be a better alternative energy source, with support from policies and regulations by governments. Another positive is its abundant nature of the biomass feedstock making gasification a desirable technology for turning waste disposal into streams of revenue for forest wood producers and owners for example.

Presently, gasification technology has applications in specific solutions such as small scale combined-heat and power plants, and a few plants producing chemicals and fuels (European Biogas Association, 2021). For gasification to reach a commercial scale, the process of production for each product – whether it be biomethane – has to be upscaled and optimized requiring specific support. In the future, more support will be needed from governments and companies to invest in gasification for it to be extended to a commercial scale. This could be through investments of the technology via capital investments, off-take support or operational subsidies (e.g. direct cash payments, tax incentives, loan guarantees or other forms of financial assistance).

**HYFUELUP's outcomes if successful**

From the above state-of-art it is evident that biogas and biomethane is an advantageous renewable energy alternative to fossil fuels. The innovative technology involved to produce this biomethane such as gasification is also a point of interest which will be on the rise in the future. The HYFUELUP project is in the forefront of accelerating the transition of fossil fuels into renewables such as biomethane using innovative research and technology.

The market penetrability of HYFUELUP's proposals will depend on a number of factors (HYFUELUP, 2022):

- Increase cost-effectiveness of the conversion in biomethane production
- Diversify the conversion technology basis for biomethane production
- Contribution to market uptake of biomethane related technologies in the gas market

- Contribute to the priorities of the SET Plan Action 8 – (Bioenergy & Renewable Fuels for Sustainable Transport)

By targeting these objectives and having this project be a success this will aid the EU's ultimate goal of decarbonization by 2050. Moreover, HYFUELUP aims to have these key impacts by 2050 (HYFUELUP, 2022):

- Reduced greenhouse gas emissions
- Increased share of biomethane from gasification
- Strengthened European leadership in terms of the renewable gas industry
- Increased commercial availability of disruptive technologies in 2050
- Reduced market risks
- Increased jobs and competitive sustainable growth

# Results & Discussion

This next part of the master thesis will focus on the (preliminary) life-cycle assessment (LCA) and techno-economic analysis (TEA) of this project which will act as the "results and discussion" section. An important consideration to note is the HYFUELUP project came to fruition last November (2022), hence there is still no experimental data available to use for the production of a full-scale LCA and TEA. With that being said, this section will compare LCA's and TEA's of biomethane production processes found in the literature already, in the hopes of having an idea of what environmental impacts and process costs HYFUELUP could have.

Thus, the aim of the results & discussion is to:

- To be able to identify life-cycle assessments (LCA's) and techno-economic analyses (TEA's) data of biomethane production processes found in the literature which use similar technology found in HYFUELUP
- To act as a "guide" or "reference" when HYFUELUP ultimately starts doing a full-scale LCA and TEA
- To be able to create and define a block diagram of the HYFUELUP process to be implemented
- To be able to create a preliminary life cycle inventory of the process

The National Laboratory of Energy & Geology (LNEG) in Lisbon, Portugal where this master thesis is being completed at, is specifically tasked with the development of a detailed LCA and TEA to assess the viability of the HYFUELUP project implementation. So, the work completed in this master thesis project will hopefully be an aid to the team at LNEG when they finally have to complete the full-scale LCA and TEA.

## *Techno-Economic Analysis*

For the techno-economic analysis, data from three different studies were analyzed and compared.

### Study A – Thermodynamic, economic and environmental assessment of renewable natural gas production (Skorek-Osikowska et al., 2020)

Study A compared three different concepts of biomethane production based on anaerobic digestion and gasification. One of the technologies they used was biomass gasification in the atmosphere of oxygen and methanation of the resulted gas. Hence this technology was chosen to be analyzed for the

purpose of this thesis. The biomass utilized was wood chips for gasification. The technology used in this study included a biomass gasification plant, hydrogen generator, shift reactor, methanation reactor and compression installation. *Figure 17* shows a simplified of the process pathway this study used. *Appendix 1* shows a detailed list of the installation costs and equipment used for the techno-economic analysis of this study. The functional unit in this study was 1 MW of renewable natural gas (RNG) - biomethane produced at plant.

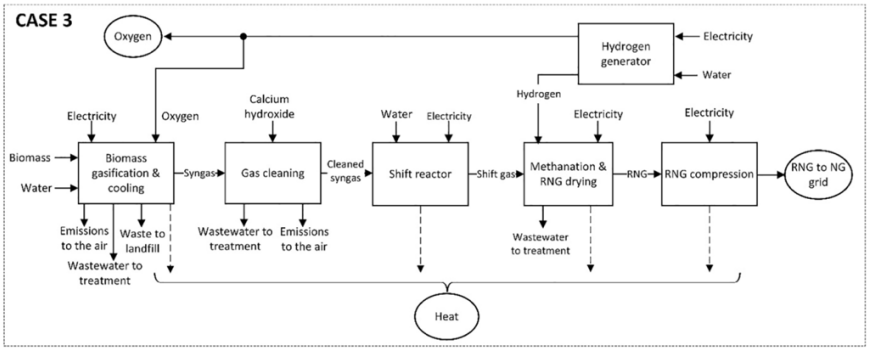



*Figure 17 - Study A: Technology process pathway taken from (Skorek-Osikowska et al., 2020)*

**Study B – Economic assessment of advanced biofuel production via gasification using cost data from the GoBiGas plant (Thunman et al., 2019)**

Study B describes an economic analysis of the GoBiGas plant – an industrial installation plant in Sweden for advanced biofuel production via gasification technology where woody biomass is converted to biomethane. The data from this study is taken from its demonstration plant with 20 MW of production. The GoBiGas plant contains a gasification via a dual fluidized bed gasifier and methanation section. A schematic of the process pathway of the technology used in this study can be seen in *figure 18.*

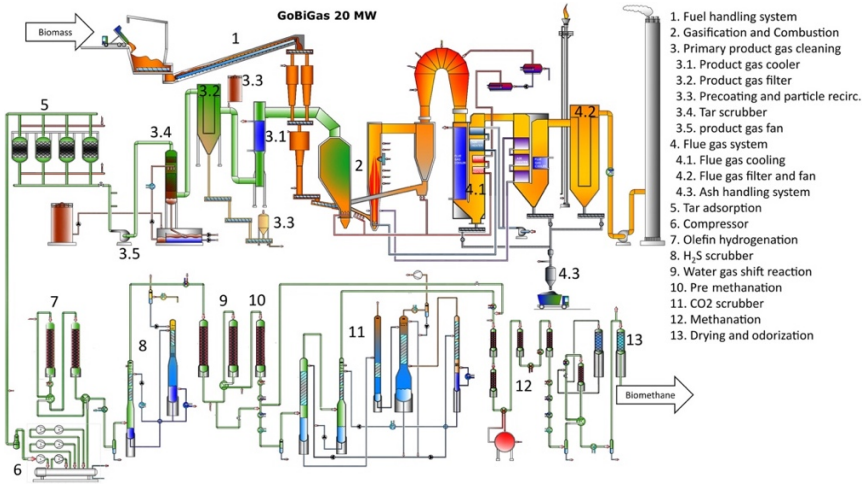



*Figure 18 - Study B: Technology process pathway taken from (Thunman et al., 2019)*

*Appendix 2* shows a detailed list of the installation costs and equipment used for the techno-economic analysis of this study.

**Study C – Techno-economic modelling of an integrated biomethane-biomethanol production process via biomass gasification, electrolysis, biomethanation and catalytic methanol synthesis (Menin et al., 2023)**

This study aimed to carry out techno-economic modelling of two processes – the first being standalone biomethanation of syngas obtained from biomass gasification and the second being an integrated biomethane-biomethanol process to recover energy and synthesis methanol via $CO_2$ hydrogenation. For the purpose of this thesis the first process of standalone biomethanation (with biomass gasification) was analyzed since this matched the aims of the HYFUELUP project. *Figure 19* shows the process flow of the technology used in this study. Their system utilized a dual fluidized bed steam gasifier, biomass dryer, syngas cooler, and particles + moisture removal system. The biomass feedstock used were wet wood pellets in a 32 MW gasification plant. *Appendix 3* shows a detailed list of the installation costs and equipment used for the techno-economic analysis of this study.

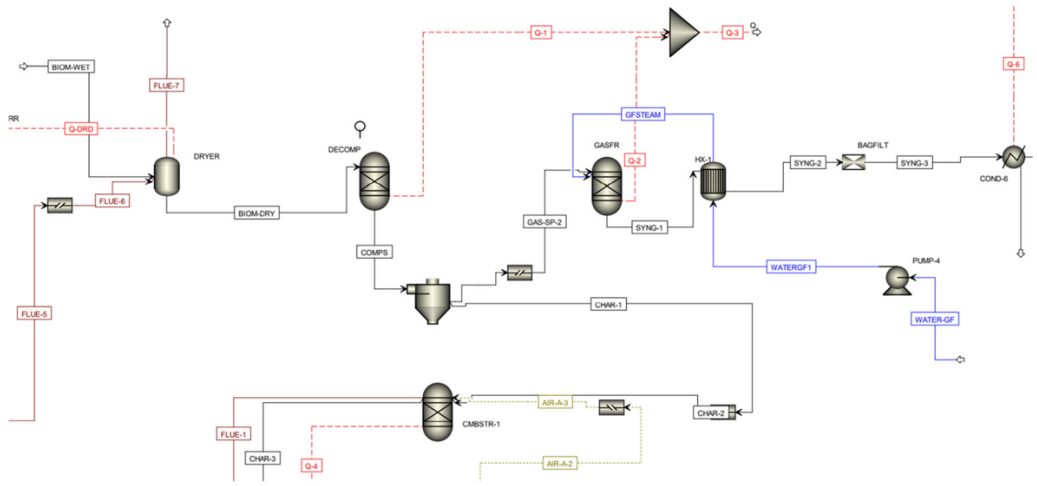



*Figure 19 – Study C: Technology process pathway taken from (Menin et al., 2023)*

In this thesis the costs taken for comparison were total capital expenditure (CAPEX), total operating expenditure (OPEX), gasification and methanation costs. These were selected as it could act as a summary of what costs could be involved in the HYFUELUP project. Knowing the specific costs of gasification and methanation are important since these technologies will be utilized in HYFUELUP.

*Table 7* shows the total CAPEX, gasification and methanation costs per € / MW. Since study B and C were conducted at 20 MW and 32 MW respectively, these costs were converted to 1 MW for comparison with the respective costs shown in *table 7*.

*Table 7 – Total Capex, Gasification and Methanation costs per € / MW for Study A, B and C*

| | Techno-Economic Analysis: € / MW | | |
|---|---|---|---|
| | **Total CAPEX** | **Gasification** | **Methanation** |
| **Study A** | 3,870,973 | 608,117 | 954,690 |
| **Study B** | 1,039,100.03 | 128,535 | 86,496.15 |
| **Study C** | 1,588,437.50 | 366,562.50 | 177,187.50 |

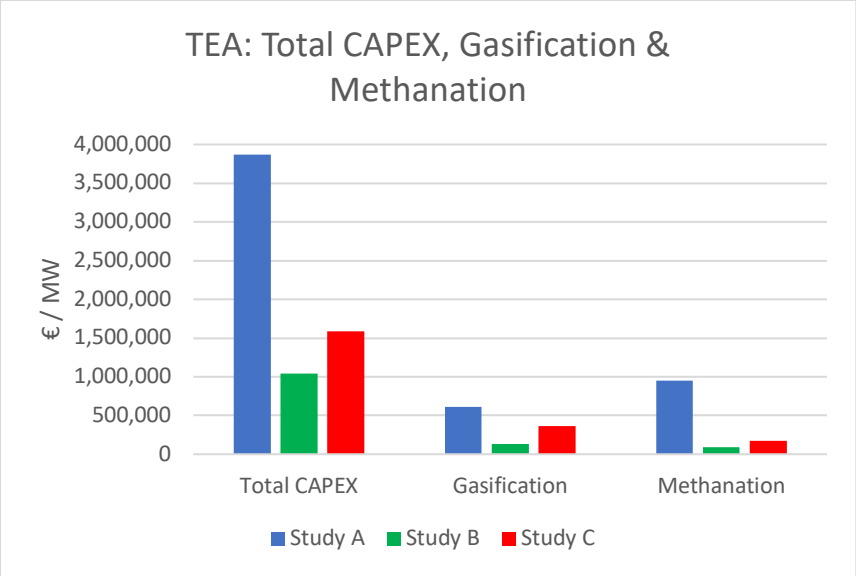



*Figure 20 - TEA: Total CAPEX, Gasification & Methanation for Study A, B and C*

From *figure 20* it is evident that study A has the highest overall costs where CAPEX is the highest difference between study B and C at around 3.8 million euros. This is compared with study B and C which has a CAPEX of around half of that at around 1.5 million euros. One possible reason why the CAPEX of study A was this high, could be because the cost of electrolysis. Electrolysis was around 1.6 million euros almost half of the total CAPEX value which can be one reason why the total CAPEX was this high for study A. Study A used a polymer electrolyte membrane (PEM) type of electrolyzer, where it was assumed that the electrolysis process was supplied with wind energy. Study C also used electrolysis; however, they utilized an alkaline electrolysis technique which has been seen to be cheaper compared with PEM in the literature (Guo et al., 2019). Study B did not use electrolysis in their technology which could be one reason why it has the lowest total CAPEX compared to study A and C.

Looking at the gasification and methanation costs, it is evident that all three studies had fairly similar costs for each technology where study A was slightly higher than study B and C again. Gasification and methanation were also similar in costs suggesting that the average investment costs for these technologies would be similar. When the average costs and standard deviations were calculated and

plotted for the three studies for total CAPEX, gasification and methanation as shown in *figure 21* there is an interesting result.

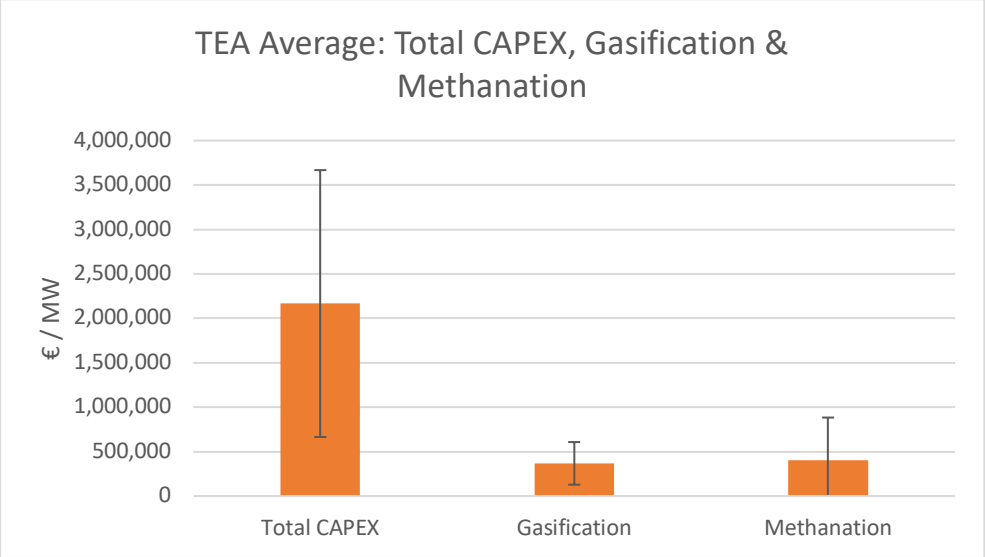



*Figure 21 - TEA: Average Total CAPEX, Gasification & Methanation for Study A, B and C*

The methanation costs have a large standard deviation resulting from the big difference in costs between study A and B as seen in the error bar in *figure 21*. A reason for this deviation in results could come from study B's methanation cost not considering the pre-methanation cost as well. Study B separated it's methanation costs into pre-methanation and methanation. Whereby pre-methanation involves gas cleaning steps such as removal of hydrogen sulfides and carbon dioxide, and methanation involves syngas conversion into biomethane. Hence, if we take into account the pre-methanation costs in the final methanation cost this will bring an extra 22,400 euros bringing up the total methanation cost for study B to around 109,000 euros which is closer to the cost of methanation seen in study C.

*Table 8* shows the total OPEX per € / year. Since study B and C were conducted at 20 MW and 32 MW respectively, these costs were **converted to 1 MW for comparison** with the respective costs shown in *table 8* and *figure 22.*

*Table 8 - TEA: Total OPEX for Study A, B, C and Average*

| **Techno-Economic Analysis: Total OPEX € / Year** | |
|---|---|
| | **Total OPEX** |
| **Study A** | 844,646 |
| **Study B** | 1,460,500 |
| **Study C** | 506,250 |
| **Average** | 937,132 |

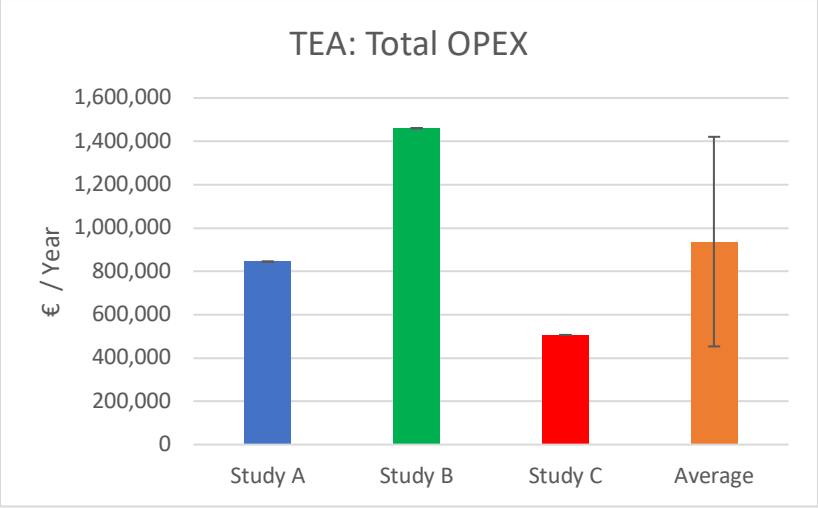



*Figure 22 - TEA: Total OPEX for Study A, B, C and Average*

It is evident that the total OPEX for study B in this case was highest at around 1.4 million euros compared with study A and C at around 500,000-800,000 euros. One explanation why study B's OPEX is very high, comes from the high personnel cost. The personnel (labor) cost for study B was around 789,000 euros compared with 72,000 euros for study A. However study A (1 MW) employed 2 people whereas study B (20 MW) employed 28 people (Thunman et al., 2019). Study C didn't have an explicit breakdown of its OPEX costs, although it did mention that 1% of the OPEX calculated came from labor costs. Another reason for the OPEX costs not following an upwards trend can come from the explanation made that 1% of OPEX comes from labor costs in study C (32 MW). If we assume that study C employs more people than study B due to a bigger plant size this could follow an upwards trend in OPEX.

Another way to observe a correlation between costs of the three studies can be shown via bar-graphs seen in *figure 23* and *figure 24*. Where the X-axis is represented by the biomethane produced in its respective units i.e., 1 MW, 20 MW and 32 MW for study A, B and C respectively. This way we can see if there are any correlations within the costs and size of the biomethane plants.
It is evident that all graphs from *figure 23* and *24* except for the total OPEX follows an upwards trend in costs as the biomethane produced per MW increases. If we assume that study C (32MW) employed more people than study B and the labor costs are the same, this could cause an upwards trend as seen by the other graphs.

The purpose of the biomethane produced from all three studies was to use the biomethane produced to inject it into the natural gas grid. Hence it is evident that all three studies have the same final outcome which makes it comparable.

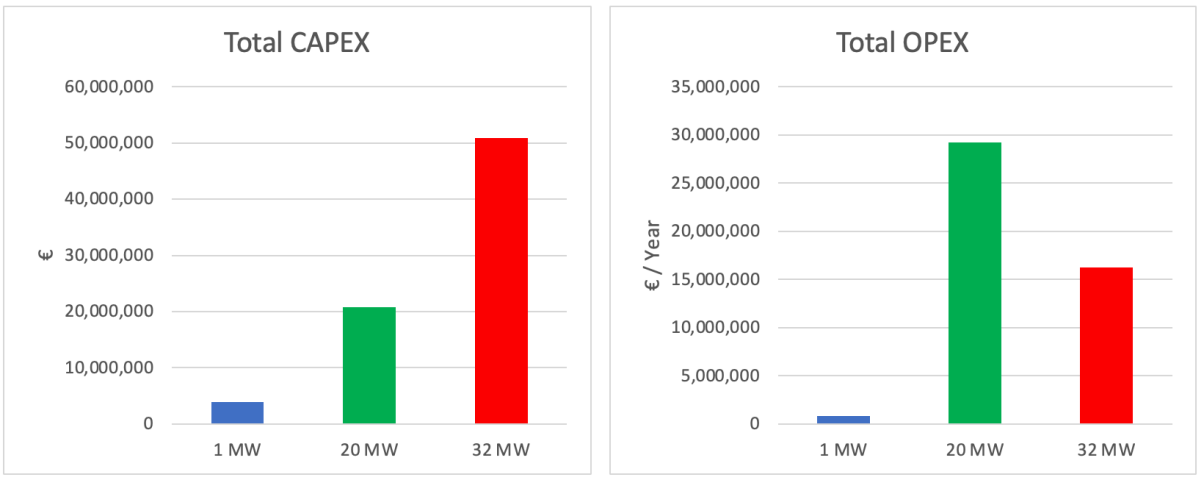



*Figure 23 - Total CAPEX & OPEX at 1 MW (Study A), 20 MW (Study B) and 32 MW (Study C)*

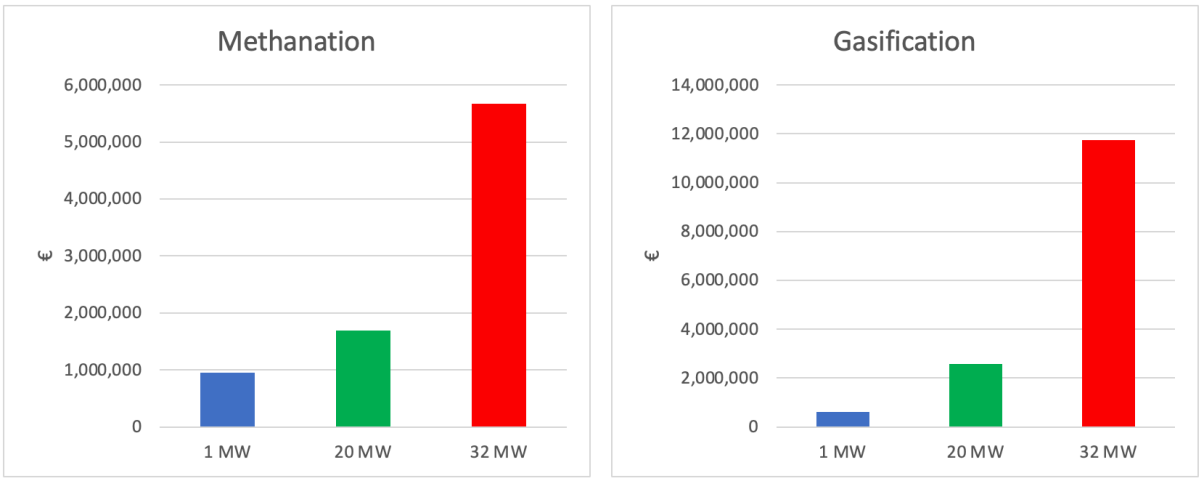



*Figure 24 – Methanation & gasification costs at 1 MW (Study A), 20 MW (Study B) and 32 MW (Study C)*

Another important factor to consider is the price of biomethane and total revenue gained from the project. *Table 9* shows the price of biomethane, and revenue generated from study A, B and C.

*Table 9 - Price of Biomethane & Revenue from Study A, B and C*

| | **Price of Biomethane, €/MWh** | **Revenue, €/year** |
|---|---|---|
| **Study A** | 92.86 | 38,704 |
| **Study B** | 51.64 | No Data Available |
| **Study C** | 0.00022 | 3,875,977 |

It is evident that study A has the highest price of biomethane at around 90 euros per MWh compared with study B and C with 51.64 and 0.00022 euros per MWh respectively. Looking at the revenue data it is evident that study C had a much bigger revenue at around 3.9 million euros compared with study A which only had a revenue of around 38,000 euros per year. This high revenue data from study C thus suggests a much lower selling price of biomethane since it has a higher revenue than compared

with study A. This low selling price of biomethane from study A is made possible due to the high revenue earned from district heat exports (Menin et al., 2023).

### *Life Cycle Assessment*

For the life-cycle assessment, data from study A and two new studies (D and E) were analyzed and compared. Each study contained different life-cycle impact categories that they measured for their respective technology, but all three studies included three main impact categories which will be examined here: global warming potential (GWP – kg $CO_2$ eq), acidification potential (AP – kg $SO_2$ eq) and photochemical ozone formation potential (POFP – kg $C_2H_4$ eq).

**Study D – Life Cycle Assessment and Economic Analysis of Biomass Energy Technology in China: A Brief Review (S. Chen et al., 2020)**

Study D compared five different biomass energy technologies, however the one focused in this thesis will be the biomass gasification power generation technology. They analyzed a 4 MW (functional unit of 1 KW) gasification power plant in China investigating its environmental sustainability and whole life cycle assessment via the LCA method which follows the ISO 14,040 standard.

**Study E – Biomethane from Short Rotation Forestry and Microalgal Open Ponds: System Modelling and Life Cycle Assessment (Tasca et al., 2019)**

Study E compared two different technologies for biomethane production however the one focused here will be the gasification of short rotation forestry (SRF) poplar wood chips. The main processes and activities considered in the life cycle assessment for this technology can be seen in *figure 25* showing the system boundaries of this biomethane production pathway. The functional unit in this study was 1 MJ of energy produced.

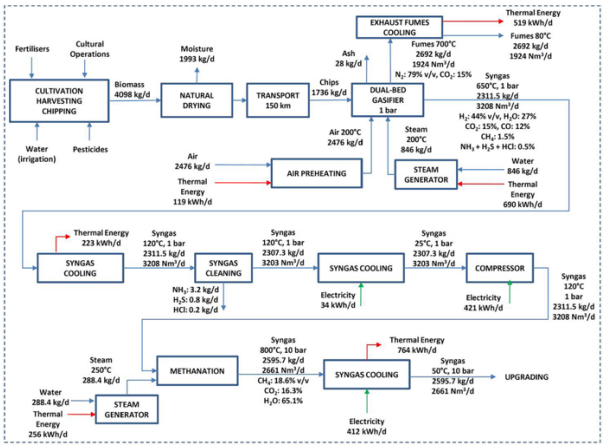



*Figure 25 - System Boundaries for the LCA of SRF biomass gasification*

*Tables 10-12* show the three main impact categories that will be compared in this thesis with their respective values converted and shown per MW. For study E's data since they were in MJ, an online MJ to MW conversion calculator was utilized.

*Table 10 - Study A: LCA data*

| **Impact Category** | **Unit** | **Total (1 MW)** |
|---|---|---|
| Global Warming Potential | kg $CO_2$ eq | 47.12 |
| Acidification Potential | kg $SO_2$ eq | 0.15 |
| Photochemical Ozone Formation Potential | kg $C_2H_4$ eq | 0.0077 |

*Table 11 - Study D: LCA data*

| **Impact Category** | **Unit** | **Total (1 KW)** | **Total (1 MW)** |
|---|---|---|---|
| Global Warming Potential | kg $CO_2$ eq | 0.0839 | 0.0000839 |
| Acidification Potential | kg $SO_2$ eq | 0.000336 | 0.000000336 |
| Photochemical Ozone Formation Potential | kg $C_2H_4$ eq | 0.000018 | 0.000000018 |

*Table 12 - Study E: LCA data*

| **Impact Category** | **Unit** | **Total (1 MJ)** | **Total (1 MW)** |
|---|---|---|---|
| Global Warming Potential | kg $CO_2$ eq | 0.124 | 0.0000344 |
| Acidification Potential | kg $SO_2$ eq | 0.0007 | 0.000000194 |
| Photochemical Ozone Formation Potential | kg $C_2H_4$ eq | 0.00021 | 0.0000000583 |

Since the data from these three studies are extremely broad in range, it is necessary to apply a normalization factor to the data in order to make the data "dimensionless" hence allowing for a more accurate comparison. For this we need to identify the LCA methods used in each of the studies. Study A used a combination of the Intergovernmental Panel on Climate Change (IPCC) and CML methods, study D used the IPCC method and study E used the ReCiPe method. Since all three studies used different LCA methods a global normalization factor (*Table 13)* was taken from the study: (Sleeswijk et al., 2008). This normalization factor offers a reference situation of the pressure on the environment for each environmental impact category, hence making it easier to translate abstract impact scores into relative contributions of the product to a reference (Sleeswijk et al., 2008).

*Table 13 - Global Normalisation Factors for GWP, AP and POFP from (Sleeswijk et al., 2008)*

| **Impact Category** | **Unit** | **Normalization Factor** |
|---|---|---|
| Global Warming Potential (GWP) | kg $CO_2$ eq | 5.76E+13 |
| Acidification Potential (AP) | kg $SO_2$ eq | 3.01E+11 |
| Photochemical Ozone Formation Potential (POFP) | kg $C_2H_4$ eq | 3.51E+11 |

To get the normalized value for each impact category of each study (as seen in *tables 14-16)*, the total values were divided by their respective normalization factor. Then once the normalized value was calculated for each impact category, the sum of all the normalized values for the study was taken and used to plot on *figure 26* via a logarithmic scale to be able to view the results on a graph.

*Table 14 - Study A: Normalisation LCA Value*

| **Impact Category** | **Total (1 MW)** | **Normalized Value** |
|---|---|---|
| Global Warming Potential (kg $CO_2$ eq) | 47.12 | 8.18E-13 |
| Acidification Potential (kg $SO_2$ eq) | 0.15 | 4.98E-13 |
| Photochemical Ozone Formation Potential (kg $C_2H_4$ eq) | 0.0077 | 2.19E-14 |
| **Total** | | **1.34E-12** |

*Table 15 - Study D: Normalisation LCA Value*

| **Impact Category** | **Total (1 MW)** | **Normalized Value** |
|---|---|---|
| Global Warming Potential (kg $CO_2$ eq) | 0.0000839 | 1.46E-18 |
| Acidification Potential (kg $SO_2$ eq) | 0.000000336 | 1.12E-18 |
| Photochemical Ozone Formation Potential (kg $C_2H_4$ eq) | 0.000000018 | 5.13E-20 |
| **Total** | | **2.62E-18** |

*Table 16 - Study E: Normalisation LCA Value*

| **Impact Category** | **Total (1 MW)** | **Normalized Value** |
|---|---|---|
| Global Warming Potential (kg $CO_2$ eq) | 0.0000344 | 5.98E-19 |
| Acidification Potential (kg $SO_2$ eq) | 0.000000194 | 6.46E-19 |
| Photochemical Ozone Formation Potential (kg $C_2H_4$ eq) | 0.0000000583 | 1.66E-19 |
| **Total** | | **1.41E-18** |

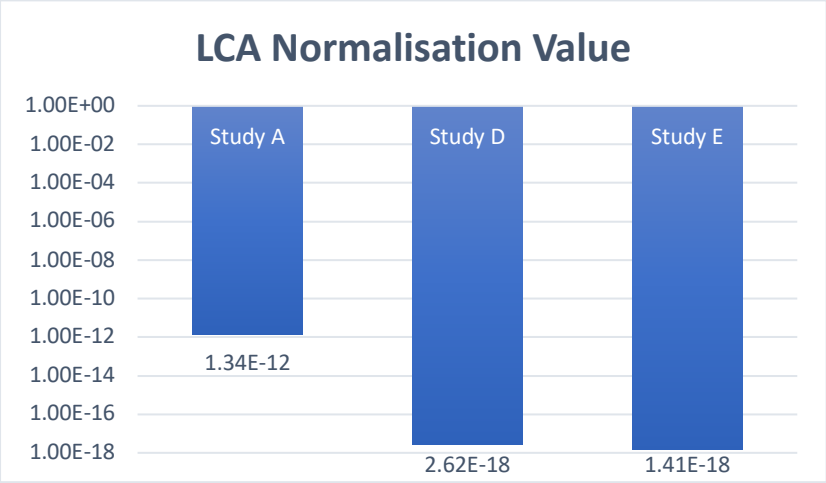



*Figure 26 - LCA Normalisation Graph of Study A, D and E*

From the above tables and figure, it is evident that study A has the highest impact compared to study D and E, where study D and E have very similar results. As we can see from *figure 17* – the system boundaries set for the LCA analysis study A includes all of the major steps for the production of biomethane. This includes gasification, gas cleaning, shift reactor, methanation, RNG compression and injection to the grid, and importantly hydrogen generation via electrolysis. If we look at the system boundaries for study D, they considered the operation stages of raw material production, raw material processing, raw material transportation and power generation (gasification). Study E's system boundaries includes biomass cultivation, transport, gasification, steam generation, syngas cooling and cleaning, compression, and methanation as shown in *figure 25.*

From the above results we can see that study A has the highest LCA impacts including higher GWP, AP and POFP. One reason for this can be due to the fact that study A involved more technological steps within the system boundary, compared to study D and E which could have caused a higher total LCA impact. For example, study A included the use of hydrogen production via electrolysis within their LCA calculations, whereas study D and E did not mention this.
From these system boundaries it is evident that study A includes most of the steps and factors that HYFUELUP will also consider when producing biomethane. So, study A could be a better representation of what the LCA impact could look like for the HYFUELUP project.

Looking at the direct emissions from *table 17-19,* it is evident that the direct emissions of $CO_2$ from study A is in fact the lowest, hence suggesting that the technology and pathway used for biomethane production in study A is in fact effective at maintaining low carbon dioxide levels to the atmosphere.

*Table 17 - Study A: Emissions data (Skorek-Osikowska et al., 2020)*

| **Emissions to the environment - emissions to the air** | |
|---|---|
| **Emission** | **kg/MWh** |
| Biogenic $CO_2$ | 0.00872 |
| $N_2$ | 6.63 |

*Table 18 - Study D: Emissions data (S. Chen et al., 2020)*

| **Emission data of the significant pollutants of biomass gasification** | |
|---|---|
| **Emission** | **kg/MWh** |
| $CO_2$ | 0.000047 |
| CO | 8.3e-8 |
| $CH_4$ | 4.71e-8 |
| $NO_x$ | 1.11e-7 |
| PM | 3.37e-7 |
| $SO_2$ | 2.58e-7 |

*Table 19 - Study E: Emissions data (Tasca et al., 2019)*

| Direct field emissions from the cultivation of biomass (poplar) | |
|---|---|
| **Emission** | **kg ha $d^{-1}$** |
| $CO_2$ | 0.29923 |
| $NH_3$ | 0.04437 |
| $N_2O$ | 0.00279 |
| $NO_x$ | 0.00059 |

Study A is interesting to take a deeper look into, since it is the closest in terms of similarity to the HYFUELUP project. In order to give some insight on the environmental suitability of this biomethane production pathway from a life-cycle view shown in study A, a preliminary comparison of the carbon footprint was conducted from the 1 MW of biomethane produced compared to that of natural gas. This reference (fossil) case was based on heat provided via combustion of natural gas from the Spanish grid in an industrial boiler with low $NO_x$ emissions (Skorek-Osikowska et al., 2020). *Figure 27* shows the differences in carbon footprint (kg $CO_2$ eq) between the two different scenarios.

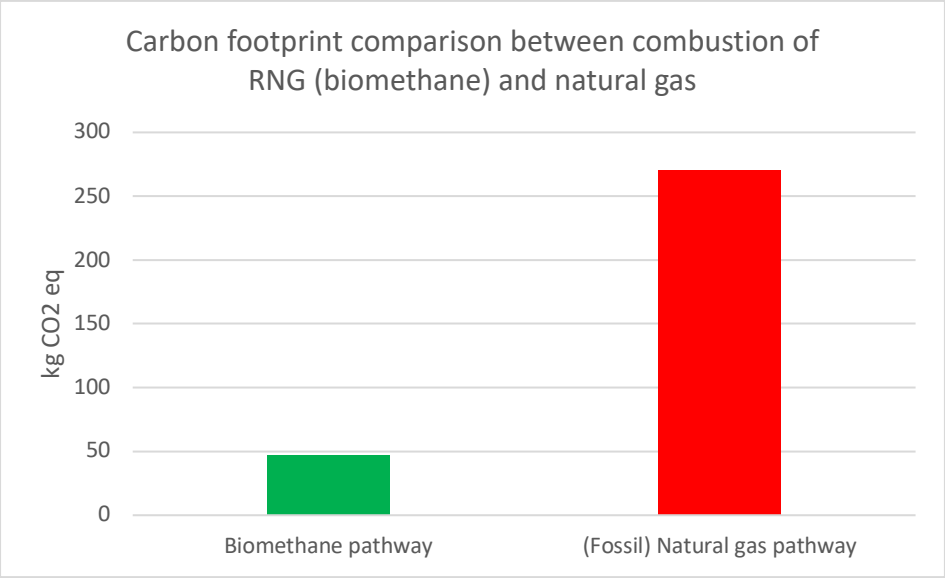



*Figure 27 - Carbon footprint comparison of biomethane combustion from study A and natural gas*

From this figure it is evident that there is an almost 90% carbon reduction when study A's technology of biomethane production was used in comparison the fossil-natural gas pathway.

*HYFUELUP preliminary block-diagram and life-cycle inventory*

Taken from the HYFUELUP website (HYFUELUP, 2022), *figure 28* shows a preliminary block diagram of the process which will be implemented.

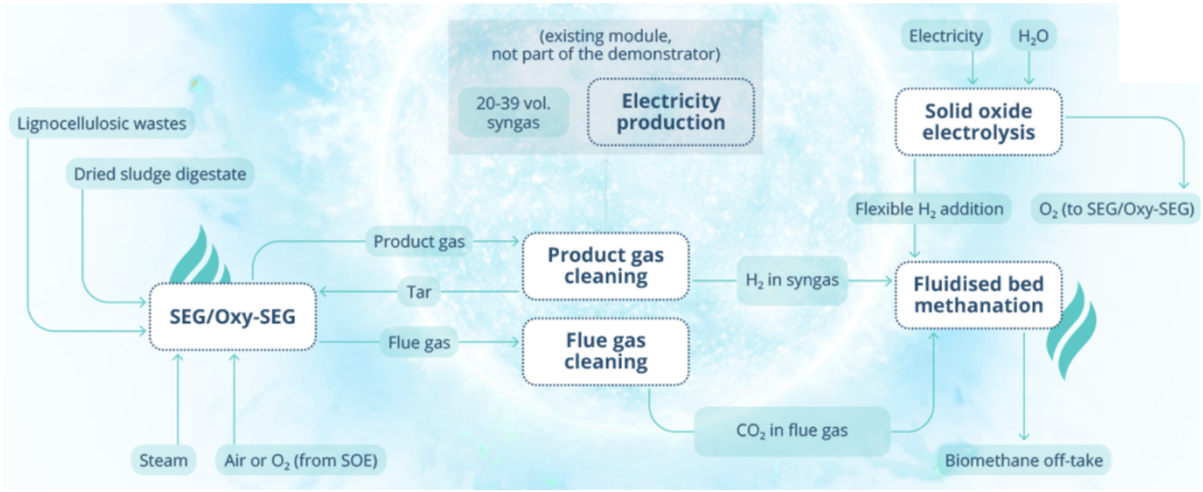



*Figure 28 - HYFUELUP Block diagram of the process (HYFUELUP, 2022)*

A potential life-cycle inventory showing the inputs and outputs of the HYFUELUP process can be seen in *table 20.*

*Table 20 - Preliminary life-cycle inventory for HYFUELUP process*

| **Inputs** | **Outputs** |
|---|---|
| Biomass<br>- Lignocellulosic Waste<br>- Dried Sludge Digestate | (Biogenic) $CO_2$ |
| Electricity | CO |
| Water | $BioCH_4$ |
| Steam (water) | $CH_4$ |
| Limestone ($CaCO_3$) | Heat |
| Heat | $O_2$ |
| | $N_2$ |

From *figure 28* it is evident that lignocellulosic wastes and dried sludge digestates will be the biomass of choice for the HYFUELUP project which will be used for the gasification process. This gasification process will either be SEG or a variant of this - oxy-SEG. Steam and air from solid-oxide electrolysis will be inputs for the gasification process which will then produce a product (syngas) gas and flue gas. In order for these gasses to be of use, it will have to undergo a cleaning process which can be via tar reforming and high-temperature sulphur removal via sorbents or catalysts (HYFUELUP, 2022). This gas cleaning system can be composed of cyclones or filters to retain any

solid particles. Once these gases have undergone the cleaning phase, the hydrogen from the syngas and carbon dioxide from the flue gas will be inputs for fluidized bed methanation. Solid oxide electrolysis (SOE) will also be an important technology used in HYFUELUP as it will act as a source for the renewable hydrogen supply for methanation. Hence electricity and water will be needed to supply the SOE system. Whereby the additional oxygen produced from this process can be used for the SEG/Oxy-SEG system as well. Thus, once fluidized bed methanation occurs this will finally produce the biomethane, which can be further purified and liquified to ultimately produce liquid biomethane for applications in the CNG vehicular market. This liquefaction process will involve the removal of any non-methane components such as hydrogen, carbon dioxide, water, and other contaminants evident in the biomethane. It is evident from *table 20* that this is just a general idea of some of the inputs and outputs that can be observed with the HYFUELUP process and will require further investigations once experimental work has begun.

*HYFUELUP preliminary techno-economic costs*

Since no experimental work has been done on the HYFUELUP project currently, *table 21* and *22* shows some of the equipment needed for CAPEX calculations and OPEX which we can assume will be likely to be present for the HYFUELUP project. The estimated costs were taken from study A (Skorek-Osikowska et al., 2020) and some of the equipment taken from study B and C.

*Table 21 - CAPEX Estimates for HYFUELUP Project*

| **Capital Expenditure (CAPEX)** | **Estimated Costs (€) based on 1 MW biomethane production** |
|---|---|
| **Biomass sorption-enhanced gasification**<br>- Reactors & Refractory<br>- Condensate treatment & steam generation<br>- Biomass storage and preparation | 600,000 |
| **Biogas Cleaning**<br>- Product gas cooler<br>- Product gas filter<br>- Bed material storage & feed<br>- Product gas scrubber<br>- Product gas fan & cooler<br>- Analyzers | 120,000 |
| **Solid oxide electrolysis**<br>- Electrolyzer | 1,600,000 |

| | |
|---|---|
| **Fluidized bed methanation**<br>- Bioreactor | 900,000 |
| **Biomethane compression** | 42,000 |
| **Secondary Equipment**<br>- Compressors<br>- Pumps<br>- Heat exchangers<br>- Refrigeration systems | 140,000 |

*Table 22 - OPEX cost possibilities for HYFUELUP*

| **Operating Cost (OPEX)** | **Unit** |
|---|---|
| **Biomass**<br>- Lignocellulosic wastes<br>- Dried sludge digestate | € / t dry |
| **Labor** | € / man-hour |
| **Electricity** | € / MWh |
| **Water** | € / $m^3$ |
| **Catalyst** | € / $m^3$ |
| **Repairs & Maintenance** | € |
| **Insurance** | € |
| **Property Tax** | € |
| **Utilities** | € |
| **Chemicals & Consumables** | € |
| **Administrative & Overhead Expenses** | € |

From the above tables it is evident that these are some of the main cost considerations HYFUELUP will have to consider when a complete TEA will be done.

# Conclusion & Future Perspectives

In conclusion, the HYFUELUP project aims to demonstrate an innovative pathway for biomethane production based on the integration of sorption-enhanced gasification, fluidized bed methanation and electrolysis (HYFUELUP, 2022). Where this biomethane produced will be liquefied and used for decarbonizing long-distance road-freight and maritime transportation. As discussed previously, the HYFUELUP project was developed at the end of 2022 hence is in its early stages of development still. Thus, this thesis aimed to provide a background of the literature available on biomethane production processes and gasification technologies. Highlighting the importance of moving away from the conventional anaerobic digestion method and transitioning to gasification technologies. Moreover, shedding light on the specific technologies that HYFUELUP will use in their experiments such as sorption-enhanced gasification and fluidized bed methanation.
The National Laboratory of Energy & Geology (LNEG) in Lisbon, Portugal where this master thesis was completed, is specifically tasked with the development of a detailed life-cycle assessment (LCA) and techno-economic analysis (TEA) to assess the viability of the HYFUELUP project implementation. Hence the aim of this thesis was also to identify LCA's, and TEA's data found in the literature that have used similar technologies as HYFUELUP for the production of biomethane. From the collected LCA and TEA data, this will hopefully be helpful to LNEG and the HYFUELUP team when they will start collecting data for their analyses. Hopefully this data will be used to compare to HYFUELUP's data.

It is evident that biogas such as biomethane is a sustainable energy alternative which can have positive impacts on society. Biomethane allows contributions to energy security which enables local production and trading within Europe, thus reducing the dependance on external providers. The application of biomethane in the transport sector can substantially decrease emissions helping contribute to decarbonization efforts. The use of sustainable biomass such as dried digestate sludge from anaerobic digestion, lignocellulosic wastes or intermediate catch crops are all viable biomass options for gasification. Anaerobic digestion is currently the most prevalent biomethane production technology, however in the coming years gasification will be increasingly prevalent where there will be a growing market potential for this technology. By utilizing sorption-enhanced gasification for example, HYFUELUP will be able to make use of the gasification process while simultaneously removing carbon dioxide. Catalysed fluidized bed methanation is also another important technology used in the biomethane production process where this involves the "upgrading" of syngas and has seen potential in the literature. In order for gasification technologies to be upscaled in the future, more support from the government and companies will be needed for investments into these technologies to a commercial scale.

Looking at the TEA data it is evident that a number of different factors are involved in the CAPEX and OPEX costs and depends on the size of production plant, and technology used. From the three TEA studies investigated here, study A seemed the most comparable to the technology used in the HYFUELUP project as it contained almost all the major components such as biomass gasification, methanation and hydrogen generation via electrolysis. This technology found in study A also showed the highest overall costs such as CAPEX which could be because of the high costs of electrolysis. From the data it was evident that when biomethane production via its respective functional units (e.g., 1 MW, 20 MW and 32 MW) was plotted against CAPEX, OPEX and price of methanation and gasification; we could see an increase in the costs as the functional unit went higher. Moreover, from the data we could also see that the selling price of biomethane in study C was much lower than that of study A and B. Where one reason this could have been attributed was because of the much larger revenue earned from district heat exports found from study C.

Moving onto the LCA data, two different studies (including study A) – study D and E were chosen since study B and C didn't have any LCA data. All three studies – A, D and E had different impact categories they analyzed, however all three had data on the global warming potential, acidification potential and photochemical ozone formation potential. All of these had to be converted to 1 MW and since the studies used different LCA methodology a global normalization factor was applied to the data in order to make the data dimensionless and comparable. It was evident that study D and E had very similar life-cycle emissions where study A showed a greater life-cycle impact. This can be due to the reasons for a larger system boundary set for study A which included all the major biomethane production steps. And when the direction emissions were analyzed, it was evident that study A had low biogenic $CO_2$ emissions to the air, study D showed the emissions data (converted to MWh) from biomass gasification and study E showed the direct emissions from cultivation of the biomass. Study E's emissions can occur via land preparation, planting, harvesting and the use of fertilisers and pesticides. Study D's emissions are specific towards the gasification process whereas study A's emissions are related to the whole process in general. Study A also compared their process to that of a fossil – natural gas pathway where they saw clear reductions in carbon footprint in their biomethane pathway which was successful.

Finally looking at the HYFUELUP project specifically, since there is no experimental data yet available for this project due to its early stage; a block diagram of the process was created by the HYFUELUP team to show what factors would be considered. This includes the use of sorption-enhanced gasification (SEG) via sustainable feedstocks such as lignocellulosic wastes or dried sludge digestate. This gas then undergoes a gas cleaning stage followed by fluidized bed methanation, where hydrogen production from electrolysis will be supplied to this process thus production biomethane. Moreover, a preliminary life cycle inventory could be created based on the studies found in the

literature. The inputs could include biomass, electricity, water, steam, limestone, and heat. And the outputs could include (biogenic) $CO_2$, CO, $BioCH_4$, $CH_4$, Heat, $O_2$, and $N_2$. With this considered, a preliminary techno-economic costs for CAPEX and OPEX can also be estimated based on the research found in the literature. Some of the CAPEX includes biomass SEG, biogas cleaning, solid oxide electrolysis, fluidized bed methanation, biomethane compression and some secondary equipment. Where it is evident that electrolysis has been seen to have the highest costs in the literature. Some of the OPEX includes biomass, labor, electricity, water, catalyst, repairs and maintenance, insurance, property tax, utilities, chemicals & consumables, and administrative & overhead expenses.

The use of biomethane has great potential however some future perspectives should be taken into consideration for biomethane to be more feasible. Future efforts to scale up on gasification technologies such as SEG, should be focused as these technologies are normally in pilot-scale and less widely used in commercial-scale facilities. Hence, governments and companies should invest and develop greater supportive policies and regulations to incentivize the use of these technologies. In order for advancements in the future, continued research and development will be crucial for technological advances, improvements in efficiency, reducing costs, and enhancing performance overall. These advancements can have significant positive impacts on biomethane yields, energy efficiency and reduced environmental impacts. The results from these future techno-economic and life-cycle assessment studies should inform on policy decisions whereby supporting the development of favorable incentives and subsidies to guide investments into the biomethane sector. As the biomethane market grows in the future, market development and infrastructure is necessary to promote the widespread adoption of biomethane within the transport sectors. For example, governments should incentivize biomethane in vehicles via regulations and policies, the building of biomethane refueling stations – thus making way for job creation and standardizing biomethane quality and certification processes.

By considering these findings from this thesis and the work that HYFUELUP is currently doing, biomethane has potential in contributing significantly to energy security, emission reduction, and the goal of sustainable transportation.

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# Appendix

**Appendix 1 – CAPEX and OPEX costs for Study A (Skorek-Osikowska et al., 2020)**

| **Investment costs (CAPEX)** | |
|---|---|
| | |
| **Installation** | **Cost €** |
| Biomass gasification | 608117 |
| Biogas cleaning | 119001 |
| Electrolysis | 1662555 |
| Shift reactor | 76754 |
| Methanation | 954690 |
| RNG Compression | 41849 |
| Injection to the grid | 84110 |
| Other unlisted | 323895 |
| **Total CAPEX** | **3,870,973** |
| | |
| **Operational Costs (OPEX)** | |
| | |
| **Variable Costs** | **€/year** |
| Biomass | 132593 |
| Non-fuel | 1540 |
| Electricity | 486375 |
| **Fixed Costs** | **€/year** |
| Repairs + Maintenance | 36008 |
| Personnel | 72,000 |
| Insurance | 77419 |
| Property Tax | 38710 |
| **Total** | **844,646** |

**Appendix 2 - CAPEX and OPEX costs for Study B (Thunman et al., 2019)**

| **Investment costs for all process sections of the GoBiGas plant at 20 MW** | | | |
|---|---|---|---|
| **Process Systems** | | **Reference Cost (20 MW Plant) - $kSEK** | **kEURO (€)** |
| Fuel Handling System | External fuel feeding system<br>Internal fuel feeding system, including lock hoppers | 50400 | 4393.47 |
| Gasification & Combustion | Reactors & Refractory<br>Condensate treatment & Steam generation | 29490 | 2570.7 |
| Primary product gas cleaning | Product gas cooler<br>Product gas filter<br>Bed material storage & feed<br>Product gas scrubber<br>Product gas fan & secondary cooler<br>Analaysers | 23780 | 2072.95 |
| Flue gas system | Flue gas cooler<br>Flue gas filter & flue gas fan<br>Ash handling system | 18930 | 1650.17 |
| Tar adsorption (AC filter) | Activated carbon beds<br>Regeneration system | 10620 | 925.77 |
| Compressor | | 34590 | 3015.28 |
| Olefin hydrogenation | | 9060 | 789.78 |
| H2S scubber | | 9150 | 797.62 |
| Water-Gas Shift reaction | | 5290 | 461.14 |
| Premethanation | | 5150 | 448.94 |
| CO2 scrubber | | 17570 | 1531.61 |
| Methanation | | 19410 | 1692.01 |
| Drying & Odorization | | 4970 | 433.24 |
| TOTAL COST, PROCESS SYSTEMS | | **238410** | **20782.68** |
| | | | |
| Total auxiliary equipment and project costs | | 955056 | 83254.13 |
| | | | |
| GRAND TOTAL | | 1193466 | 104036.81 |
| | | | |

| | | | |
|---|---|---|---|
| **Aggregated costs - predicted costs for 20 MW reference plant** | | | |
| | | | |
| | Cost | Estimated capital cost (MSEK) | Estimated capital cost (MEUR) |
| | *Initial investment cost* | | |
| | Reactor systems | 238 | 20.75 |
| | Auxillary equiptment & project costs | 955 | 83.25 |
| | Steam cycle, external fuel handling & drying | 182 | 15.87 |
| | **Total** | **1375** | **119.86** |
| | *Operating costs (excluding feedstock)* | | |
| | Personnel | 181 | 15.78 |
| | Maintenance | 89 | 7.76 |
| | Consumables and waste products | 55.1 | 4.8 |
| | Activated carbon/BTX removal | 10 | 0.87 |
| | | | |
| | **Total** | **335.1** | **29.21** |

**Appendix 3 - CAPEX and OPEX costs for Study C (Menin et al., 2023)**

| Process System | | S0 | S | Unit | C0 (M€) | C (M€) |
|---|---|---|---|---|---|---|
| | Gasifier | 32 | 33.3 | MWth | 11 | 11.36 |
| | Biomass storage, preparation, feeding to atmospheric pressure | 64.6 | 7.09 | twet/h | 1.83 | 0.37 |
| **Gasification** | Air drier | 0 | 16.42 | 0 | 0 | 0 |
| | Fabric filter | 15.6 | 4.85 | m3/s | 0.06 | 0.03 |
| | Water scrubber | 12.1 | 0.02 | m3/s | 2.7 | 0.03 |
| | Water stripper | 24123 | 380.21 | kmol/h | 3.6 | 0.22 |
| | Methanol scrubber | 6021.1 | 215.95 | kmol/h | 8.81 | 1.2 |
| | CO2 desorption | 6021.1 | 215.95 | kmol/h | 2.1 | 0.29 |
| **Cleaning section** | Methanol regeneration column | 6021.1 | 215.95 | kmol/h | 1.08 | 0.13 |
| | Bioreactor | 5 | 15.68 | MW LHV | 2.46 | 4.89 |
| **Biomethanation** | PSA (pressure swing adsorption) | 1 | 1582.42 | Nm3/h | 0 | 0.78 |
| **Biomethanol synthesis & purification** | Catalytic reactor | 5000 | 226.38 | t/d | 61.6 | 7.74 |
| | Distillation system | 5292 | 226.38 | t/d | 14.4 | 1.74 |
| **Steam cycle - energy recovery** | Combustor | 20 | 7.84 | MW LHV | 1.97 | 0.91 |
| | Turbine cycle | 25 | 1.28 | MW output | 8.47 | 1.06 |
| **Electrolysis** | Electrolyser | 1 | 24.47 | MWinstalled | 0.64 | 15.66 |
| | Compressors | 413 | 2932.16 | kWinput | 0.49 | 1.86 |
| | Pumps | 10 | 0.03 | m3/s | 0.1 | 0.01 |
| | Heat exchangers | 1000 | 2596.24 | m2 | 0.26 | 0.68 |
| **Secondary equipment** | Refrigeration system | 500 | 1149.28 | kWinput | 1.06 | 1.87 |
| | | | | | **Total** | 50.83 |

**Summary of main direct operating cost items**

| Item | Cost (€) | Unit |
|---|---|---|
| Labour | 24 | man-hour |
| Biomass | 100 | t dry |
| Electricity | 90 | MWh |
| Power-to-gas electricity | 35 | MWh |
| Water | 2 | m3 |
| Catalyst | 56.8 | m3 MeOH output |
| Wastewater management | 2.5 | m3 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | **OPEX** | | | | | | |
| M€ | | M€/year | | | | | | |
| PEC (purchased equiptment cost) | TCI (total capital investment) | D-OPEX (direct yearly operating cost) | T-OPEX (total yearly operating cost) | | | | | |
| 32.3 | 125.5 | 9.8 | 16.2 | | | | | |