# REGATEC 2025

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# Conference Proceedings

## 11th International Conference on Renewable Energy Gas Technology

## 20-21 May 2025, Weimar, Germany

Editor: Jörgen Held



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**PREFACE**

The transition to a renewable energy system and Europe´s strong dependency on natural gas provides an excellent opportunity for renewable methane, especially with the need to replace the natural gas which was previously imported from Russia. Other renewable energy gases, such as green LPG, are also attracting increased attention.
The strong focus on electrification and the rapid deployment of intermittent power production (wind and PV) will result in longer and more frequent periods with a very low, or even negative, electricity price. Here, power-to-gas provides an attractive path to store large amounts of excess electricity as e-methane in the existing gas infrastructure, or as other e-fuels.

The European Commission has announced a target of 35 bcm of renewable methane (approx. 350 TWh) per year in 2030 as part of the REPowerEU plan, and the Biomethane Industrial partnership was launched in September 2022 to support the achievement of this target. The number of sites in Europe where biomethane is injected into the gas grid is rapidly increasing and there are several industrial scale power-to-methane projects running and new concepts developed.

**Synergies between different renewable methane conversion routes**
The production of biomethane and bioSNG can provide the carbon source (i.e., carbon dioxide from upgrading) needed in the power-to-gas concept. Syngas fermentation where thermo- and biochemical conversion are combined to reduce the cost of extensive gas cleaning and eliminate the need of expensive catalysts, is another concept under strong development.
There are several other synergies between bio-, thermo- and electrochemical conversion that are waiting to be exploited such as innovative heat integration, better utilization of the feedstock, increased security of methane supply, and cost sharing for the upgrading, distribution, marketing and utilization of renewable methane.

REGATEC has the ambition to bring these three renewable methane sectors together, i.e., biogas, biomass gasification and Power-to-gas, together with, for the first time, renewable LPG, and provide a platform where the latest advances are highlighted.

**Cooperation partners**
REGATEC 2025 is organised in collaboration with the national BioGenGas Innovation Cluster and the Horizon Europe project CarbonNeutralLNG.

Please enjoy two days of exciting oral presentations, the poster session, the exhibition, the Network Plus and the excellent possibility to make new contacts.

Dr. Jörgen Held and Prof. Frank Scholwin

11th International Conference on Renewable Energy Gas Technology, REGATEC 2025
20th-21st of May 2025, Weimar, Germany

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The 11th International Conference on Renewable Energy Gas Technology is organized by Renewable Energy Technology International AB, Sweden and Institute for Biogas, Waste Management & Energy, Germany in collaboration with the national *BioGenGas Innovation Cluster* and the Horizon Europe project *CarbonNeutralLNG*.

RENEWABLE ENERGY TECHNOLOGY INTERNATIONAL AB    Institute for Biogas Waste Management & Energy Prof. Dr.-Ing. Frank Scholwin    Bio Gen Gas    Carbon Neutral LNG

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BIOGAS
BIOMETHANE

# Biogas and biomethane in Thüringen – a regional perspective.

Frank Scholwin[1]

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## 1. Introduction

Biogas is produced decentrally at around 260 locations in Thuringia - so far dominated by local decentralised electricity and heat generation. Due to the expiry of the attractive incentives for renewable electricity from biogas, operators must reorient themselves and develop future concepts for the biogas plant locations.

One of the options for continuing to operate biogas plants is to process the biogas to natural gas quality and feed it into the natural gas grid, which some operators are pursuing despite the difficult market situation for biomethane sales.

## 2. Current biogas and biomethane production in Thuringia

Thuringia has one of the lowest population densities among the German federal states. It is characterised by rural areas and has only a few large industrial locations. The situation is similar in the neighbouring federal states. Bioenergy accounted for around 16 % of the electricity supply in 2020 [1].

Around 260 biogas plants are operated in Thuringia, most of them for local electricity and heat generation. Only 5 biogas plants are operated on the basis of municipal and industrial waste. The 12 biogas upgrading plants in Thuringia to date have a feed-in capacity of approx. 6,500 Nm³ of biomethane/h into the public natural gas grid [2].

The substrates used for biogas production are predominantly agricultural residues and renewable raw materials. With approx. 71 % of the substrate input materials (mass-based), mainly farm manure in the form of cattle and pig slurry, solid manure and chicken manure are used. The potential pig manure (43.5 %) and stable manure (37.8 %) is not yet fully utilised. Maize silage accounts for the majority of renewable raw materials at approx. 70 %. Grass silage, whole crop silage (GPS), cereals and other crops are also used. The land used for the provision of renewable raw materials amounts to approx. 7% of the agricultural land in Thuringia and is comparatively low compared to the national average. [2]

To date, around 80-90% of biomethane has mainly been used in combined heat and power plants to generate electricity and heat. In addition, some of the biomethane is used to provide heat and the approximately 26 CNG fuelling stations in Thuringia are probably operated 100% on biomethane. [2]

## 3. Current developments

The main driver for current developments is the expiry of subsidies for electricity generation from biogas for a large number of biogas plants (up to 1,000 plants per year in the coming years in whole Germany). Future biomethane production with grid feed-in is particularly of relevance for biogas plants with a raw biogas production of 500 m³/h and more, which cannot realise economically attractive marketing of the heat from combined heat and power generation and at the same time have gas grid access in the immediate vicinity. For Thuringia, it is clear that more than 50% of existing biogas plants could have gas grid access, and this is probably also true for the whole of Germany. However, many biogas plants do not reach the required capacity. For this reason, clusters of smaller biogas plants are being formed at many locations, which then combine the biogas via raw biogas pipelines to a centralised, larger biogas processing plant at a location with a gas grid connection.

**4. Biomethane market situation**

Demand for biomethane for all market segments in Germany has stagnated for several months, and market prices have fallen compared to 2024. The demand for biomethane from renewable raw materials continues to be dominated by its use in biomethane CHP plants, the profitability of which is generally secured by fixed EEG feed-in tariffs from 2009-2014. Following two insolvencies of the largest biomethane traders, which had a major impact on this market in particular, there is a great uncertainty in this market. In contrast, demand for biomethane in the heating market is rising continuously. Here, biomethane from all feedstocks is recognised, regardless of whether it comes from residues, excrement or renewable raw materials, as long as the requirements of 70 or 80% greenhouse gas reduction are met. However, the very hesitant German energy transition policy has so far only set very clear targets for the use of renewable heat in new buildings or when installing new heating systems; for old buildings, there will only be clear minimum requirements for renewable heat supply from 2029, which will then lead to a significant increase in demand for renewable gases.

In addition, there is lively interest in the use of biomethane in industry, where the use of biomethane can offset obligations to purchase European $CO_2$ certificates (ETS) and national $CO_2$ certificates.

However, the biomethane market is particularly challenging for the fuel sector, where high prices for biomethane have been achieved in recent years due to the high prices of greenhouse gas reduction quotas (GHG quota). Biomethane with particularly high greenhouse gas reductions from slurry and manure is traded on this market, with prices depending on the achievable GHG quota. This market is currently experiencing the greatest stagnation, combined with a sharp fall in prices.

**5. References**


[1] Thuringian State Office for Statistics (TLS), 2022.

[2] Siegert, G.; Rönsch, C.; Beyer, A.-K.; Scholwin, F.; Clinkscales, A.; Hering, T.; Kurth, K.; Ehrich, M.; Krieg, D.; Thüringer Energie- und GreenTech-Agentur GmbH (ThEGA): Zukunftsfähige Energie-versorgung mit Bioenergie in Gewerbe und Industrie, 20

# Biomethane and Trade in, from and to Germany - Implications on Business Concepts in Light of the Union Database and the Upcoming *Herkunftsnachweisregister* (proof of origin registry)

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## 1. Introduction

The European gas and electricity grids are already regarded and treated as one mass balance system. The transport of certified renewable gases and bioenergy within and beyond geographical Europe requires a traceability of their proofs of sustainability and their origin. This is important to avoid multiple counting on member states' individual climate goals and targeted greenhouse gas emissions.

## 2. Results

For liquid and gaseous fuels, including bioLPG, the Union Database (UDB) is already available - even if not yet fully functional. In this context, the upcoming *Herkunftsnachweisregister* for gas, heat and cold (proof of origin registry, HKNR) and for both an outlook on the current status and implications on business models will be given. Both UDB and HKNR are to be implemented within the execution of the RED III on national level. Specifically, bioLPG or bioPropane would be an option to lower GHG emissions for those biomethane production plants connected to the transmission grid.

## 3. Conclusions

Although the coming up usage of “yet another database” bears bureaucratic burdens for all economic operators along the value chain of biomethane – on the other hand, risks of fraudulent or double accounted biomethane volumes can be avoided. Further, physical and trading of the individual properties of a renewable gas can be harmonised throughout the EU and beyond.

Fachverband Biogas, alongside with other organisations and stakeholders, closely monitors the development and offers trainings and advocating for the most effective implementation of such registries.

## 4. References

[1] Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652. Brussels, 2023. https://eur-lex.europa.eu/eli/dir/2023/2413/oj/eng

# BioLNG in a challengning market.

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## 1. Introduction

For 55 years, Air Liquide Advanced Technologies has applied its skills in cryogenics, its experience of the scientific & industrial domain, its capacities to innovate in the development of low temperature installations, as LNG.

Air Liquide Advanced Technologies delivers well-proven machines and installations derived from Air Liquide Advanced Technologies' long & worldwide experience in low temperature. Our systems are equipped with the latest proven and high-quality technologies in the market (sensors, instrumentation, valves, PLC…)

Our recent references show our competencies and know-how in the LNG field. For example, Air Liquide Advanced Technologies has delivered in the last few years or is presently constructing 200 Turbo Brayton refrigerators for LNG shipping and bioLNG industry.

## 2. Technology description

The cooling and liquefaction of natural gas or bio-$CH_4$ is performed after complete removal of undesirable components in pre-treatment units. It is ensured by a cryogenic system consisting of a Turbo-Brayton refrigerator.

The treated natural gas or bio-CH4 is cooled down and then condensed in a plate-fin heat exchanger. The LNG produced is then sent to a cryogenic storage.

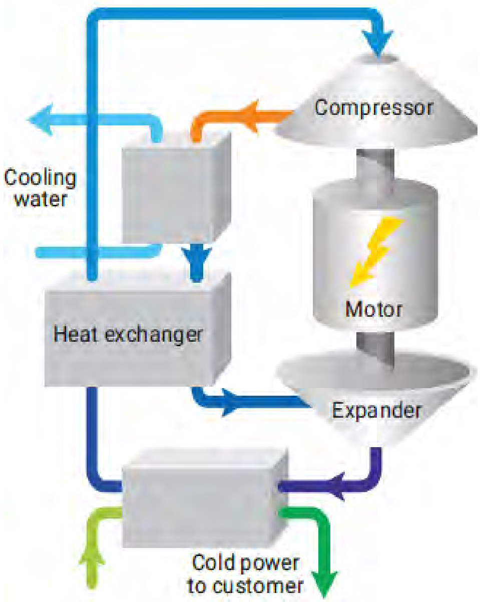


*Figure 1. The principle of a reverse Turbo Brayton cycle.*

The cold power is supplied thanks to a reverse Brayton cycle providing low temperature power at around 120 K (-153°C)@2 bar :

- Cycle gas is compressed in a 2-stage efficient centrifugal compressor,
- Heat resulting from compression is removed with cooling water,
- Compressed cycle gas enters the exchanger for cooling down,
- The cycle gas stream is expanded, generating the cold power of the system,
- Low Pressure cycle gas flows back in the plate fin heat exchanger and cools down both natural gas and HP streams.

The cycle gas involved in this cryogenic equipment is a mixture of inert gases which allows safe operations, no pollution risk from hydrocarbons leak and no process contamination thanks to oil free bearings. Explosion risk is then reduced.

The main improvement, compared to other refrigerant systems, is the assembly of all active elements on a single shaft:
• Centrifugal compressor,
• High-speed motor,
• Cryogenic turbo expander.

Compared to state of the art of cryogenic, the Turbo-Brayton electrical power consumption is 40% lower. High efficiency is due to:
• Cryogenic expander power recovery
• High efficiency centrifugal compressors
• High efficiency centripetal expander
• High efficiency direct drive motors
• High flexibility: At 50% of nominal liquefaction capacity, global efficiency is decreased only by 3 %. The motor's speed adjusts automatically to match the load and operating conditions for maximum efficiency.

The Turbo-Brayton high efficiency, even for lower liquefaction capacity, is very convenient for demand fluctuation on markets such as biogas, virtual pipeline or flare gas recovery.

The Turbo-Brayton is designed to be a low maintenance cryogenic refrigerator due to:
• Oil free system
• Contact free for rotating part
• Hermetic System
• Low number of valves
• Single system, single skid, factory tested
• MTBF 105,000 hours
• No leakage of cycle gas, make up is not required

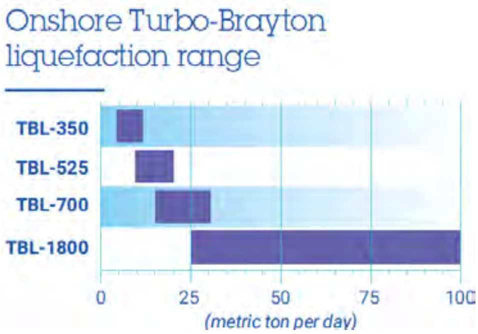


*Figure 2. Capacity range of onshore Turbo-Brayton crygenerators.*

**3. BioLNG – entry barriers**

Due to the higher price of decarbonized energy compared to fossil fuels, and despite all the benefits provided by domestically produced bioLNG, it acts on a very challenging market.

Three simple conditions must be reached for bioLNG project completion:

- **Off grid location.** Otherwise, the molecule will be simply fed into the grid and monetized through a BPA (Biogas Purchase Agreement) and exchanged with fossil LNG by mass balance mechanism (virtual liquefaction). No need to invest in a liquefaction plant.
- **Local consumption.** Avoiding the expensive logistic cost of long-haul transportation. Ideally in the frame of a circular economy scenario for trucks or ferries fuelling.
- **Cost compensation.** The price difference between bioLNG and the much cheaper fossil LNG or alternative decarbonized fuel such as biodiesel from China, must be compensated either by a penalty on $CO_2$ emission of fossil LNG (ETS) or subsidies.

# Introduction to the BioGenGas Innovation Cluster.

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## 1. Introduction

The Innovation Cluster for Sustainable Biogenic Energy Gases – BioGenGas – aims to develop and implement biogenic energy gases, such as biogas, biogenic hydrogen, biopropane, and bioDME. The cluster will serve as a platform for collaboration between industry, academia, and the public sector to increase knowledge and innovation in the field.

The Innovation Cluster is expected to contribute to several positive effects, including achieving Sweden's climate goals, cleaner air, and a resource-efficient circular economy.

A total of 25 companies, universities, and research institutes are participating in the cluster.

The Innovation Cluster BioGenGas is led by The Swedish Gas Association and is part of the Swedish Energy Agency's Bio+ program.

In summary, the Innovation Cluster BioGenGas aims to promote the development of biogenic energy gases in Sweden by creating collaborations, increasing knowledge, and contributing to a fossil-free future.

## 2. The Bio+ Programme

Bio+ is a research and innovation program funded by the Swedish Energy Agency. The program aims to develop bio-based solutions and value chains and increase knowledge and competence on how these should interact with each other and with other energy systems. The Bio+ program will contribute to Sweden achieving its energy and climate policy goals and becoming a fossil-free welfare state.

Bioenergy is an important renewable energy source. As an industrial raw material and energy source, biomass has a central position in Sweden's economy. Sweden has good access to biomass, and in addition to forest resources, there is also potential for developing bio-based value chains from agriculture, the sea and water, as well as side streams and residues from industries and communities.

The Bio+ program aims to develop bio-based solutions and value chains and increase knowledge and competence on how these should interact with each other and with other energy systems. The Bio+ program will contribute to Sweden achieving its energy and climate policy goals and becoming a fossil-free welfare state.

## 3. BioGenGas Project Goals

The BioGenGas project has several goals, including establishing the cluster as a recognized national platform where actors from the entire value chain for biogenic energy gases can meet to collaborate, learn, and create new partnerships. The project also aims to promote dialogue and exchange of experiences within the cluster, spread knowledge to actors outside the cluster, and eliminate barriers that hinder a growing market for biogenic energy gases.

The project is crucial for Sweden to achieve its energy and climate goals. Biogenic energy gases have the potential to improve air quality, create jobs, and ensure a fossil-free energy supply.

**4. Specific Challenges**

The BioGenGas project faces several specific challenges that need to be addressed to achieve its goals:

*Limited Availability and Production*

One of the biggest challenges is that users see a risk that the availability of biogenic energy gases is limited, while production is jeopardized by the lack of established secure outlets. To solve this problem, the project needs to create new collaborations and connect users in different sectors with existing or potential producers of biogenic gas.

*Large-Scale Production*

For biogenic gases to contribute to the transition within industry and shipping, more large-scale production is required. The Innovation Cluster BioGenGas will take an active role in promoting cross-industry collaborations and developing the interface between several different industries to realize new concepts.

*Market Models and Business Models*

New market models and business models need to be developed to steer towards an increased share of biogenic energy gases.

The platform aims to foster the development of new business models and deliver updated information to end-users regarding biogenic gas. It will highlight how the gas can enhance profitability and contribute to sustainability objectives.

*Knowledge-Enhancing Measures*

Knowledge-enhancing measures aimed at politicians and the public are crucial to removing barriers in legislation and increasing acceptance for investments in biogenic energy gases.

The project will develop knowledge bases and carry out information dissemination to increase knowledge about biogenic energy gases.

*Supply Security and Energy Preparedness*

The situation in the world today has increased the focus on supply security and energy preparedness. Through biogenic energy gases, dependence on imported fossil fuels is reduced, and the energy mix becomes less vulnerable.

The project will contribute to increasing Sweden's supply security and energy preparedness by spreading knowledge about how biogenic energy gases can contribute to this.

*Liquefied Gas*

For the whole of Sweden to benefit from the great potential of biogenic energy gases, investments in production of liquefied gas are needed. The project will increase knowledge about liquefied gas and create new collaborations and business models to increase this market, both in Sweden and internationally.

*Electricity and Heating Sector*

In the electricity and heating sector, Sweden needs energy gases as a partial solution to the power and capacity challenges that come with increased electricity use and a larger share of variable electricity production from wind and solar.

The project will increase decision-makers' knowledge about the opportunities of biogenic energy gases in the electricity and heating sector.

## 5. Results so far

The Innovation Cluster has from the start in May 2023 arranged and/or participated in 213 dedicated meetings, seminars and conferences on a national or international level promoting biogenic energy gases.

The Coordinator has also participated in a total of 8 reported or ongoing Projects involving the use of biomass in various applications highlighting the importance of sustainable value chains and cross-over different sectors, such as agricultural and transport or industry.

The Innovation Cluster has financial support from the Swedish Energy Agency to the end of 2025, after a report will be presented. The results so far indicates that the overall goal for the Innovation Cluster will be met.

## 6. References


- Innovation Cluster BioGenGas [http://www.biogengas.se]
- The Swedish Energy Agency: [https://www.energimyndigheten.se/]
- The Swedish Gas Association [https://www.energigas.se/in-english/]
- Bio+ Programme [https://bioplusportalen.se/]


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# Recent Innovative Pathways to Renewable LPG.

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## 1. Introduction

Liquified Petroleum Gas (LPG) is an important fuel in the world, composed mainly by propane and n-butane, used for cooking, heating and transportation, whose yearly consumption is around 342 million metric tonnes [1], contributing to 74.1 gr $CO_2$/MJ when burnt [2]. The majority of the bioLPG currently produced in the world is coming from the hydrotreatment of biological oils and fats as a co-product of the HVO process with low yields (below 5%). BioLPG capacity was estimated to be 200,000 — 250,000 tonnes per year in 2023, and if all pipeline projects were to come on-stream then the capacity could reach 625,000 tonnes by 2025 [3]. However, the actual available bioLPG can be impacted by the practice of reforming the bioLPG to make hydrogen to feed the hydrotreater. Hence the necessity of developing new technologies and pathways to produce on-purpose bioLPG that can replace fossil LPG in the future to meet the global climate targets for reducing greenhouse gases.

New pathways and technologies are in development at different technology readiness levels (TRL) using different feedstocks such as bio-oil, glycerine, sugars (via fermentation), cellulosic wastes and wet wastes but in most cases the LPG is a byproduct [4]. Others have tried feedstocks such as butyric acid [5], n-butanol [6], bio-syngas [7] [8] (from biomass gasification or biogas) or carbon dioxide and water (the so-called Power-to-LPG) [9]. Although these latter pathways are preferable because they are on-purpose to bio-/e-LPG some of these pathways require either expensive catalysts using rare or noble metals and/or extreme process conditions (high pressure and temperatures) as well as high energy consumption. In addition, some of these technologies have low conversions, requiring large recycles and extra separation units in the process. That said, the respective research groups are working diligently to improve the performance of these processes and to make them techno-economically viable.

In this paper, two new innovative routes are presented using short chain alcohols: ethanol and isopropanol.

## 2. Ethanol to rLPG and green aromatics

One of the potential pathways to produce rLPG is via bioethanol as a feedstock using modified zeolite ZSM 5 as catalyst. This pathway has the advantage of not requiring costly green hydrogen, producing mainly paraffinic hydrocarbons in the range of $C_3$ – $C_4$, and monoaromatics, with the potential to reduce 70% the $CO_2$ emissions compared to fossil LPG. This technology started to be developed together with Drochaid Research where a suitable modified ZSM-5 was found. Figure 1 shows laboratory results comparing commercial ZSM-5 and modified ZSM-5, including the proprietary one of SHV-Energy.

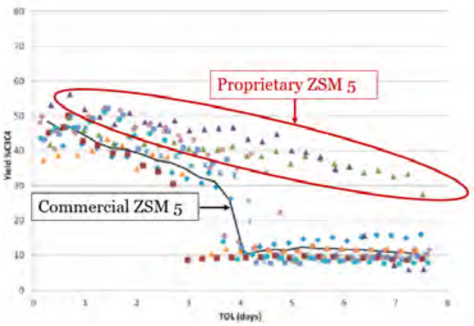


*Figure 1. Screening tests (powder form) for bioethanol to rLPG over catalyst candidates. Only rLPG yields shown.*

The technology was scaled up together with GTI-Energy to a 1 inch reactor where tests have proved 5 times more catalyst stability compared to the commercial ZSM-5 (260 vs 50 hours). Figure 2 shows the comparison between both catalysts tested at GTI-Energy in the 1 inch reactor and at the proprietary conditions.

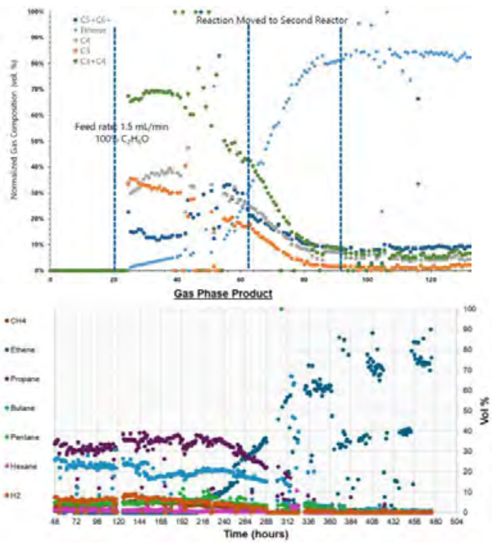


*Figure 2. Tests at 1 inch reactor. Above: Commercial catalyst. Below: Proprietary catalyst.*

The technology has shown the potential to produce mass yields of 30 – 40% rLPG (with a composition of 50% propane and 50% butanes) and 20 – 30% green aromatics depending on the conditions at which the reactor is operated. The potential process could look like the one shown in Figure 3.

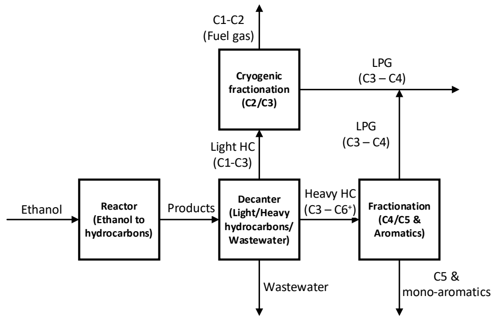


*Figure 3. Process block diagram of the technology Ethanol to rLPG and green aromatics.*

### 3. Isopropanol to r-Propane

Futuria Fuels has developed a new catalytic pathway using isopropanol plus hydrogen at the laboratory scale with conversions higher than 95% and selectivity towards propane higher than 90% in one single reactor. The process requires mild conditions, and the catalyst performances were tested for more than 160 hours. In addition to that, the catalyst was tested varying the water concentration since water is one of the products of the reaction (as is typical for many processes to make renewable fuels) that often causes rapid degradation of the catalyst. Even at concentrations up to 5 wt%, the water did not affect the catalyst performance. Figure 4 shows the conversion at different water concentrations.

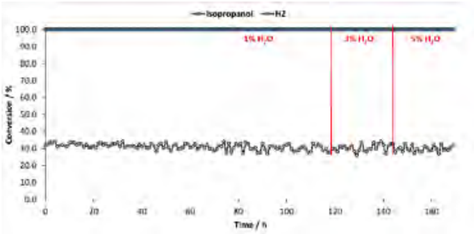


*Figure 4. Isopropanol and hydrogen conversion at different water concentrations.*

A small formation of heavier oxygenated hydrocarbons was detected as a byproduct, but the selectivity was below 1% during the whole tests. Figure 5 shows the product selectivity.

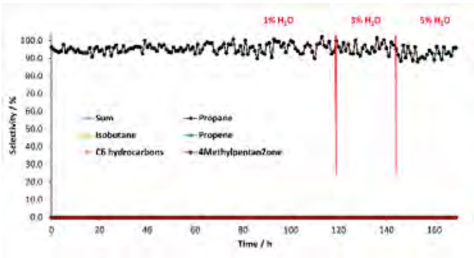


*Figure 5. Product selectivity distribution.*

The importance of this work is that these results have not been reported in the literature by using single reactor system but at least two reactors [10].

The process block diagram shows (Figure 6) how only one separation unit is required to obtain high propane purity that can meet purity specification of LPG in many countries (such as the US, UK, Japan and many countries within the EU) where more strict regulations applied. The potential $CO_2$ reductions compared to fossil LPG can be up to 80%, depending on the hydrogen and IPA source.

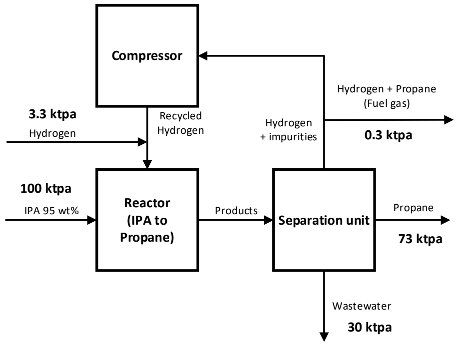


*Figure 6. Process block diagram of the technology isopropanol to propane.*

## 4. Conclusions

The tests carried out at the 1 inch reactor scale using bioethanol as feedstock proved the potential of producing rLPG and green aromatics from this feedstock without the need of requiring hydrogen. The challenges in catalyst deactivation were overcome with the modified ZSM-5, achieving 5 times higher catalyst stability and rLPG mass yields above 35%.

In addition, Futuria Fuels proved at lab scale to successfully convert isopropanol and hydrogen into propane in a single reactor under mild conditions with high conversions (above 95% for isopropanol) and high selectivity (above 90% for propane). This allows to meet strict LPG requirements in many countries such as US, UK, Japan and the EU.

These two new technologies have the possibility to provide rLPG/propane with $CO_2$ savings around 70 – 80% compared to fossil LPG, providing clean and sustainable energy to the off-grid communities and businesses.

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# Green LPG in Germany – Market Overview

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## 1. Introduction

Germany has set ambitious climate targets in its Climate Protection Act, that passed the German Bundestag in 2019: By 2030 greenhouse gas emissions are to be reduced by at least 65% compared to 1990 levels. By 2045 the country aims to achieve climate neutrality. This goal of climate neutrality by 2045 was recently incorporated into the constitution of Germany. Reaching these goals requires not only electricity from wind and solar power but also renewable alternatives in sectors that are difficult to electrify—such as heating and mobile applications.

Biogenic liquefied petroleum gas (Bio-LPG) is a suitable option for these applications. Chemically identical to fossil LPG, it can be used without any technical modifications in existing heating systems, vehicles, or industrial processes as a drop-in fuel. It is a renewable energy source produced as a byproduct from the HVO/HEFA process [3]. There are also many researchers looking into on-purpose production of Bio-LPG from organic residues or biomass [4] [5], alcohols [6], and even $CO_2$ [7]. Depending on the production pathway, Bio-LPG can reduce $CO_2$ emissions by up to 90% [8].

Another alternative to fossil LPG is renewable Dimethyl Ether (rDME) that can be used as a drop-in fuel in the current LPG infrastructure with blends up to 12% [9].

Renewable DME can nowadays be produced from the dehydration of green methanol [10] or by the direct synthesis from bio-syngas or $CO_2$ and green $H_2$ [11], and has the potential to reduce $CO_2$ emissions by at least 60% and at times by over 100% compared to fossil LPG, depending on the feedstock and the production pathway [8].

Both Bio-LPG and rDME, are considered renewable liquid gases that can be used using the existing infrastructure showing the enormous potential to support the energy transition, especially in applications that are difficult to electrify and in off-grid areas where electrification is challenging.

## 2. Regulatory Framework

The regulatory framework for biogenic liquefied petroleum gas (Bio-LPG) in Germany is shaped by national climate and energy laws, particularly in the heating and building sectors. Bio-LPG is officially recognized as a renewable energy source under current legislation, making it a viable option for meeting Germany’s ambitious climate targets.

*Federal Climate Change Act (Klimaschutzgesetz – KSG):*
This act sets binding targets for greenhouse gas reductions—65% by 2030 and climate neutrality by 2045 [12]. Bio-LPG contributes to these goals, especially in hard-to-decarbonize sectors such as rural heating and transport.

*Building Energy Act (Gebäudeenergiegesetz – GEG):*
The GEG explicitly recognizes Bio-LPG as a renewable energy source. This means that

heating systems powered by certified Bio-LPG can be used to fulfill the legal requirements for renewable energy use in new and existing buildings. For example, condensing gas boilers fueled by Bio-LPG are compliant if the fuel is sustainably sourced. [13]

*EU Renewable Energy Directive (RED II & RED III):*
These directives define sustainability and greenhouse gas savings criteria for biofuels. Bio-LPG made from waste and residues is eligible under these rules, provided certification requirements are met. [14][15]

*National Fuel Emissions Trading System (nEHS):*
Fossil fuels used in heating and transport are subject to $CO_2$ pricing in Germany. Certified Bio-LPG is exempt from these $CO_2$ charges, making it a more attractive and cost-effective alternative [16].

*Certification and Sustainability:*
To qualify as renewable, Bio-LPG must be certified under schemes such as ISCC or equivalent systems. This ensures compliance with sustainability criteria and access to regulatory benefits [17].

*Market Incentives:*
Although there are no direct subsidies for Bio-LPG, its official recognition under the GEG, exemption from $CO_2$ pricing, and compatibility with existing infrastructure make it a promising fuel in the transition to low-carbon heating

## 3. Market Potential

In 2024 the results of a study [1] commissioned by Primagas Energie GmbH and conducted by Frontier Economics were presented in Berlin. The study was the first of its kind to quantify the potential of renewable liquid gases like Bio-LPG and rDME with a focus on the domestic sector.

The study – among other sources - is based on detailed calculations of the building stock in Germany conducted by the ITG Dresden [2]. It incorporates various scenarios outlining the path toward a defossilized domestic sector by 2045, including all viable alternatives and solutions for the German building stock. The conservative scenario results in 827,000 homes that can only be defossilized using renewable liquid gases. In the high scenario, up to 1.85 million homes can be defossilized exclusively through the use of renewable liquid gas. In addition to the already fossil LPG used for heating homes, this results in a demand of at least 2.7 TWh in 2030 and 14.3 TWh in 2045. The high scenario results in a demand of up to 6.7 TWh in 2030 and 26.2 TWh in 2045.


*Figure 1. Demand for renewable liquid gases to defossilize German homes.*

When today's consumption of sectors such as industrial, commercial and agriculture are taken into account, total demand rises to 4-8 TWh in 2030 and 20-32 TWh in 2045.

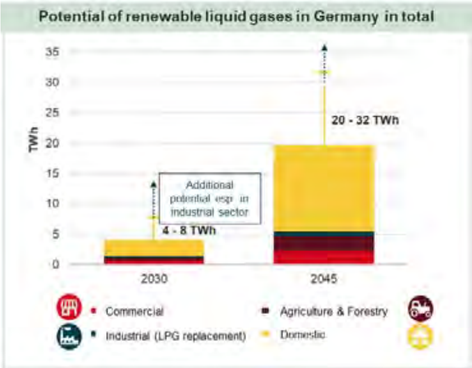


*Figure 2. Demand for renewable liquid gases in all sectors.*

## 4. Conclusions

The study shows the enormous potential for renewable liquid gases like Bio-LPG in the German market. Given the fact that electrification is no suitable solution for many industrial high temperature processes, the potential demand is expected to be even higher.

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# Towards Efficient Biological Methanation: The Role of Site-Specific Conditions.

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## 1. Introduction

The technical feasibility and economic viability of integrating power-to-gas technology of biological methanation has been subject of many different studies in the past as well as in ongoing project developments. Especially the integration of this technology into existing biogas plants and wastewater treatment plants with an anaerobic sludge treatment is approaching realisation on a commercial scale, like several pilot and demonstration plants / projects show.
Nevertheless, the size of the market for the biological methanation is difficult to predict. Today there is still no common, simple multipliable standard business case applicable to future projects, which guarantees sufficient return on investment [1]. On one hand this is caused by fast transition processes in energy infrastructure sectors as well as in energy economic and environmental regulations. But the other reason is the complex character of the technology itself, because of coupling of at least three different energy sectors - electricity, gas and heat - under non-stationary conditions on both supply and demand side. Therefore, high quality engineering preparation will become mandatory for future investment decisions, with a key focus on overall energy efficiency.

## 2. Site-specific Interfaces

Typical application cases of power-to-gas-technologies with E-Methane as final product consist of both electrolyser and methanation technology.

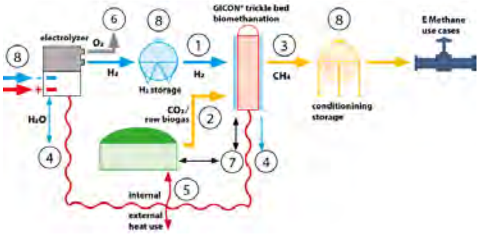


*Figure 1. Overview about typical site-specific interfaces between local infrastructure and methanation technology*

Based on this precondition Fig. 1 and Tab. 1 summarize a minimum of 8 different interface topics to be considered in the framework of such a project.

*Table 1. Explanation of numbers in Fig. 1.*

| Nr. | **Medium** | **Typical design Parameter(s)** |
|---|---|---|
| 1 | $H_2$ | p, $\dot{V}$ |
| 2 | $CO_2$ / raw biogas | p, $\dot{V}$, $c_{components}$ |
| 3 | E-Methane demand side | transfer point/ use case conditions |
| 4 | $H_2O$ (in / out) | purity, $\dot{V}$ |
| 5 | Heat (sources / sinks) | T, Q |
| 6 | $O_2$ (side product) | p, $\dot{V}$ |
| 7 | nutrients / inoculate | diverse composition |
| 8 | Energy supply data / optional storages / process control | XYZ ~ f (time) |

## 3. Energy conversion efficiency – lose or use the "losses"?

Every energy conversion is associated with an increase in entropy and decrease in exergy, respectively. In practice this means "losses", if the amount of input energy at the beginning (e. g. in Fig. 1: Electricity) of the process chain is compared with the main energy "product" at the end (e. g. in Fig. 1: energy content of E-Methane). But energy doesn't get lost, we find the difference in other types of energy, often waste-heat, bio-sludge etc.

A part of energetic transformation "losses" in the power-to E-Methane process chain is not avoidable because of laws of thermodynamics. For instance, the theoretical heat release of the methanation process is 17 % of the energy content of input hydrogen:

$$4H_{2_{(g)}} + CO_{2(g)} \rightarrow CH_{4_{(g)}} + 2H_2O_{(g)} \qquad \text{Eq. 1}$$

$$\Delta H_R^0 = -165\,kJ/mol$$

But in practice the conversion efficiency is less than theoretical values, depending on process designs. State of the art electrolysis converts at minimum 30 % of input electricity into "waste" heat. Further on, there are "byproducts" due to material transformation, e. g. in electrolysis (0.5 Nm³ $O_2$/Nm³ $H_2$) and methanation (1.6 l $H_2O$/Nm³ $CH_4$).

Two strategies in process design are most important in commercial use cases to maximise the overall process chain efficiency as well as the economic profitability:

(1) Minimising avoidable losses
(2) Beneficial use of waste heat and byproducts

The beneficial reintegration of "losses" requires a thorough analysis of the site situation, including the often predefined framework of upstream and downstream requirements such as system pressure of electrolysis and gas systems, temperature of heat sinks and time-dependent availability of renewable electricity as well as time-dependent requirements on the demand side.

The general system parameters used (p, T) must not impede the operational flexibility of the biological methanation process. This means, every step in the conversion chain must be considered under dynamic load changes and the resulting changes in material flows and heat demand. This may make various intermediate storages an option if lower operating costs compensate for higher investment costs.

Overall system simulation capabilities (e. g. development and use of digital twins) are very helpful for the design processes. The main objective of this integrated engineering approach is to minimize stand-by and optimize energy consumption within a flexible load environment, ensuring stable product quality.

## 4. Examples for optimal process design for maximising process efficiency

*Example1: Pressure levels*

The least changeable site parameters are pressure levels of the gas product demand and the hydrogen source. A combination of standard storage systems with 45 barg and matching electrolyser output pressure is the most efficient option, regardless of downstream pressures. Though differences in energy consumption exist among electrolysers the pressure dependency is neglectable [1-4]. The transfer point pressure for local gas application and the $CO_2$-source pressure are competing priorities in terms of system pressure definition. The closer these levels are, the smaller the energy losses of the process chain. The transfer point determines the required gas product pressure. For example, for the pressurization of a biological methanation of 10 bar, theoretically 133 Wh/Nm³ are required for biogas compression if the reactor obtains the carbon dioxide from a low pressure source. Exceedance of transfer point pressure levels leads to non-recoverable loss of compression work (Fig. 2). Likewise, pressure reduction from a $CO_2$-source and methanation at ambient levels followed by pressurization to the transfer point level leads to a comparable amount of work loss.

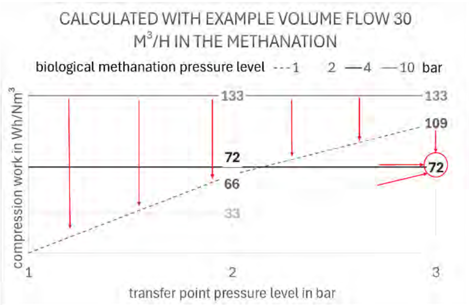


*Figure 2. specific compression work for operational pressures of biological methanation and different transfer point pressures (in bar abs).*

Nevertheless, the volume-specific energy required to compress biogas is lower than that required for methane. For instance, using a transfer point pressure of 3 bar, it is more efficient to operate the biological methanation at 4 bar instead of 1 bar. Alternatively, operating the biological methanation at 2 bar, compressing the methane afterwards to 3 bar, leads to the same additional energy consumption (Fig. 2).

The biological system has limitations regarding both negative and positive pressure gradients. This leads to the conclusion that ensuring a feasible pressure window is crucial for a stable process, which must be achieved for any non-ambient-pressure methanation without energy consumption to avoid losses.

*Example 2: Heat recovery*

State-of-the-art process chains of methanation processes (inclusive electrolysis) convert more than 45 % of the electrical energy input into thermal energy. The more of this energy potential can be recovered and used, the better the overall process efficiency, especially if the heat can be directly applied to a demand side and avoid there an additional energy consumption from high exergetic sources. Obviously this topic will be a key factor of site specific engineering of the energy system. Because of the low temperature level, the possible applications of recoverable waste heat are limited to the heating of other biological processes or buildings. But these demands occur at wastewater treatment and biogas plants, therefore, regularly exists a significant potential for using the synergies at such sites. Apparently small differences in process design – e. g. hyperthermophilic conditions instead of thermophilic in the biological methanation – may significantly improve the options with respect to heat recovery.

## 5. Conclusions – Advantages of TBR System

The economic competitiveness of a power-to-methane technology is largely determined by the following criteria

(1) Flexibility in relation to fluctuating supplies of renewable electricity
(2) Flexibility in adapting to site-specific infrastructure and
(3) High energy efficiency of the overall process chain.

During the development of the GICON® TBR technology, these criteria were taken into account comprehensively and tested in long-term practical operation on test systems. The technology is robust against load changes, has a low internal energy requirement and can be designed for different operating pressures between 1 and 10 bar [6].

Moreover, the operation under hyperthermophilic conditions has been identified as advantageous, with respect to the process stability as well as efficiency and options for heat recovery.

## 6. Next Project with application of GICON®-TBR-Technology

The large-scale demonstration project WeMetBio2 is currently in the planning phase and will be realised at the Nordhackstedt site in 2026 (Fig. 3, [7]).
The direct utilisation in BioCNG/BioLNG-powered vehicles, in particular agricultural vehicles such as tractors, is alternatively planned as special topic for the long term at this site.

*Figure 3. View on the project site of the Nissen Biogas GmbH & CO.KG in Nordhackstedt with the image GICON®-TBR-demonstration plant*

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# Biogas and fatty acids produced from agricultural biomasses for industrial use.

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## 1. Introduction

The Swedish Industrial Biogas Commission has set a target of producing 10 TWh of biogas per year by 2030 through anaerobic digestion and gasification [1]. Currently, the production of biogas in Sweden stands at approximately 2 TWh per year, primarily from waste and sludge. However, the supply of organic waste is insufficient to meet the required biogas production. Agriculture, with its significant amounts of residual biomass such as manure and straw, presents a viable solution. The project also explores the potential of using smaller portions of arable land to grow nitrogen-fixing grass/clover ley for biogas production, possibly in combination with producing protein feed for agriculture and fatty acids for industry within a biorefinery concept [3].

## 2. Conditions

In the western part of Sweden (Västra Götaland, Skåne, and Halland), it is feasible to use manure, straw, and ley with smaller amounts of waste to produce 3.5 to 5 TWh of biogas per year in large biogas plants (approximately 100 GWh per plant per year) for industrial use. Co-production of fatty acids and biogas is also possible, with at least 16 plants needed to cover identified industrial needs.

There are also good opportunities for Bio-CCS (Carbon Capture and Storage) at the biogas plant when biogas becomes biomethane and in the industry where biomethane is used. This can lead to negative emissions, significantly reducing climate gases when biomethane replaces natural gas.

The price of natural gas, including national tax, compared to biogas with existing subsidies, is estimated to be relatively similar. However, the current subsidy system is directed towards manure digestion, which only produces about one-fifth of the potential biogas from agricultural biomass. Therefore, subsidies need to be modified to meet the biogas demand.

Fatty acids can also be produced using primarily pasture and waste via a biological process at a similar price level as today's fossil-based production method.

## 3. Value chains

Investing in building biorefineries that generate renewable commodities can be a solution for the industrial green transition, utilizing agricultural biomasses. This can also contribute to the green transition of agriculture. However, the system is large and involves many actors, requiring significant investment and clear incentives for participation, including farmers. There are also technical and biological uncertainties in the system's function.

A key question remains: who is prepared to take the lead in realizing this potential?

## 4. The projects aim and methodology

The project aims to investigate the conditions for increased production of biogas and high-value raw materials, focusing on volatile fatty acids, for the transition of the west coast's process industries through greater utilization of agricultural residual streams and residues from protein feed production with cultivated ley in the Västra Götaland region [2 & 3].

The methodology developed will also estimate the potential contribution to biogas production from agriculture in Skåne and Halland [2]. The goal is to demonstrate that biogas produced in Västra Götaland with agricultural biomass can replace approximately 1.2 TWh per year of fossil natural gas without significantly reducing the agricultural production of food raw materials. Similarly, biogas produced in Skåne and Halland can replace approximately 1.5 TWh per year of fossil natural gas.

The project also aims to map the needs of biogas and fatty acids among industrial partners and conduct an indicative calculation of the potential to produce these fatty acids from the available biomass for digestion in the studied biogas alternatives.

Additionally, the project will propose support and control measures for competitive biogas production and develop proposals for future steps towards establishment and investment.

## 5. Conclusions

In conclusion, the project highlights the potential of utilizing agricultural residual biomass for biogas and fatty acid production, contributing to both industrial and agricultural green transitions. However, significant investment, clear incentives, and addressing technical and biological uncertainties are crucial for realizing this potential.

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# Biomethane production from straw

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## 1. Introduction

Biomethane is one of the promising energy carriers for the green transition and especially suited for the decarbonisation of hard-to-electrify sectors such as heavy transport and shipping, but also important for the future production of green chemicals. Biomethane has the advantage that it can tap directly into the natural gas infrastructure, and the biogenic $CO_2$ produced from biogas plants as a byproduct is an important feedstock for Power-to-X plants for production of e-fuels such as e-methanol or e-SAF.

A key challenge for biogas is the establishment of large-scale plants. Since many biomasses are wet and often quite dilute, the plant sizes are limited by transportation and logistics constraints, limiting how much biomass can be economically transported to and stored at the plant.

Straw is an important biomass resource and increasingly used in biogas plants in Denmark and other countries [1]. Green2x commercializes a technology for conversion of briquetted straw and other agricultural residues to biomethane, biogenic $CO_2$ and a fertilizer product (Figure 1). This technology enables large-scale biogas plants by two key enablers (1) Biomass is transported to the plant in the form of dense straw briquettes, allowing for efficient transport (2) the conversion process has high biomethane yields, short residence time and recirculates most of the process water. This allows for large-scale and cost-effective production of biomethane and biogenic $CO_2$.


*Figure 1. Green2x will produce biomethane, biogenic CO2 and fertilizer from briquetted straw and other agricultural residues.*

## 2. Technology description

Green2x technology and process is based on the CELLEBRIQ™ technology, originally developed by the company Biofuel Technology and licensed to Green2x.

A principal scheme of the process steps is shown in Figure 1.

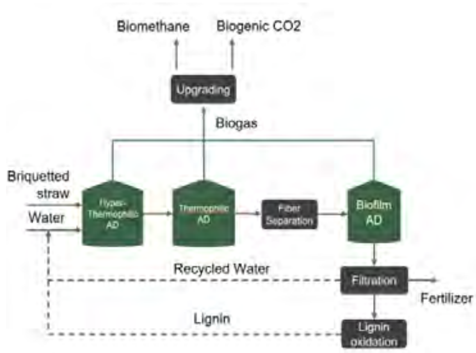


*Figure 1. Principle scheme of process steps for conversion of straw to biomethane, biogenic CO2 and a fertilizer product. Straw is used as a mono-feedstock.*

Straw is pre-treated by a briquetting process under very high pressures exceeding 1000 bar, inducing a steam explosion locally in the straw. This modifies the properties of the straw from hydrophobic to hydrophilic and makes it more accessible to anaerobic digestion. It also produces high density briquettes that can be stored and transported efficiently. The briquetting can be done in decentral stations close to the straw harvesting location, and the briquettes can be subsequently transported to the biogas plant.

The briquettes are mixed with water in which they easily dissolve, and enter a hyperthermophilic anaerobic digestion reactor, followed by a thermophilic anaerobic digestion step. The process stream then enters a fibre separation steps where fibres are separated and recirculated to the digesters. After fibre separation, the biomass enters a biofilm reactor followed by a filtration section. In the filtration train, lignin is filtered out and subjected to oxidation, followed by recirculation to the digesters. The filtration train also removes minerals from the process, which are retrieved as a fertilizer product. Nutrients have to be added separately to the process and the levels have to be controlled. The produced biogas is upgraded to biomethane and biogenic $CO_2$.

The process produces thus biomethane, biogenic $CO_2$ and a fertilizer product. The biomethane can subsequently be converted to biofuels such e.g. biomethanol, whereas the biogenic $CO_2$ is an important feedstock for e-fuels. The fertilizer product contains mostly minerals and minor amounts of organics but can be adjusted according to offtaker needs.

**3. Technology demonstration results**

Up to now, the process has been developed and tested at Aarhus University's biogas R&D facility in Foulum, in collaboration with Biofuel Technology and Aarhus University. Test results have shown that biomethane yields higher than 400 Nm3 $CH_4$/ton VS can be achieved over extended periods of time. The tests have also confirmed that the water and process stream recirculation work and have given important insights into required nutrient levels. Lignin oxidation has been tested offsite and has shown the first promising results.

The next step for Green2x is to demonstrate the entire process in a dedicated pilot plant and in this way mature the technology to TRL 7. This is a key prerequisite for commercialization and successful financing of commercial plants.

**4. Plans for commercialization of the technology**

In parallel to the technology development, Green2x is developing the first commercial project at the Port of Vordingborg in Denmark.

The plant will treat 500.000 tons of briquetted straw per year and produce mor than 170 million $Nm^3$/year of biomethane and more than 350.000 tons/year of biogenic $CO_2$, making it one of the largest biogas plants in the world. In addition, 26.000 tons/year of minerals (dry basis) will be extracted for use as fertilizer. The biomethane will be injected to the gas grid and the majority of the $CO_2$ will be piped to a neighbouring e-SAF plant (also under development). The site for the plant is secured at the port of Vordingborg and the environmental permit was granted in 2024.

A second plant is being studied in Malmö, Sweden, where an agreement with the port authorities is in place.

## 5. Conclusions

Straw is an important biomass resource that is increasingly used as feedstock in biomass plants. The Green2x technology offers a route to large-scale production of biogas by mono-digestion of briquetted straw. The technology is in the late development stage and a pilot plant demonstration is planned.

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# The GreenMeUp project.

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## 1. Introduction

The ultimate objective of GreenMeUp is to facilitate the wider market uptake of biomethane in the European energy and transport sectors by strengthening the market in countries with slower market development policies. GreenMeUp addresses Advanced European countries, Target countries and a set of Mission Innovation (MI) countries (Brazil, Canada, China, India and USA) participating in the International Advisory Board (IAB) to assure an additional flow of information on biomethane production lessons-learnt, enablers and barriers. This interaction steered the development of more informed and targeted policies in the target countries and support them in building a robust, incentive-compatible biomethane market, in order to achieve an increased share of renewable gaseous fuels in their final energy consumption by 2030 and beyond.

## 2. Approach

The approach used is two-fold: In one work-package the framework conditions and market dynamics for biomethane were analysed in the top 10 advanced European countries (having the highest market shares covering > 95% of the biomethane produced in Europe (Germany, UK, Denmark, France, The Netherlands, Italy, Sweden, Norway, Switzerland and Austria, and in selected 5 MI countries. The analysis addressed all production routes, feedstocks and end-uses.

A second work-package did similar work at national level for seven selected European target countries with low developments (Greece, Spain, Poland, Latvia, Estonia and Czech Republic). As a result, comprehensive overviews of the existing market situation and future market trends in Europe and in each of the selected countries were produced.

In the target countries, stakeholder engagement and societal acceptance is achieved with the establishment of policy, market and societal Hubs, which apart from stakeholders' engagement provide information on the situation of the biomethane sector in each of the target countries.

Final country-tailored market uptake measures are being deigned following the country reports, the input from the hub meetings and a world-café workshop, SWOT analyses, targeted questionnaires, as well as fuzzy cognitive mapping techniques focused on the most crucial parameters for the effective penetration and use of biomethane in each country.

In addition to the above thorough assessments have been concluded on the feedstock resources at European level and on the technology developments along the value chain for biogas, biomethane and biohydrogen production.

## 3. Results

*The biomethane market in the Target countries*

Among the Target countries, Czech

Republic and Estonia are leading the way. In Czech Republic 8 plants are in operation by the beginning of 2024, producing 12 GWh, having a capacity of 372 m3/h of biomethane. Apart from the biomethane plants, another 603 biogas plants are in operation showing the huge biomethane potential of the country. In Estonia on the contrary to all countries, only 17 biogas plants are operating, however the 7 of which are producing biomethane, and another one is currently under a start-up process. Moreover, in Estonia 28 CNG filling stations, 2 LNG filling stations and 5 grid injection points on distribution network grids are built facilitating thus the use of biomethane in the transport sector mainly.

*The production routes and end uses in the Target countries*

Production routes mainly refer to agricultural resources (manure and agricultural residues), with municipal wastes holding a lower share. Biomethane plants in all countries are mostly agricultural ones and prospects show that this trend will continue until 2030 and beyond.

All target countries have in place gas infrastructure and storage.

In most of the target countries the main existing or foreseen use is in transportation and to a lesser content for power and heat.

*The regulatory framework and supportive policies in the Target countries*

The existence, stability and reliability of targeted policy and financial support is considered as the number one enabler, regardless of whether they already have a mature biogas/biomethane market in place or not. Dedicated national targets are also identified as an important driver for the sector, as is the year-round availability of suitable feedstocks

The policy and regulatory framework is still limited in all countries, consisting mainly of the National Energy and Climate Plans (NESPs) and adjustments of the REPowerEU.

Production-side direct investment supports is the usual supporting system in almost all target countries. Demand-side supports exist in Estonia that has a robust biomethane roadmap with identified strategies and has set mixing obligations to fuel companies which has created a demanding market for GOs.

*The feedstock availability in the Target countries*

In EU-27, the theoretical biomass potential from livestock manure, grain straw, agro-industrial waste and food waste amounts to 1,393,068,304 tons/year (Table 1), with a biomethane energy content of 382,89 TWh/year or 39,71 bcm/year (Table 2). The availability of biomass production throughout the year in the wider area of EU is guaranteed by at least 40% if it is accompanied by contract farming conditions. France is leading the way with, followed by Germany, Spain, Poland and Italy. The main feedstock is manure but considerable contributions may be given by the available quantities of cereal straw that is not used for animal feeding. Straw demonstrates technical challenges when it has to be used as feedstock for AD, which however can be tackled successfully. According to the analysis performed in this report, there are enough quantities of straw in EU for complementing the rest AD feedstock sources in order to achieve the biomethane target for 2030.

Another type of feedstock that has to be considered is the sewage sludge derived primarily form municipal waste water treatment plants. This sludge has considerable biogas generation potential and there no other competitive uses that compete the valorisation as AD feedstock.

*Table 1. Theoretical biomass potential in EU27 and the Target countries*

| BIOMASS POTENTIAL | MANURE '000t/year | WHEY & FOOD WASTE '000 t/y | STRAW '000t/y | TOTAL BIOMASS '000t/y |
|---|---|---|---|---|
| **EU - 27 Countries** | **1,156,438** | **168,149** | **68,480** | **1,393,068** |
| **Belgium** | 35,110 | 6,139 | 480 | 41,730 |
| **Bulgaria** | 9,899 | 1,312 | 2,449 | 13,661 |
| **Czech Republic** | 19,089 | 3,295 | 2,171 | 24,556 |
| **Denmark** | 36,896 | 5,262 | 2,191 | 44,350 |
| **Germany** | 184,883 | 33,755 | 9,486 | 228,126 |
| **Estonia** | 3,875 | 760 | 608 | 5,244 |
| **Ireland** | 81,988 | 7,147 | 484 | 89,620 |
| **Greece** | 11,986 | 3,439 | 900 | 16,325 |
| **Spain** | 116,121 | 10,197 | 8,805 | 135,124 |
| **France** | 208,218 | 26,308 | 12,577 | 247,104 |
| **Croatia** | 6,248 | 661 | 142 | 7,052 |
| **Italy** | 96,503 | 17,794 | 4,054 | 118,352 |
| **Cyprus** | 2,084 | 608 | 41 | 2,734 |
| **Latvia** | 5,853 | 973 | 392 | 7,219 |
| **Lithuania** | 9,903 | 1,457 | 2,225 | 13,586 |
| **Luxem-bourg** | 2,555 | 411 | 38 | 3,004 |
| **Hungary** | 15,854 | 2,336 | 2,730 | 20,920 |
| **Malta** | 274 | 108 | 0 | 383 |
| **Nether-lands** | 73,268 | 13,328 | 68 | 86,666 |
| **Austria** | 28,261 | 4,014 | 835 | 33,111 |
| **Poland** | 100,380 | 14,913 | 8,198 | 123,491 |
| **Portugal** | 20,098 | 3,242 | 137 | 23,478 |
| **Romania** | 45,025 | 3,127 | 5,089 | 53,242 |
| **Slovenia** | 5,587 | 1,017 | 92 | 6,697 |
| **Slovakia** | 6,149 | 1,291 | 974 | 8,415 |
| **Finland** | 12,215 | 2,519 | 1,681 | 16,416 |
| **Sweden** | 18,105 | 2,723 | 1,621 | 22,450 |

## 4. Conclusions

The existence, stability and reliability of targeted policy and financial support is considered as the number one enabler, regardless of whether they already have a mature biogas/biomethane market in place or not.

*Table 2. Potential biomethane production (in bcm) for the natural gas grid and energy content (TWh/y) in EU and Target countries*

| 2022 | POTENTIAL BIOMETHANE FOR GAS NETWORK bcm/y | BIOMETHANE ENERGY CONTENT TWh/y |
|---|---|---|
| **EU - 27 countries** | **39.71** | **382.89** |
| **BOVINE** | 7.87 | 75.88 |
| **DAIRY COW** | 5.77 | 55.59 |
| **SHEEP** | 1.3 | 12.58 |
| **GOATS** | 0.25 | 2.4 |
| **SWINE/PIGS** | 1.97 | 18.99 |
| **TOTAL** | **17.16** | **165.44** |
| **WHEAT STAW** | 10.07 | 97.07 |
| **OAT** | 1.15 | 11.12 |
| **BARLEY** | 4.5 | 43.4 |
| **RYE** | 0.85 | 8.19 |
| **TOTAL** | **16.57** | **159.78** |
| **WHEY/MILK** | 1.58 | 15.22 |
| **BIO-FOOD WASTE** | 4.4 | 42.45 |
| **TOTAL** | **5.98** | **57.67** |

Dedicated national targets for advanced biofuels and biomethane are also identified as an important driver for the sector.
Feed-in tariff and Feed-in Premium were present in most of the countries as an effective mechanism to assist investments.
A cost-sharing mechanism for grid connection is considered as a major financial support for new biomethane plants, especially for small to medium-sized project developers who cannot afford the full investment cost.
A major barrier though in all countries was the lengthy licencing and permitting procedures.
Integration with agricultural policy is essential to improve the profitability of biomethane plants in terms of the digestate use in the fields but also in terms of accessing sufficient feedstock from the farmers throughout the year.
If all the available feedstock consisting

of livestock manure, food waste and whey is utilised then 23.14 bcm of biomethane can be produced. This quantity approaches the target set by EU and foresees delivering 35 bcm of biomethane in the natural gas grid by 2030.

# Gas converting bioprocesses as sector coupling technology.

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## 1. Introduction:

Biological processes, and gas converting bioprocesses in particular, have a great potential to link different industrial sectors in the future. A major advantage is their ability to effectively convert $CO_2$ into a variety of intermediates for chemical and other industries. Krajete GmbH has been involved in the development of gas converting bioprocesses and gas cleaning processes for more than a decade, with our flagships being the $CO_2$ based biological methanation and the non-destructive and reversible NOx purification processes. The biomethanation process enables to directly upgrade $CO_2$ to $CH_4$ using $H_2$ as reducing agent. The process offers high volumetric productivities (up to 2 [mol $L_{reaction\ volume}^{-1}$ $h^{-1}$] or 45 [$Nm^3$ $m^{-3}_{reaction\ volume}$ $h^{-1}$]), high flexibility for intermittent operation and a high tolerance against a broad spectrum of impurities. In the last decade, biomethanation processes have been discussed mainly in the context of power to gas. However, in recent years Krajete GmbH has focused on integrations beyond the power to gas frame. This has allowed the potential of biomethanation and gas converting bioprocesses in general to be demonstrated in new interesting application scenarios. Examples include integrations into a process for the production of man-made diamonds (Skydiamond Ltd, UK), a process for the permanent sequestration of $CO_2$ in the form of black carbon for the cement industry (Project Grüner Kalk, Hyson institute, Sonneberg, GER) or a process for the creation of a range of value added products from DAC derived $CO_2$ and hydrogen from renewable sources as part of the H2020 Celbicon project. Also an acetone production process from $H_2$ and $CO_2$ was developed together with European academic and industrial partners as part of the European H2020 Engicoin project, and we are currently working, with other partners under the leadership of the Italian Institute of Technology on the development of a biological Hexanol production process from $H_2$ and $CO_2$ and its integration into an energy-independent biorefinery concept as part of the Horizon Europe CBE-JU GoodByO project. These integration examples show the great potential of gas-converting bioprocesses as sector coupling technologies, using renewable electricity as energy input and $CO_2$ as carbon source for greener (chemical) production processes by turning $CO_2$ emitters into $CO_2$ sinks. Furthermore, Krajete GmbH foresees the need to implement a holistic approach that creates synergies between NOx removal and $CO_2$ utilization in order to propose new circular value chains starting from emissions gases and in line with circular economic goals. In the paper and out talk, we will present you advances in gas converting bioprocess kinetics using active and passive pressurized systems as well as synergies and innovative integration concepts between $CO_2$ utilization and sustainable production.

## 2. Technology description

The $CO_2$ based biological methanation process ($CO_2$-BMP) uses archaea microorganisms as biological catalyst to perform a carbon activation and methanation reaction by converting hydrogen ($H_2$) and carbon dioxide ($CO_2$) directly into methane ($CH_4$), water ($H_2O$) and biomass (the biocatalyst). The methanation reaction itself follows the subsequent stoichiometry:

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

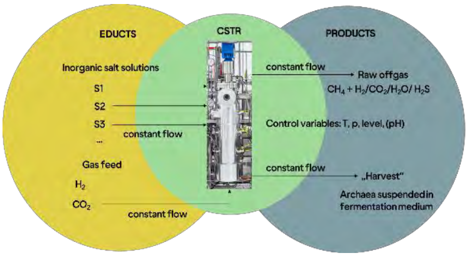


*Figure 1. graphic description of the process and respiration equation of the micro-organisms employed*

In this bioprocess, the only carbon source fed to the bioreactor is $CO_2$ and the biocatalyst eats it while breathing $H_2$ to self-replicate and produce $CH_4$. The bioprocess is operated using a defined, cheap and sustainable, medium made of few inorganic salts and is controlled by a feed forward control strategy [1]. As in every bioprocess, a maximum concentration of inhibitory compounds can be tolerated by specific methanogenic strains [2]. This maximum concentration depends on the strain and its specific metabolism (we worked with > 80 different methanogenic strains from psychrophilic to hyperthermophilic temperature domains) as well as on the desired operating conditions (*i.e.* operating pressure and volumetric productivities) [3]. The reference biocatalyst revealed to have tolerances for a wide range of impurities that can potentially be found in *e.g.* waste hydrogen streams originating from a chemical industrial frame [4]. Some of them are listed below:

- **Organic compounds such as:** CO, Ethane, Ethene, Toluene, Naphthalene, Benzene, Propane, Butane, Pentane, Hexane, Carbon Disulfide.
- **Inorganic anions such as:** CN(1-), S(2-), $SO_4$(2-)
- **Inorganic cations such as:** Ba(2+), Sn(2+), Zn(2+), Cu(2+), Mn(2+), Hg(2+), Pb(2+), As(3+), Cr(6+)
- **Air compounds:** No compounds present in air are toxic unless Oxygen ($O_2$) which is still tolerated to a certain extent

With different methanogenic strains other tolerances can be obtained as it was *e.g.,* reported in a study published in Nature communications where even the conditions of Enceladus moon have been mimicked in a pressurized bioreactor system [5]. Overall, the $CO_2$-BMP process is a very generic process and can be integrated into a broad variety of processes and applications. Amongst others the following concepts have already been tested and evaluated:

- Biogas upgrading
- Power-to-Gas (PtG)
- Waste gas conversion
- Pyrolysis gas conversion
- Grid independent solutions
- C-neutral fuel production for mobility
- Green methane production as intermediate (and intermittent) process step

## 3. Mass and energy balances

The biomethanation process development was assessed thermodynamically using experimental data generated at the time in a slightly pressurized bioreactor [6]. This showed the benefits of exploiting, when available, pressure from selected hydrogen production steps. This directed us into the development of pressurized bioreactor system for various application concepts [7]. Because of the high pressure tolerance of certain microorganisms (static and dynamic) the pressure dimension was integrated in custom designed systems and soon after commercialized, based on operating regimes at MER < 750 [mmol $L_{R.vol.}^{-1}$ $h^{-1}$]. However, the process showed further potential to improve kinetics since, with an appropriate feeding, biomass concentrations above 25 $g_{dcw}$ $L^{-1}$ can be maintained in a biomethanation system. High biomass concentrations offer conversion capabilities at high volumetric productivities (e.g. with operations up to $q_{CH4,max}$).

## 4. Results

Our study will present preliminary versions of the models obtained from the treatment of ca. 120 steady operational states. The process was always controlled in a gas transfer limited state with hydrogen transfer rate being the process kinetic determining step or *i.e.* the biocatalyst was operated below the maximum specific productivity ($q_{CH4,max}$). More information on gas converting bioprocess technologies and relation between key process parameters and process kinetics are available in published literature [8], [9], [10].

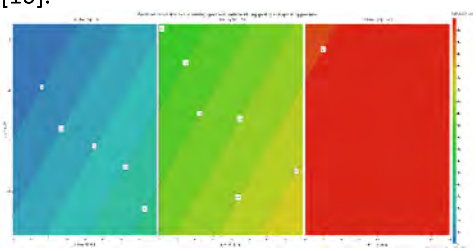

*Figure 2: Conversion model over variable pressure, gassing rate and stirring frequency*

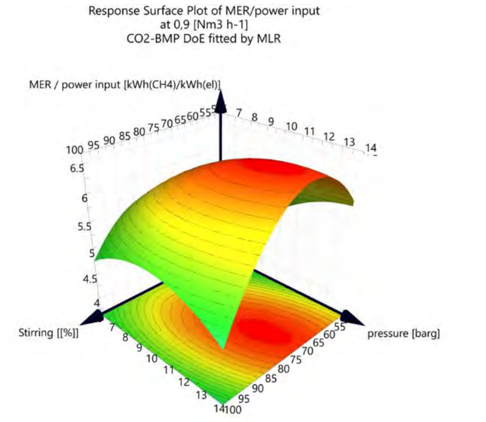


*Figure 3: Visualization of the optimal return on energy consumption in relation to the produced methane*

**Figure 2** presents, for our 15 L reaction volume R&D reactor that can be operated up to 16 barg, the trends for conversion of input gas as function of variable process parameters in active (with stirring) and passive (no stirring, conversion measured over full reactor length) reactors. **Figure 3** shows how in active systems you reach an optimum for the energy return, but this does not necessarily superpose fully with a full conversion target for the input gas and therefore a compromise is needed between full upgrade in a single passage of the gases and a given target purity.

## 5. Conclusions

The kinetics of gas converting bioprocesses have been studied over a broad range of process parameters and system designs. From this R&D emerged that depending on the frame conditions, certain approaches (active vs. passive, single step vs. multi step, intermittent operation vs. fix load operation vs. variable load operation) provide a superior performance when it comes to exploitation. During our presentation, we will provide the audience with concrete examples of how frame conditions, target product(s), purities or operating profile can influence the design of a gas converting bioprocess involved as a sector coupling technology. In fact, as postulated several years ago in an academic thesis, the advances in genetic modification and process know-how involved with gas converting microorganisms or even the integration of gas converting metabolic pathways in other microorganisms opens the door on the use of $CO_2$ as a substrate and building block to create value added products beyond the respiration metabolism end product (*e.g.,* $CH_4$ in biomethanation).

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# Synergies between biomethane and e-methane

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## 1. Introduction

The historical and actual consistent consumption of natural gas in OECD countries and especially in Europe, poses a pressing need to find and develop sustainable alternatives for its decarbonization. While for electricity production already more than 30% in OECD countries and 40% in Europe is coming from renewable sources, gas consumption is covered by less than 1% by renewable sources (Figure 1).

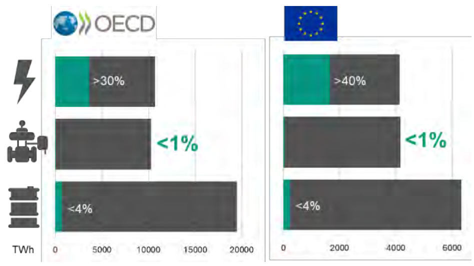


*Figure 1. Energy Total Final Consumption per source (data elaborated from IEA, 2023)[1]*

Biomethane and e-methane represent two sustainable alternatives to natural gas and offer valuable and promising options to continue to exploit the existing grid infrastructure (a crucial and strategic asset for most of OECD countries) and logistics (CNG/LNG) without upsetting today's final consumption modes (primarily heating and road/maritime transport). Moreover, the production of e-methane allows to absorb surplus renewable electricity and valorize it in an easy-to-handle form. This is crucial to mitigate the increasingly intense and frequent curtailment phenomena coming from the rapid growth of installed renewable power capacity. Variable Renewable Energy Sources (VRESs), in fact, cannot even at present match electrical demand to 100%[2] and their fast-growing trend makes increasingly important to find solutions that mitigate the resulting offer-demand mismatch.
To absorb variable excess power, a flexible and reliable conversion system is required. Biological methanation, able to transform green hydrogen coming from electrolysis and $CO_2$ into methane thanks to the metabolism specific micro-organisms called *Archaea* (Figure 2), meets these needs well.

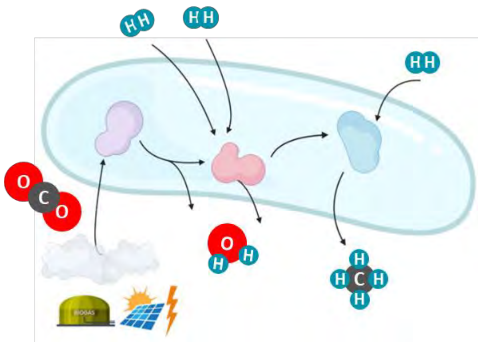


*Figure 2. The principle of biological methanation: Sabatier reaction ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$)*

*Archaea*, in fact, are naturally found thriving in energetically limited environments[3] and have been able to ecologically adapt to adverse physical-chemical conditions (e.g., high temperature and pressure) being resilient to frequent and intense flow variations and able to maintain their biological activity even in absence of continuous $H_2$ and $CO_2$ supply.

As explained in the next paragraph, biomethane and e-methane production share lots of synergies. The main one is the possibility of exploiting and valuing into additional methane a stream of $CO_2$ already concentrated and separated out by biogas upgrading plants.
The contexts for the joint application of biomethane and e-methane production are increasing consistently. In Europe, biomethane plants have seen a very important growth in the past years, passing from 243 in 2012 to more than 1.500 in 2023[4] and have the potential to grow 10 times in the next decade.

MicroPyros, a company of Pietro Fiorentini Group, owns and harvests several *Archaea* strains performing biological methanation in an optimized way, according to varying gas compositions. While Pietro Fiorentini engineers, builds and supplies biomethane Power-to-Methane complete systems, MicroPyros develops the biology, thanks to its R&D facility BioFARM and its micro-biological laboratory MioLAB, both located in Straubing, Germany (Figure 3). The first Italian Power-to-methane plant, SynBioS, is now under construction and represents a good example of synergy between biomethane and e-methane production.

## 2. Integrating biomethane & e-methane

Bio-methanation has many favourable reasons for its integration with biomethane production.

a) Plant integration: bio-methanation can follow biogas upgrading by taking the off-gas produced by it, containing mainly $CO_2$ (usually >95% v/v). The amount of $CH_4$ already contained in this off-gas has been proven not to be an inhibitive factor, being a natural product of *Archaea* metabolism.
Depending on electricity availability, $CO_2$ can also be stored and used during absorption periods, when $H_2$ production can allow $CO_2$ conversion into e-methane.

b) Biological integration: bio-methanation fits well with biogas production, also thanks to its affinity to the anaerobic biology already present in the digestors.


*Figure 3. Biological methanation - a flexible resilient process*

Indeed, anaerobic digestate can be used as a substrate rich in nutrients for *Archaea* growth, while the liquid residue from bio-methanation can be circulated back to anaerobic digestion, as a bio-enhanced sludge rich in *Archaea*.
These micro-organisms can bring benefit to biogas production itself, especially to one of the final biological processes responsible for methane generation (*Hydrogenotrophic methanogenesis*), which usually represents a limiting step in anaerobic digestion[5].

c) Exploitation of biomethane logistics: producing e-methane at same spot as biomethane, allows to exploit the existing distribution framework set up for biomethane. In case of grid injection, the access to the infrastructure follows the same principles as for biomethane, where the injection point can be shared as well as the technology used (unless its necessary expansions). The same is valid when methane is distributed as CNG or LNG; in this case transport logistics shares a common scheme and biomethane plants can benefit from economy of scale for both molecule handling (liquefaction or compression) and transport.
d) Emission control: when integrated with biogas upgrading plants, bio-methanation can also reduce consistently or even completely avoid methane losses. It is estimated that, depending on the upgrading technology, methane losses in biomethane plants can range from 0,1 to 2,9%[6]. In view of $CH_4$ high global warming potential[7], this can cause significant environmental impacts. The direct methanation of the off-gas coming from upgrading allows to capture $CH_4$ losses and valorise them together with the produced e-methane, giving a consistent enhancement of the carbon footprint of the overall integrated system.

## 3. SynBioS commercial project

At the wastewater treatment plant of Bologna, which is already producing biogas, Pietro Fiorentini is building an integrated system generating simultaneously both biomethane and e-methane (SynBioS). As depicted in Figure 4, the system comprises: biogas upgrading, Protonic Exchange Membrane (PEM) electrolysis of 1 $MW_{el}$ power, biological methanation and injection of bio/e-methane directly into the local grid.
This system represents a good example of the successful integration between biomethane and e-methane production and has been designed to ensure maximum

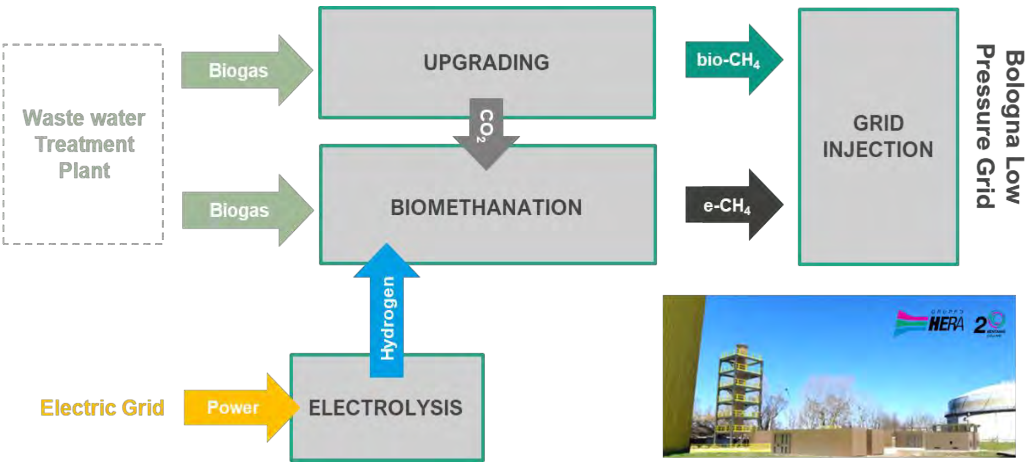


*Figure 4. The concept of SynBios project in Bologna, Italy*

flexibility. In fact, while biogas is continuously converted to biomethane, electrolysis + biomethanation are working in on/off mode, exploiting the oscillating electricity availability and price over the year and treating directly the off-gas coming from membrane upgrading. If necessary, biomethanation can also treat biogas directly, converting all the $CO_2$ contained in it.

This configuration allows to valorise at maximum both $CH_4$ and $CO_2$ produced at the facility and, in parallel, to absorb when necessary excess electricity from the grid, valorizing it in a storable form.

Thanks to its high level of innovation, the project has obtained PNRR funding under the Next Generation EU and it is expected to be one of the firsts of several future installations that will exploit the synergy of producing e-methane at biomethane plants' site.

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# Carbon Dioxide Utilisation at Biogas Plants for Enhanced Methane Production

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## 1. Introduction

The ongoing energy crisis, driven by geopolitical instability, has increased natural gas prices and drawn attention to biomethane as a renewable alternative. Demand for biomethane is growing beyond its traditional markets (e.g., light transport) to include heavy-duty vehicles, industry, shipping, and energy production. In response, Sweden and the EU have introduced incentives to accelerate the transition, from tax exemptions and Klimatklivet investment support in Sweden to the EU's proposed biomethane production target of 35 bcm per year by 2030 [1].

Among biofuels, liquefied biogas methane (LBG) is also gaining traction due to its suitability for heavy transport and long-distance distribution [2]. Biogas (>60 V% $CH_4$ content), produced via anaerobic digestion of organic waste streams (e.g., municipal solid waste -MSW, sludge, manure, etc.), contains ~40% $CO_2$, which is removed during upgrading to achieve the right quality (>97% $CH_4$). Rather than being released, this $CO_2$ can be combined with renewable hydrogen via methanation (so-called Power-to-Gas) to produce more biomethane, enhancing efficiency in the conversion of organic substrates. This is also a measure that enables energy storage, since intermittent renewables can be used for producing the hydrogen.

In 2023, Sweden produced 2.3 TWh of biogas but consumed 4.3 TWh—importing 95% of the shortfall from Denmark [3]. Integrating methanation could increase domestic biomethane production, reduce reliance on imports, cut down $CO_2$ emissions from biogas plants, and support a more robust renewable gas sector. Methanation reactors can be biological (ex- and in-situ) and catalytic. Several of these technologies are mature, with a high TRL-level and commercial-scale implementation. However, questions remain regarding which methanation technology could potentially be more suitable and economically favourable for different biogas plants; how much biomethane production could increase if methanation were implemented at Swedish biogas plants; and what the theoretical production potential would be if all upgrading facilities adopted the technology.

This study was financed by the Ingvar Kamprad Foundation and evaluated the integration of different methanation technologies into Swedish co-digestion and wastewater treatment plants through a techno-economic assessment addressing energy efficiency, methane yield, and economic feasibility. Additionally, the theoretical production potential was estimated in order to show the overall methanation potential in Sweden. An additional production of methane could also mean that economies of scale for a liquefaction plant are achieved at more sites, offering an opportunity to reach more markets.

## 2. Methodology

For the technology assessment, technoeconomic assessment and increased production potential analysis, three main methanation technologies were selected (Figure 1): Ex-situ biological methanation, In-situ biological methanation and Thermocatalytic methanation. Data for each route was compiled using open sources, interviews, and information provided from technology providers. Regardless of the type of methanation route, green hydrogen from an electrolyser is required to convert $CO_2$ into methane. Different electrolyser technologies were evaluated, but PEM (Proton Exchange Membrane) was chosen as a suitable alternative.

Key factors including plant performance, capital and operating costs and emissions were considered in the techno-economic assessment. To evaluate profitability, techno-economic modelling of ex-situ biological methanation combined with LBG production was conducted for both co-digestion plants and wastewater treatment plants (WWTPs) across a scale of 5–160 GWh/year.

The potential increase in production of renewable methane using methanation technologies at Swedish biogas plants was carried out using in-data from the project calculations. This calculation was performed for both current and planned production. The planned production units were mapped using open sources and interviews.

The analysis of liquefaction units and the conditions under which economies of scale can be achieved for these were discerned through interviews, data from technology providers, and calculations within the project.

## 3. Results

The assessments within the project showed that the potential increase of methane production with methanation technologies is 61.9%. This gain is achieved without the need for additional biomass and only by the conversion of the corresponding $CO_2$ (from biogas production) into methane, supplemented by renewable hydrogen from electrolysers.

Techno-economic assessments identified a production capacity of 40–60 GWh per year as a practical threshold for economic feasibility. While the exact viability depends on site-specific factors, such as plant ownership, business model, electricity and biomethane prices, these size ranges serve as useful indicators for assessing implementation potential. Currently, biogas plants with capacities above 40 GWh (biogas output) produce around 1,300 GWh biogas annually. With methanation, this biogas production capacity could increase to 2,100 GWh. Similarly, plants with a biogas production capacity exceeding 60 GWh currently produce 1,100 GWh, which could increase to 1,700 GWh. Considering all existing and planned plants above 60 GWh/year, the combined production capacity is estimated at 3,200 GWh.

The results indicated that profitability is achieved at different levels for different types of biogas plants. For co-digestion plants, the increased biogas production level is approximately 50 GWh/year (break-even range of 30–80 GWh/year). However, for WWTPs, the mentioned level is 32 GWh/year, since oxygen and excess heat can be utilized to a greater extent at these sites.

The findings suggest that methanation can enhance the feasibility of liquefaction at plants from about 50 GWh per year by increasing methane output and helping them reach the size needed for cost-effective LBG production. The level was decided to be 60 GWh yearly production capacity based on additional data. Methanation could therefore lead to an additional 500 GWh of liquefied renewable methane being produced at sites, which will reach a production volume of over 60 GWh due to the implementation of methanation.

## 4. Conclusions

The results of this study demonstrate that implementing methanation technologies at Swedish biogas plants can substantially increase domestic biomethane production (by up to 61.9%) without the need for additional biomass. This not only strengthens Sweden's energy security by reducing reliance on imported renewable gas but also supports more efficient use of existing resources. Additionally, methanation enhances the economic conditions for liquefied biomethane production by increasing methane volumes, making it more feasible for biogas plants to reach the scale required for cost-effective liquefaction. Methanation represents a strategic pathway to expand the use of biomethane in transport, industry, and the energy sector without increasing the use of biomass.

## 5. Acknowledgements

The project group would like to thank Ingvar Kamprad Foundation for funding the project, Jörgen Held at Renewtec AB for valuable insights into the subject and the time and engagement from the reference group that has guided the project.

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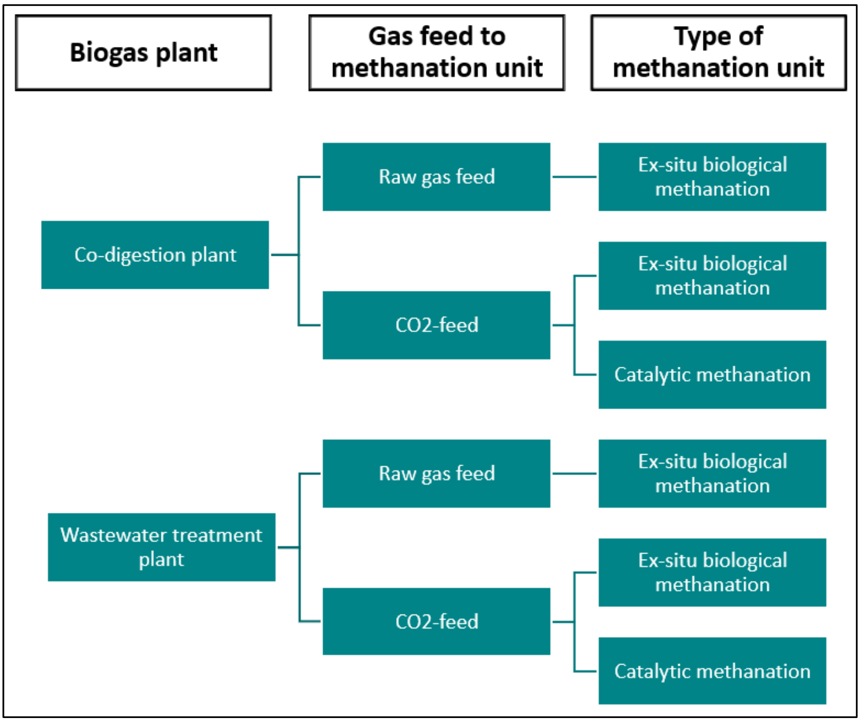


*Figure 1. Overview of the selection of analyzed routes.*

# Sustainable bioenergy and green chemical production from biomass using an innovative MVR-based thermal heat recovery system.

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## 1. Introduction

This study explores how efficient use of agricultural non-food biomass particularly from sugarcane can transform the socio-economic landscape by replacing fossil-based raw materials. Saving and utilizing this biomass enables the production of value-added products such as compressed biogas, green chemicals, biofuels, 2G ethanol, and sustainable aviation fuel. The authors present a low-temperature evaporation technology based on mechanical vapour recompression (MVR) system that recycles thermal waste heat, eliminating the need to burn biomass. This carbon-negative and water-positive system, powered by solar energy, avoids fuels burning thus no $CO_2$ emissions, conserves water and save bagasse, and supports green chemicals and hydrogen production.

## 2. Technology description

The indigenously developed patented mechanical vapour recompression (MVR) based low temperature evaporation (LTE®) system using thermal heat recycling was designed to operate at very low temperature range by recycling of vapour enthalpy. With such an innovation recycling process is achieved in a closed loop, resulting no heat loss and zero carbon emissions.

MVR based thermal heat recycling technology at low temperature as shown in figure 1 depends on the flow capacity and consists of three principal elements: heat transfer, vapour-liquid separation and efficient utilization of heat energy.

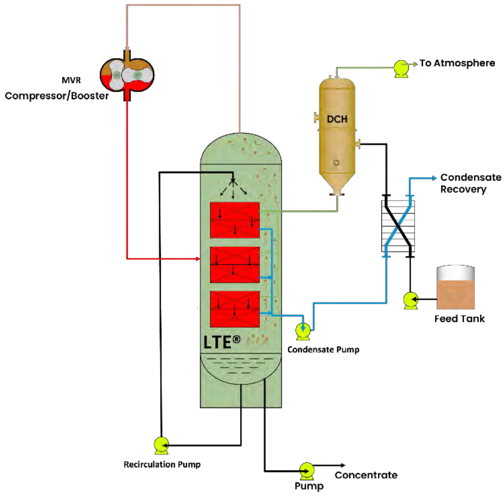


*Figure 1. MVR based Thermal Heat Recycling System*

This technology with small footprint design delivers higher evaporation capacity. The major advantage is that it can operate on direct evaporative liquids. It operates at the lowest operating cost with maximum condensate recovery that is recycled back to the process. This product is designed for separating excess water (85-99%) from any type of evaporative liquid which in turn concentrates into discharge fluid. This is highly reliable, robust, and very easy to control, which operates automatically. The user-friendly operating conditions make this technology an ideal for wide scale industrial as well as domestic applications.

*Process design of technology*

The technology is operated without the use of any external heat source like boiler, turbine or heat rejection source like condensers, cooling towers. For the initial startup of the system, make up steam or a heat pump hot side connection is provided of the first stage heating. To increase energy efficiency, this innovative technology is manufactured using plate packs heat exchanger stacked one above the other as per figure 1 keeping some distance between both plate packs heat exchangers.

The purpose of this technology is to use compressed vapour for increasing concentration of feed, eliminating the need of boiler (except for start-up of the plant) and turbine in the plant. A mechanical vapour recompression (MVR) system with falling film plate evaporation requires a heat pump to create make up steam initially to bring the system up to boiling temperature during startup, and once operating at steady state, the compressor adds energy to the system (Verma 2021, 2022, 2023, 2024). The solar panels are installed for power generation to run the plant. Using electrolyzes; hydrogen is produced from the solar panels for further value addition.

This design arrangement helps to operate with minimum delta T and consequently lower MVR power (Verma 2023). Because of the falling film technology, the liquid is pumped to the top of the plate packs heat exchanger and distributed with a special distribution system which allows to generate a thin liquid film on the heat exchanger surface. The liquid feed is then concentrated with the application of thermal waste heat of the compressed vapour (Verma 2023, 2024). The design of the new evaporator operates as a single or multi-effect evaporator for sugar complex with many other significant technological and economic advantages (Verma et al. 2023, 2022):

*Salient features of technology*

- No heat generation unit (no boiler and no turbine in the plant)
- No heat dissipation unit (No cooling tower and no condensing station)
- No fuel burning thus zero $CO_2$ emissions
- Maximum evaporation & concentration
- Low footprint due to compactness
- 100 bagasse saving
- 100% clean water recovery & recycling

This product is available in all type of MOC like SS304, SS316, Ti SS etc. with the available capacity from 0.5m$^3$/h to 80m$^3$/h for any type of evaporative liquid handling and processing for almost 100% high quality clean water recovery.

Using this technology, authors have tried to save 100% biomass first then utilize this saved non-food biomass for value-added products. This article describes the running of the 750 TCD sugarcane processing plant for 100% bagasse saving and 170 KLPD grain-based distillery using MVR based system with thermal heat recycling on minimum power demand eliminates the need of boiler, turbines, condenser and cooling tower as well as saved bagasse into value-added products.

## 3. Case studies

*Case 1: MVR based sugarcane processing (Plant capacity 750 TCD)*

The EcoTech Agro based sugarcane processing plant in Assam, India is running successfully without biomass burning with total power consumption 45 kW per ton of cane. It lets the boiling of the liquid and vapour generated is compressed by compressor which delivers a heating stream to raise the temperature of overall mass of the feed progressively. After concentration with compressed vapour, the concentrated syrup was sent for solidification into jaggery and saved 100% bagasse is utilised for value added products like CBG, 2G Ethanol, Green Chemicals, Aviation Fuels, Fertilizers, degradable and non-degradable Polymers.

*Figure 2. MVR based sugarcane processing plant*

*Case 2: MVR based distillery (Plant Capacity 170 KLPD)*

The Dalmia Bharat Sugar and Industries Ltd., Jawaharpur, Uttar Pradesh, India is a well-known brand in Indian Sugar Industry and one of the fastest-growing sugar and ethanol manufacturer in India. It is the first kind of plant which has been designed, engineered, supplied, erected and commissioned using MVR based system for 170 KLPD grain-based distillery. This plant is running successful with overall 50% steam reduction and elimination of cooling tower to achieve zero $CO_2$ emission. Major design parameters for distillery are shown in table 1.

*Table 1: Major design parameters*

| Sr. No. | Parameters | Quantity | Capacity |
|---|---|---|---|
| **1.** | **Evaporation Section** | | |
| i | Tubular FFE (HSA in $m^2$) | 6 nos. | 9000 $m^2$ |
| **2.** | **Distillation Section** | | |
| i | Transformer 1 (HSA in $m^2$) | 1 no. | 1500 $m^2$ |
| ii | Transformer 2 (HSA in $m^2$) | 1 no. | 1000 $m^2$ |
| **3.** | **Reboiler** | | |
| i | Tubular FFE HSA in $m^2$ | 1 no. | 1500 $m^2$ |
| ii | Tubular FFE HSA in $m^2$ | 1 no. | 1000 $m^2$ |
| **4.** | **Distillation Column** | | |
| i | Degasser Column, Diameter, m | 1 no. | 1.4 m |
| ii | Analyzer Column, Diameter, m | 1 no. | 2.0 m |
| iii | AC & DG Column, Overall Height, m | 1 no. | 30 m |
| iv | Rectification Column, Diameter, m | 1 no. | 2.0 m |
| v | RC Column, Overall Height, m | 1 no. | 30 m |
| **5.** | Forced Circulation Evaporator HSA in $m^2$ | 1 no. | 500 $m^2$ |

*Figure 3. MVR based 170 KLPD grain-based distillery plant*

**4. 2G Ethanol/Biofuels production**

Producing 2G & 4G ethanol/biofuels and green chemicals from 100% saved sugarcane-based bagasse / biomass as per figure 4 involves the conversion of lignocellulosic biomass into fermentable sugars, followed by their fermentation to ethanol. Sugarcane non-food biomass is an abundant by-product of the sugarcane industry and contains cellulose, hemicellulose, and lignin, making it an excellent feedstock for 2G ethanol production. Solar panels are used to generate power to run the processing plant and green hydrogen can be produced from this renewable resource. The schematic diagram for ethanol production have following major steps:

- MVR based drying
- Pyrolysis
- Gasification
- Syngas cleaning & filtration
- Fermentation
- MVR based distillation

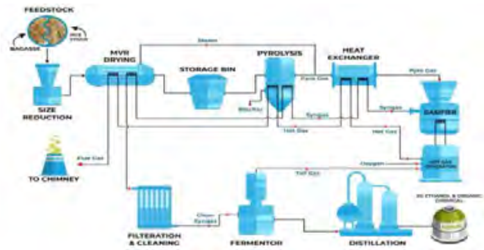


*Figure 4. Scheme for 2G ethanol/biofuel production from feedstock*

2G ethanol production from non-food biomass is a key driver of a green and sustainable circular economy. It not only reduces waste and enhances energy security but also creates employment opportunities, food security and fosters rural and technological development. Over time, it strengthens the world economy by reducing dependence on fossil fuels and mitigating the economic impacts of climate change.

## 5. Conclusions

This study demonstrates the effectiveness of MVR based low temperature evaporation system to recycle thermal waste heat for concentrating liquids. The process enables 100% bagasse savings and complete water recovery, offering a sustainable alternative to conventional evaporation methods without burning fuel. It is suitable for a range of applications for industrial as well as domestic sectors. The technology marks a transformative shift in industrial processing, achieving carbon-negative and water-positive outcomes. Solar-powered, boiler-free sugarcane units eliminate $CO_2$ emissions and pollution while enabling on-site green hydrogen production. Operating at lower $\Delta T$, the system reduces the need for high-pressure steam, lowers scaling risk, and preserves products quality by minimizing various industrial losses. Overall, this innovation supports zero-emission goals, enhances resource efficiency, and enables the conversion of saved bagasse into value-added products like 2G ethanol, biofuels, green chemicals, green hydrogen, fertilizers, aviation fuels, contributing to a sustainable and circular economy.

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# European Gasification Potential: Techno-Economical, Regulatory and Geographical Interplay

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## 1. Introduction

The European Union's commitment to achieving net-zero emissions by 2050 has spurred interest in renewable gases as part of its broader strategy for decarbonising the energy sector. Among the various renewable energy technologies, gasification has emerged as a promising solution, offering a versatile approach to converting organic materials into clean energy [1,2].

According to the estimate provided in the European Commission's report on biofuels development [3], under current market conditions, the energy contribution of gasification technologies can only reach 0.62 bcm by 2030 and 9.9 bcm by 2050. However, according to Guidehouse modelling in the "Biogases towards 2040 and beyond" [4] report, the potential for biomethane production from thermal gasification can reach 37 bcm. When feedstocks are utilized accordingly, market conditions have evolved and technological advances happened, biomass and waste gasification could play an integral role in transitioning towards sustainable energy solutions, while mitigating the environmental impacts associated with fossil fuel consumption.

## 2. Methodology

There is a need to map regional technological deployment, and policy tends alongside market considerations to bring technology into perspective and to accelerate its adoption. To provide a comprehensive understanding of the current landscape of thermal gasification in Europe, The European Biogas association (EBA) conducted an analysis of various aspects related to gasification, results of which were presented in a recent publication [5].

The technical overview primarily focused on setting the scene of existing and state of the art emerging technologies, as well as process parameters influencing system efficiencies. The economic analysis concentrated on general market drivers and challenges, in addition to cost benefit assessment of operational plants, including CAPEX, OPEX and ROI timelines. A mapping analysis of existing gasification installations across Europe was also conducted, identifying key regional clusters and feedstock availability patterns. Further, a policy review on EU and national levels was conducted outside the scope of the white paper, but will be integrated in the discussion section below.

## 3. Findings

As of 2023, 141 existing biomass and waste gasification installations were identified in Europe, as well as 54 installations at different stages of development or with an unknown construction date. Germany is the leading country regarding the number of installations, with 61 (Figure 1). The majority of the plants are in the pilot or demo stage. The country with the second largest number of projects is France. In France, five plants are in operation, while 34 plants are under development. Finland and Italy share third place in the number of installations (18 each), as well as the fact that over 80% of their installations are TRL ≥ 8 [5].

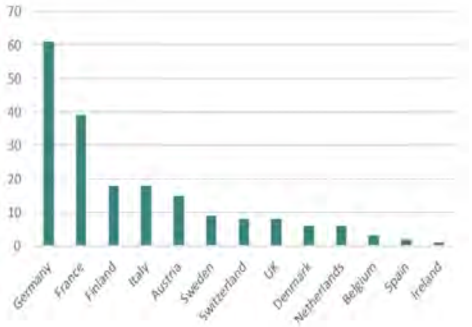


*Figure 1. Plant distribution across European countries.*

There was significant plant building activity in the late 2000s and early 2010s. This was most likely a response to various legislation adopted in 2008-2009. The Renewable Energy Directive (RED), adopted in 2009, set binding targets for the share of renewable energy sources for Member States. Many European countries introduced feed-in tariffs (FiTs) and other financial incentives for renewable energy production after RED implementation, making investments in biomass gasification technology more attractive. The introduction of carbon pricing mechanisms, such as the EU Emission Trading System (ETS), created financial incentives for reducing greenhouse gas emissions. The EU Waste Framework Directive was adopted in 2008 and emphasised waste management practices, including energy recovery from waste.

A series of crises in the early 2020s put a constraint on building new projects, but there are signs of revitalisation of the sector. It remains to be seen, however, if these emerging installations can progress to operating on an industrial scale.

The majority (61%) of existing gasification plants are reported to be at a TRL of 9 (Figure 2). Nevertheless, there are a number of projects that have not achieved a high technological readiness level over the years (24% of plants built before 2018 are not yet at full maturity, with a TRL ≤7).

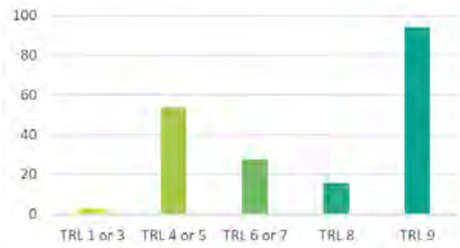


*Figure 2. TRL prevalence among European gasification installations*

The plant output at the moment is primarily CHP (84% of all installations), whether utilising both power and heat or just one of the components. The minority of plants upgrade syngas to further products, with a couple of installations each for hydrogen, methanol, SAF and other products (Figure 3).

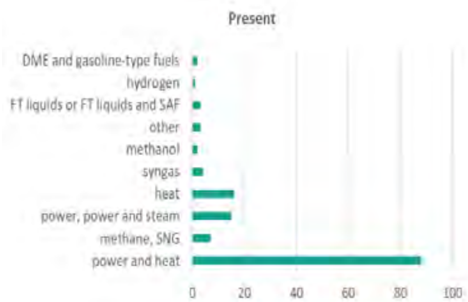


*Figure 3. Gasification products dynamic: only currently operating facilities*

The feedstocks used in thermal gasification play a crucial role in determining the process efficiency and the quality of the produced syngas. A wide variety of biomass resources can be utilised, including agricultural residues (corn stover, rice husks and wheat straw), forestry wastes (sawdust, bark and logging residues), energy crops (switchgrass, miscanthus and short-rotation woody crops like willow and poplar) and municipal solid waste (MSW).

The majority of gasification plants (75%) are reported to use lignocellulosic materials, such as forestry and agricultural residues. Waste streams contribute around 5%. The remaining plants use mixed feedstock sources (Figure 4).

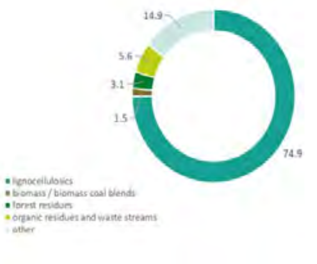


*Figure 4. Proportions of feedstocks (%) for biomass and waste gasification*

## 4. Discussion

Gasification technology holds significant promise for advancing the EU's renewable energy goals, yet its deployment is shaped by a complex interplay of geographical, economic, and policy factors. The analysis reveals that while gasification projects are concentrated in specific regions such as Germany, Sweden, and Finland, driven by favorable subsidies and national policies, other areas like Southern and Eastern Europe remain underutilized despite abundant feedstock availability. For instance, Nordic countries benefit from carbon tax rebates and direct subsidies for bio-SNG production, creating a robust environment for waste-to-energy projects. Likewise, Germany's Renewable Energy Sources Act (EEG) provides feed-in tariffs that encourage biomass utilization. In contrast, Southern Europe struggles with fragmented policies and limited financial support, leaving agro-residues like olive pomace largely untapped. The findings underscore the need for a more cohesive approach to gasification deployment across the EU.

Economic viability is another critical factor influencing gasification adoption. Feedstock procurement costs dominate operational expenses, accounting for 55–70% of total costs. However, policy-driven mechanisms such as International Sustainability and Carbon Certification (ISCC) and Guarantees of Origin (GOs) have proven effective in enhancing project profitability by increasing biomethane prices by 15–25% in markets like Germany and France. Furthermore, the lack of uniform EU-wide funding schemes has led to disparities in project development.

From a policy perspective, the alignment of EU directives such as RED III with national strategies remains inconsistent. RED III's stringent sustainability criteria favor waste-based feedstocks but inadvertently exclude certain biomass sources used in existing gasification plants. This misalignment creates regulatory uncertainty that stifles investment in regions with high feedstock potential but low compliance rates. Additionally, emerging technologies like pyrogasification face significant barriers due to outdated permitting processes and a lack of adapted regulations. For instance, France's experimental contracts for innovative renewable gas production show promise but remain insufficient to launch large-scale industrial units.

Noteworthy, lessons from the analysis of variety of climate legislations accentuate that there is never a single most efficient policy or subsidy scheme that can drive the technology forward, rather it is always a carefully crafted mixture with the best complementarity for the region [6].

## 5. Conclusions

To address these challenges and accelerate gasification deployment across the EU, several key actions are recommended below.

*Legislative Harmonization.* Streamline permitting processes for waste-fed gasification plants and expand RED III's definitions to include a broader range of biomass feedstocks. This would reduce regulatory uncertainty and enable greater flexibility in project design.

*Economic Incentives.* Carbon Contracts for Difference (CCfDs) could de-risk investments in gasification technologies by guaranteeing stable revenue streams for hydrogen or synthetic methane production.

*Strategic Regional Development.* Establish regional gasification hubs tailored to local feedstock availability and infrastructure capacity.

*Integrated Policy Frameworks.* Align national strategies with EU directives through coordinated research initiatives and funding programs. For instance, Horizon Europe could allocate a larger share of its energy budget to gasification R&D while fostering partnerships between member states. Additionally, there is a need for support of emerging technologies which could be done by adapting regulations to accommodate advanced technologies.

By addressing these legislative, economic, and strategic gaps, stakeholders can unlock the full potential of gasification as a key contributor to the EU's renewable energy transition while ensuring equitable resource allocation across regions. Future research should focus on optimising operational efficiencies and reducing costs to enhance the competitiveness of biomass gasification in the renewable energy sector. A coordinated effort involving policymakers, industry stakeholders, and research institutions is essential to harmonize regulations, optimize funding mechanisms, and leverage regional strengths.

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# Demonstration of DFB-to-SNG Process Chains at the Syngas Platform Vienna

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## 1. Introduction

Alternative fuels and technologies for energy and resource conversion are necessary to substitute the currently fossil-dominated energy carriers with a sustainable energy mix. A promising technology for a sustainable transition is the combination of dual fluidized bed (DFB) gasification with subsequent synthesis processing such as syngas methanation [1]. Depending on the operational parameters of the DFB system, the product gas can be used for the production of specific biofuels or chemical commodities. A schematic description of the most important DFB operational modes and two synthesis options is shown in ***Figure 1***. DFB-to-SNG routes target the conversion of the product gas into $CH_4$ for chemical and energy purposes via catalytic methanation.

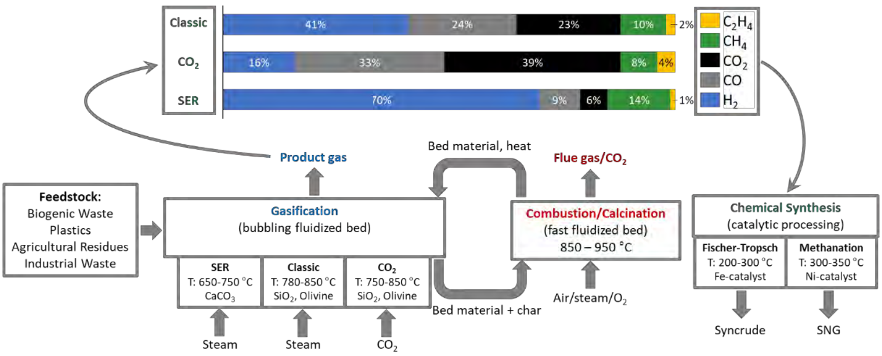


*Figure 1: Dual fluidized bed (DFB) operational modes*

## 2. Technology Description

The technology of the DFB-to-SNG process chain starts with the feedstock used for DFB gasification. The list of possible feedstocks comprises a wide range of biomasses and wastes, although a lack of practical experience and encountered operational issues are limiting factors for industrial applications. The gasification in the dual reactor system makes use of the advantages of fluidized bed conversions systems such as enhanced load and feedstock flexibility and good particle mixing while maintaining the heat and energy balance between the gasification reactor and the combustion reactor. For this purpose, bed material and feedstock char are transported from the gasification reactor to the combustion reactor through a connection in the lower reactor zones and heated bed material is transported from the combustion reactor to the gasification reactor.

The 1 MW steam gasifier at the Syngas Platform Vienna is based on the advanced dual fluidized bed (aDFB) reactor concept established by TU Wien in a 100-kW pilot-scale unit. Research in both mentioned facilities has targeted the conversion of alternative, i.e., non-woody, biomass and waste feedstocks to syngas of different qualities according to the requirements of subsequent synthesis processes [2,3]. A process scheme of the gasification reactor and subsequent coarse gas cleaning units is shown in ***Figure 2***.

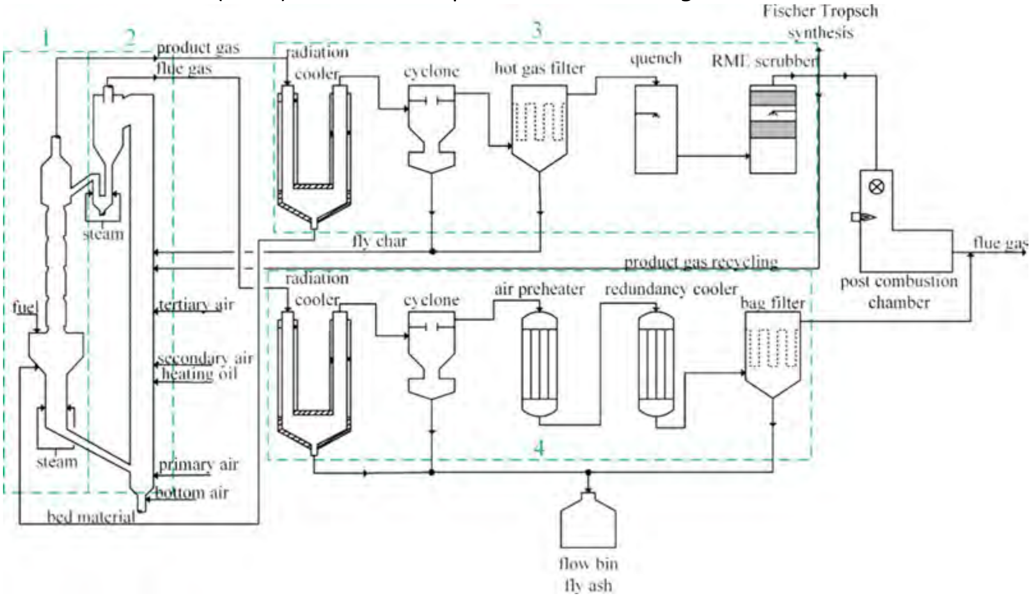


*Figure 2: Process scheme of the 1 MW demonstration aDFB gasifier at the Syngas Platform Vienna* **[3]**

The fine gas cleaning for the generation of syngas ready for methanation at the Syngas Platform Vienna comprises a temperature swing adsorption (TSA) unit and a gas bottling station. The TSA cleans a fraction of the coarse-cleaned product gas from the 1 MW steam gasifier and a dual column TSA setup shown schematically in ***Figure 3***.

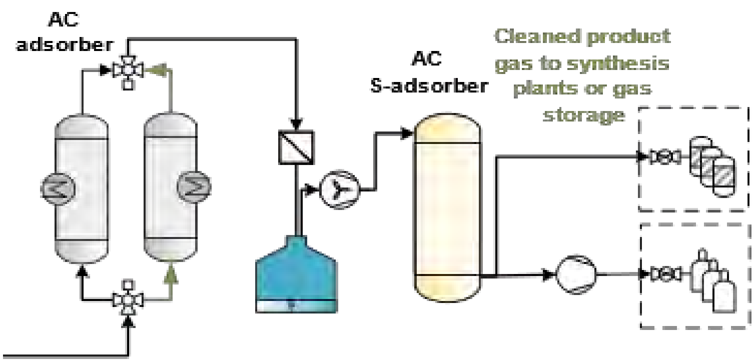


*Figure 3: Process scheme of the TSA gas cleaning at the Syngas Platform Vienna*

The methanation technology referred to in the projects later on is the fluidized bed methanation developed by TU Wien. The investigations of the DFB-to-SNG process chain use syngas from the 1 MW steam gasifier for methanation in a 10-kW fluidized bed methanation reactor. The feasibility of this methanation method has been demonstrated in pilot-scale process chains already [4].

## 3. DFB-to-SNG Research in Demo-Scale

Ongoing research projects targeting the production of SNG from syngas produced by DFB steam gasification of biomass and waste feedstocks at the Syngas Platform Vienna are:

*BIG – GreenGas*

The goal of the BIG – GreenGas project is to research new processes for upgrading biogenic residues into green gas, thereby enhancing the regional potential for climate-neutral gases in Austria. To this end, the regional availability of biogenic residues suitable for use in gasification was first determined. Selected residues were tested in a 1 MW gasification plant (Syngas Platform Vienna) for their suitability. The resulting product gas can subsequently be tested to produce synthetic natural gas (SNG) or hydrogen. Based on experimental data, costs for production chains can be estimated, an environmental balance can be created, and recommendations for adapting existing legislative guidelines (e.g., limits for impurities developed with biogas in mind) can be given.

The key outcomes of the project so far are:

• Technical biomass potential in Austria: 12 TWh of $CH_4$ per year, of which 55% is wood-based

• 15% of Austria's demand for green gases (SNG, $H_2$) can be supplied through gasification

• Bark has the highest potential in Austria and was therefore chosen as the first feedstock for the demonstration at the 1 MW Syngas Platform Vienna

• Paper sludge from paper recycling was chosen as second feedstock. During the operation a $H_2$:CO ratio of 2.3 could be reached.

• The composition of product gas from both operations is comparable to product gas from wood chip gasification.

• Operation of the fluidized bed methanation over 2 days showed promising results regarding raw SNG quality and catalyst stability

• The main drivers of the processes global warming potential are electricity, the biodiesel used for tar removal and the amine used for $CO_2$ removal

*BioHEAT*

The project BioHEAT aims to promote the utilization of bio-based opportunity fuels in DFB steam gasification and the optimization of aDFB steam gasification by optimized operation monitoring to produce a product gas used for combustion applications. Furthermore, the generation of bioSNG based on aDFB steam gasification and subsequent combustion or methanation with a focus on a stable, load flexible and feedstock flexible operation is targeted. This leads to a technical and environmental proof-of-concept of the full process chain DFB-to-SNG.

Results from the BioHEAT project include a first-of-its-kind classification scheme for opportunity feedstocks based on technological criteria. This work is coupled with the evaluation of the economic feedstock potentials. The process chain DFB-to-SNG was investigated with two of the selected opportunity fuels: waste wood and corn spindles. The project is accompanied by process simulation tasks for the methanation setup.

*SuSNG*

In the project SuSNG, the process chain DFB-to-SNG is evaluated based on the individual process steps with the target of supplying $H_2$-enriched syngas, i.e., sufficiently clean, for methanation and subsequent upgrading of raw $CH_4$. The project focuses on:

- Establishing suitable models and simulation setups for the DFB-to-SNG process chain
- Systematic investigations of the necessary fine gas cleaning units
- Demonstrating the operation of a 1 MW aDFB gasifier towards H2-enriched product gas generation
- Methanation of the produced syngas in a fluidized bed methanation reactor
- Scaling considerations for industrial applications of the process chain

## 4. Conclusions

Research on innovative processes for the production of sustainable methane from aDFB gasification is a focus topic at the Syngas Platform Vienna. Process chain demonstrations have been achieved, but adapted DFB-processes for the production of $H_2$-enriched product gas are yet to be demonstrated to enable industrial implementations.

## 5. Acknowledgements

We want to acknowledge the funding agencies (ERA-NET, FFG) supporting the abovementioned projects and our project partners:

- ÖVGW
- TU Wien
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- Energy and Chemical Engineering GmbH
- Montanuniversität Leoben
- Jagiellonian University Krakow
- Danex sp.z.o.o.
- Aichernig Engineering GmbH

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# The FlexSNG project.

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## 1. Introduction

In the context of urgent energy system decarbonization, biomass-based solutions offer promising opportunities—especially when paired with waste valorisation. Various technological pathways exist for converting biomass and waste into valuable products, depending on the desired outputs. As Europe phases out coal and oil-based energy sources in the coming decade, natural gas is expected to remain a key transitional fuel. To support its decarbonization, the FlexSNG project—Flexible Production of Synthetic Natural Gas and Biochar via Gasification of Biomass and Waste Feedstock—aimed to demonstrate a flexible and efficient route for producing renewable synthetic natural gas and biochar, leveraging advanced gasification technologies.

## 2. The FlexSNG Project & Concept

The FlexSNG project was launched in 2021 under a European call for international cooperation with Canada on advanced biofuels and bioenergy. The project, awarded €4.5 million in funding, brought together 12 partners from 8 countries: Finland, Greece, Italy, Denmark, Sweden, Germany, the UK, and Canada.

The consortium covered the entire value chain as illustrated in Figure 1. More information on the consortium is available at: https://www.flexsng.eu/


*Figure 1. FlexSNG project consortium and task contribution.*

*The FlexSNG Concept*

FlexSNG aimed to develop and validate—up to TRL 5—a highly efficient, cost-effective, and feedstock-flexible process for producing intermediate bioenergy carriers (biomethane and biochar) and heat. The concept targets low-cost, non-food biomass residues and biogenic waste feedstocks.

Cost-effectiveness is pursued by:

- optimizing feedstock supply chains (targeting 20% cost reduction),
- reducing the conversion process CAPEX by 30%,
- lowering biomethane production cost by 30%.

Flexibility in feedstock and gasification operation modes further enhances the commercial viability of the process that is presented in Figure 2.

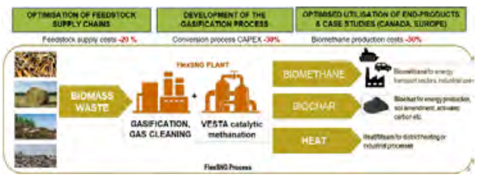


*Figure 2. FlexSNG concept and expected outcomes.*

*FlexSNG Approach – "One plant, two modes"*

The core concept of FlexSNG is the ability of a single gasification plant to operate in two distinct modes, depending on market demand. Mode 1 represents the co-production of biomethane, biochar, and heat by operating the gasifier at a lower temperature (750–800 °C). This results in partial carbon conversion, yielding lower biomethane output but producing biochar—advantageous when biochar prices are high and biomethane prices are low. Mode 2 focuses on maximizing biomethane and heat production by operating at higher temperatures (around 900 °C), leading to near-complete carbon conversion and optimal syngas production for methanation. Figure 3 illustrates the FlexSNG plant configuration that allows for such operational flexibility.

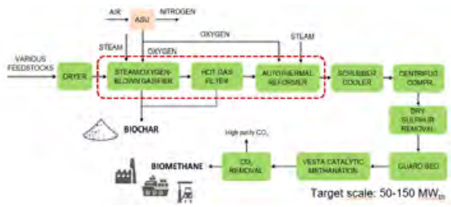


*Figure 3. FlexSNG Process Scheme for Flexible Production of SNG and Biochar.*

## 3. FlexSNG Pilots and Tests

Two gasifier configurations—a Bubbling Circulating Fluidized Bed (BCFB) and a standard Circulating Fluidized Bed (CFB), both operating at atmospheric pressure—were initially evaluated to identify the most suitable setup for the FlexSNG concept.

*Preliminary Pilot Gasification Tests 2021-2022*

Three week-long pilot tests were conducted between 2021 and 2022 to assess alternative designs and operating conditions for both target modes, using bark, straw, and clean wood pellets as feedstocks. Both configurations produced high-quality biochar with no impact on raw gas quality. However, the standard CFB was ultimately selected due to its operational flexibility and smoother transition between modes.

In the CFB setup, bed material recycling was implemented. Gas cleaning in both configurations included hot filtration, catalytic reforming, and final purification steps. Table 1 summarizes the main operating parameters from the preliminary tests [1].

*Table 1. Preliminary Pilot Test Parameters 2021-2022.*

| | **Value** |
|---|---|
| Feed Rate [kg/h] | 20-40 |
| Operating Pressure [bar] | 1 |
| Gasifier Temperature [°C] | 700-900 |
| CFB Gasifier [m/s] | 1-3 |

*Table 2. Feedstocks for Validation Test Campaigns in 2023-2024.*

| Feedstock (Pellets) | **Wood** | **Forest Residue** | **Straw** | **Waste Wood** | **Biochar** | **SRF** |
|---|---|---|---|---|---|---|
| LHV [MJ/kg] (dry basis) | 18.9 | 19.3 | 17.6 | 18.9 | 32.2 | 21.4 |
| Moisture [wt-%] | 7.5 | 11.7 | 10.2 | 7.5 | 2-3 | 3.4 |
| Volatile Matter [wt-%] | 78.0 | 75.0 | 76.1 | 79.4 | 7.4 | 74.2 |
| Fixed Carbon [wt-%] | 21.7 | 20.7 | 19.3 | 19.1 | 91.1 | 7.3 |
| Dry Matter Analysis [wt-%] | | | | | | |
| C | 50.2 | 49.8 | 44.8 | 50.2 | 91.4 | 50.0 |
| H | 6.5 | 5.7 | 6.2 | 5.9 | 1.7 | 6.4 |

| | | | | | | |
|---|---|---|---|---|---|---|
| N | <0.1 | 0.5 | 0.7 | 0.5 | 0.6 | 1.0 |
| O | 42.9 | 39.6 | 43.5 | 41.8 | 4.7 | 21.8 |
| Ash | 0.3 | 4.4 | 4.6 | 1.5 | 1.5 | 18.6 |
| S | 0.01 | 0.049 | 0.10 | <0.1 | <0.1 | 0.60 |
| Cl | 0.002 | 0.022 | 0.15 | 0.0019 | nd | 1.67 |

*Validation Test Campaigns in 2023-2024*

Following the selection of the CFB as the preferred gasification technology, a 500 $kW_{th}$ pilot plant was equipped with an integrated Oxygen Transport Membrane (OTM) module. The OTM offers a cost-effective alternative to conventional Air Separation Units (ASUs), which are typically expensive components in gasification systems. Figure 4 illustrates the pressurized fluidized-bed gasification test rig at VTT Bioruukki, Finland, used for the FlexSNG validation test campaigns conducted in 2023 and 2024 [1].

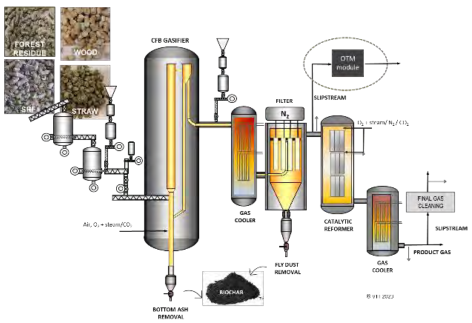


*Figure 4. Scheme of 500 $kW_{th}$ Pressurised Fluidised-Bed Gasification Pilot Plant at VTT Biorukki, Finland.*

The feedstocks tested in the validation campaigns include clean wood, forest residue, straw, waste wood, biochar, and SRF pellets of which Table 2 presents the main properties.

## 4. Results

The pilot campaigns ran for a total of 191 hours, demonstrating the FlexSNG concept's capability to seamlessly switch between the two operating modes and feedstocks, while maintaining good conversion efficiencies for both biochar and biomethane [1]. As shown in Figure 5, smooth transitions were achieved between different feedstocks and between operating modes, with the latter requiring approximately three hours to reach stable conditions. Operating the FlexSNG plant in maximization mode (850–900 °C) enabled carbon conversion rates of 97–98%. In co-production mode, adjusting the temperature from 860 °C to 725 °C allowed biochar yields of up to 11%, as illustrated in Figure 6.

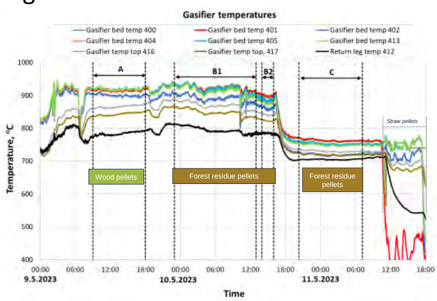


*Figure 5. Gasifier Operation in co-production of Biochar and Maximized Syngas Mode.*

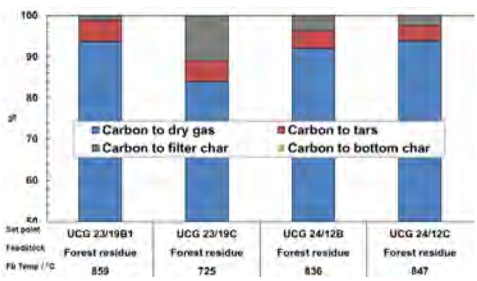


*Figure 6. Carbon Conversion for Forest Residues Pellets at different set temperatures and operating point.*

*Biochar and Biomethane Quality*
The produced biochars were analysed to assess their quality and their potential applications. The results confirmed compliance with the requirements of the European Biochar Certificate and the International Biochar Initiative. FlexSNG biochars showed high potential for carbon sequestration, soil amendment, and use as a material additive in construction [1]. Due to their high calorific value and carbon stability, they are also suitable for energy applications, though high ash content limits their use in small-scale burners. Figure 7 presents the imagery results of the biochar analysis carried out in the first campaign.

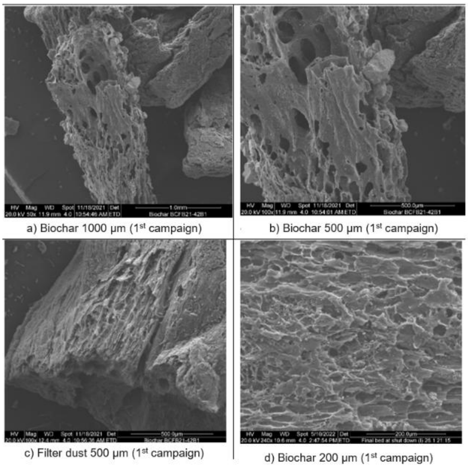


*Figure 7. FlexSNG biochar imagery.*

The biomethane produced met quality standards for use in combined heat and power (CHP) systems and hard-to-electrify sectors, confirming its suitability as a renewable substitute for natural gas [1].

*Economic Assessment*
The project successfully achieved its target of a 20% reduction in feedstock supply costs, driven by optimized logistics and supply chain planning. The 30% CAPEX reduction target for the conversion process was also met and even surpassed, largely due to the cost-efficient integration of the Oxygen Transport Membrane (OTM), which reduces oxygen supply costs compared to conventional ASUs. The biomethane production cost reduction target of 30% was nearly reached, with reductions ranging between 20–29% compared to state-of-the-art GoBiGas benchmarks, depending on the operating mode.

To assess profitability, 17 case studies (8 in Europe, 9 in Canada) were conducted, covering diverse feedstocks, plant sizes, end uses, and operating modes. The analysis revealed that plant size significantly affects profitability, with larger configurations achieving higher Internal Rates of Return (IRR). In a comparative analysis of the cases, it was found that, under current market conditions and policy support, the most viable scenarios were in Sweden (IRR: 11.4%) and Finland (IRR: 17%) [1].

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# Influence of ash-forming elements and lignocellulosic structure on the evolution and transport of S and Cl in a dual fluidised bed gasifier

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## 1. Introduction

Biomethane production through pyro-gasification of waste wood, solid recovered fuel (SRF), agricultural residues, manure and organic waste could contribute to the global biogas demand, providing a low-carbon energy solution. However, the syngas produced from these feedstocks contains gaseous pollutants like Cl and S, which must be removed to avoid damaging downstream processes, poisoning syngas valorisation catalysts of methanation. The aim of the partnership (named TIGRE chair) between the ENGIE R&D lab. CRIGEN and M2P2 (Aix Marseille university) is to better understand, so to predict, the behaviour of inorganic compounds in a dual fluidized bed reactor. This study focuses on solid phase interactions, which are expected to be a solution to maximize the retention of S and Cl in the nascent char [1,2].

## 2. Technology description

Gasification tests were performed on the GAYA semi-industrial scale FICFB (Fast Internally Circulating Fluidised Bed). This plant was designed to convert a wide range of feedstock into a $N_2$-free syngas suitable for Synthetic Natural Gas (SNG) production (Figure 1). FICFB consists of two connected fluidised beds. One dedicated to steam gasification and another one to heat-up the circulated catalytic bed material (olivine) , combusting residual char, tars, carbonaceous residue and part of the produced syngas. As a result, two gas streams (syngas and flue gas) are produced [3].

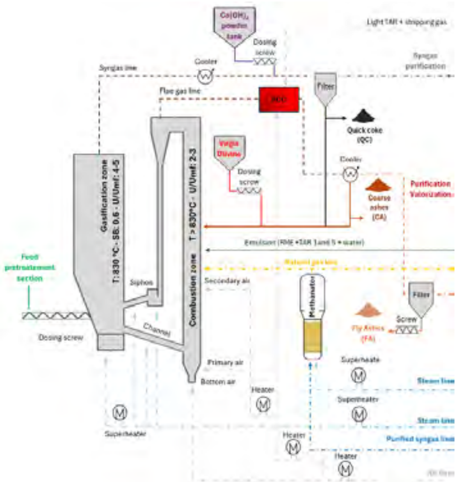



**Figure 1** *FICFB plant (400 to 600 kW).*

## 3. Materials and methods

Experimental campaign has been carried out by gasifying at 830°C three different feedstocks:

- Feed 1: 100% Forestry Chips (FC)
- Feed 2: 80% FC + 20% Straw Pellet (SP)
- Feed 3: 80% FC + 10% SP + 10% Pine Bark (PB)

**Table 1** *Feedstock main characteristics*

| Feed | Proximate analysis [w/w%]$_{db}$ | Ultimate analysis [w/w %]$_{daf}$ | Elemental analysis [mg/kg]$_{db}$ | |
|---|---|---|---|---|
| | Ash | C | Cl | S |
| Feed 1 | 0.6 | 50.5 | 160.0 | 160.0 |
| Feed 2 | 1.5 | 49.8 | 352.0 | 454.0 |
| Feed 3 | 1.2 | 50.7 | 258.0 | 314.0 |

The only feedstock pelletized (length 20 mm, diameter 5 mm) was SP. FC and PB were instead reduced to small chips with a granulometric Dv (90) of ~ 20 mm.

Solid samples from syngas (Quick Coke: QC) and flue gas lines (Fly Ash: FA), together with initial feedstock were characterized by proximate, ultimate and elemental analysis, granulometry, densitometry, sequential extraction[4], XRD, SEM-EDS and μ-XRF.

## 4. Results

As reported in Table 2, particle size of QC and in a more marked way of FA was found to be significantly higher for Feed 3 compared to Feeds 1 and 2. Same trend has been observed for fixed carbon and carbon content in QC and demonstrate a higher structural resistance to the gasification conditions. With Feed 3, the ratio between ash content in FA and QC is higher than for other Feeds (ash content ratio values for Feed 3: 3.23, Feed 2: 1.69, Feed 1: 1.46). Those elements demonstrate how, trapped into the more resistant structure of nascent char, a larger quantity of the ashes fed with Feed 3, are transported from the gasification side to the combustion one, resulting in higher density ratio between FA and QC in Feed 3 (Value: 3.5) respect to Feed 1 and 2 (Values respectively: 2.85 and 1.14).

**Table 2** *QC and FA granulometry and density.*

| Feed | Density in vrac [Kg/m$^3$] | Granulometry [μm] | | |
|---|---|---|---|---|
| | ρ | Dv (10) | Dv (50) | Dv (90) |
| QC Feed 1 | 400.0 | 9.7 | 45.2 | 122.0 |
| QC Feed 2 | 640.0 | 7.7 | 39.0 | 108.0 |
| QC Feed 3 | 240.0 | 19.9 | 62.5 | 137.0 |
| FA Feed 1 | 1140.0 | 1.0 | 4.1 | 27.0 |
| FA Feed 2 | 730.0 | 1.1 | 3.6 | 23.1 |
| FA Feed 3 | 840.0 | 1.4 | 8.7 | 47.2 |

The QC analyses of Feeds 2 and 3 show a higher content of volatile matter (VM) compared to Feed 1, mainly due to the presence of SP. Additionally, as reported in Table 3, the VM content in the fly ash (FA) from Feed 3 is higher than that of both Feed 1 and Feed 2. This indicates that a greater amount of VM remains in the gasification char of Feed 3, which is consistent with the observed trends in ash content and density ratio. This behavior can be attributed to the reduced ability of VM to diffuse out of a less-reacted char with larger particle size.

| Feed | Proximate analysis [w/w%]$_{db}$ | | | Elemental analysis [mg/kg]$_{db}$ | |
|---|---|---|---|---|---|
| | VM | FC | Ash | Cl | S |
| QC Feed 1 | 7.0 | 25.6 | 67.4 | 579.0 | 802.0 |
| QC Feed 2 | 21.0 | 20.6 | 58.5 | 299.8 | 735.5 |
| QC Feed 3 | 21.7 | 49.0 | 29.4 | 1425.0 | 1372.0 |
| FA Feed 1 | 1.1 | 0.3 | 98.6 | 133.0 | 404.0 |
| FA Feed 2 | 0.8 | 0.2 | 99.1 | 136.7 | 591.5 |
| FA Feed 3 | 4.6 | 0.5 | 94.9 | 1360.7 | 1317.0 |

**Table 3** *QC and FA proximate analysis with S and Cl elemental analysis.*

Moreover, elements such as K, Ca, Al, Zn, S and Cl are found in higher concentrations in ashes of Feed 3 compared to Feed 1 and 2. As more, concentration ratio between FA and QC for each of those elements is higher in Feed 3 respect to 1 and 2.

XRD analysis allowed to identify the presence of Cl in the form of KCl (Sylvite) and $Na_8(Al_6Si_6O_{24})(SO_4)_6Cl_2$ (Hauyne) in the QC of Feed 2, and in the form of Sylvite and $Ca_2Al_2(SO_4)_4 \cdot 22H_2O$ (Caminite) in the FA of Feed 3. This can be explained by considering the thermal and mechanical resistance of the carbon structure in Feed 3, which hinders the devolatilization of sulfur and chlorine during gasification. As a result, these elements exhibit a higher retention in the nascent char. Upon complete char combustion, S and Cl are released into flue gas and subsequently found as simple salts (e.g., Sylvite) and complex alumina salts (e.g., Caminite).

In contrast, Feed 2 has a carbon structure richer in cellulose compared to Feed 3 [5], leading to a more complete conversion of the organic fraction during gasification. This promotes a higher release of S and Cl into the gas phase, allowing them to be captured in the QC as Sylvite and Hauyne.
The identification by SEM-EDS, confirmed by µ-XRF, of a KCl-rich slag layer deposited on the surface of Feed 2 QC supports the XRD observations and reinforces the supposed evolution scheme.
In the QC from Feed 2, sequential extraction reveals an increase in sulfur content during gasification, both in the organic fraction and in the insoluble mineral fraction. The latter includes sulfur bound in the form of alkaline earth metal salts, heavy metal sulfites, alumina, and aluminosilicates. This result is supported by µ-XRD observations, which indicate a sulfur-trapping mechanism facilitated by Zn and Cu aluminates formed during gasification. In contrast, sequential extraction of the FA from Feed 2 indicates that sulfur is released during combustion and subsequently deposited in the flue gas purification line, primarily as alkali metal salts and hydrated aluminates.

Finally, total theoretical sulfur and chlorine retentions in the ashes of the system were calculated (equation 1) based on the molar content of elements known to contribute to the retention (Ca, Mg, Na, K, Fe, Cu, Mn, Zn, Ni, Al) and release (Si, P, Al, Cl, and S) of these target elements.

$$S_{Th.ret.tot} = \frac{Fe \cdot 1.25 + K \cdot 0.5 + Na \cdot 0.5 + Ca + Mg + Cu \cdot 0.75 + Mn + Zn + Al \cdot 1.5}{Si \cdot 2.17 + P + Al \cdot 0.75 + Cl \cdot 0.53}$$

$$Cl_{Th.ret.tot} = \frac{Ni \cdot 2.5 + K + Na + Al \cdot 3 + Ca \cdot 2}{Si \cdot 2.5 + P \cdot 2.25 + Al \cdot 2 + S \cdot 2}$$

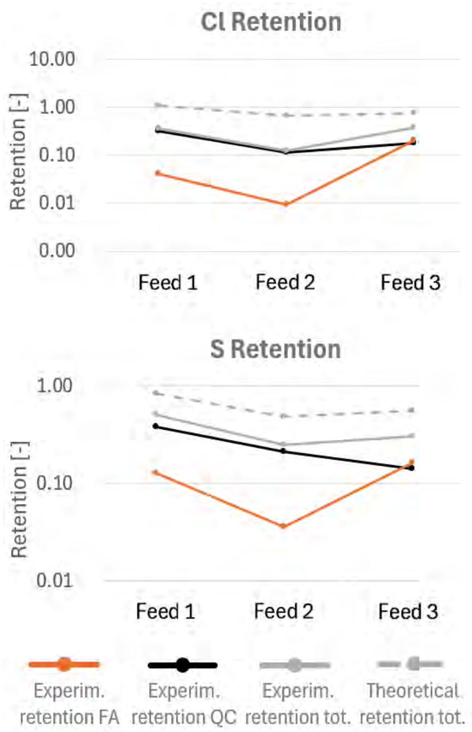
**Equation 1** *Theoretical retention factors.*

Theoretical total retentions were compared to experimental values (Equations 2), where M represents either S or Cl. These retentions are the summatory of S and Cl retentions in QC and FA.

$$M_{Exp.ret.tot.} = \frac{(m_{QC} \cdot x_{M_{QC}})_{n°} + (m_{FA} \cdot x_{M_{FA}})_{n°}}{(m_{feed} \cdot x_{M_{feed}})_{n°}}$$

**Equation 2** *Experimental retention factors with: n° = number of the Feed; x = concentration of the element; m = mass.*

Graph 1 shows that S and Cl total theoretical retention in all three feeds overestimates the real retention. This is because theoretical retention considers the total concentration of the elements present in the feed, while in the process they are not just involved in reactions with S and Cl. Total experimental and theoretical retention trend of Cl and S appears to decrease in feed 2 compared to feed 1. In addition, it can be noted that feed 3 has a higher retention (theoretical and experimental) than feed 2. Despite this, it can be observed that the variations between the experimental retention across the different feeds are more pronounced (especially for Cl) than the theoretical ones. These last results confirm, as previously supposed, that the higher content of lignin fraction in Feed 3 enhances the feed resistance to degradation during gasification step. This resistance likely hinders the diffusion of sulfur and chlorine within the nascent char, promoting interactions with the surrounding ashes before their complete release during combustion.




**Graph 1** *Retentions comparison.*

## 5. Conclusions

This study provides initial insights into the mechanisms governing sulfur and chlorine retention during steam gasification.

It demonstrates how the increase of S and Cl in the gasification feed leads to a not proportional decrease in their retention. The theoretical retention factor, linked to the elemental characterization of the feed, further explains this trend, placing an emphasis on the discrimination between addition of elements that can favor or not the trapping of the target elements during gasification. Finally, the importance of the preservation of a carbonic structure, less subject to thermal and mechanical degradation, to hinder S and Cl during gasification step has been observed as a complement of ashes role in target element retention. Further investigations, currently underway within the TIGRE Chair, aim to confirm and expand upon these preliminary findings by evaluating the role of inorganic fractions using mixed feedstocks in a pilot-scale fluidized bed reactor.

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# Towards Efficient Biological Methanation: The Role of Site-Specific Conditions.

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## 1. Introduction

The technical feasibility and economic viability of integrating power-to-gas technology of biological methanation has been subject of many different studies in the past as well as in ongoing project developments. Especially the integration of this technology into existing biogas plants and wastewater treatment plants with an anaerobic sludge treatment is approaching realisation on a commercial scale, like several pilot and demonstration plants / projects show.

Nevertheless, the size of the market for the biological methanation is difficult to predict. Today there is still no common, simple multipliable standard business case applicable to future projects, which guarantees sufficient return on investment [1]. On one hand this is caused by fast transition processes in energy infrastructure sectors as well as in energy economic and environmental regulations. But the other reason is the complex character of the technology itself, because of coupling of at least three different energy sectors - electricity, gas and heat - under non-stationary conditions on both supply and demand side. Therefore, high quality engineering preparation will become mandatory for future investment decisions, with a key focus on overall energy efficiency.

## 2. Site-specific Interfaces

Typical application cases of power-to-gas-technologies with E-Methane as final product consist of both electrolyser and methanation technology.

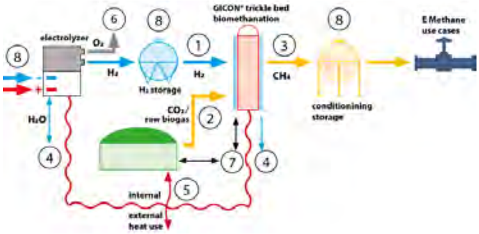


*Figure 1. Overview about typical site-specific interfaces between local infrastructure and methanation technology*

Based on this precondition Fig. 1 and Tab. 1 summarize a minimum of 8 different interface topics to be considered in the framework of such a project.

*Table 1. Explanation of numbers in Fig. 1.*

| Nr. | **Medium** | **Typical design Parameter(s)** |
|---|---|---|
| 1 | $H_2$ | p, $\dot{V}$ |
| 2 | $CO_2$ / raw biogas | p, $\dot{V}$, $c_{components}$ |
| 3 | E-Methane demand side | transfer point/ use case conditions |
| 4 | $H_2O$ (in / out) | purity, $\dot{V}$ |
| 5 | Heat (sources / sinks) | T, Q |
| 6 | $O_2$ (side product) | p, $\dot{V}$ |
| 7 | nutrients / inoculate | diverse composition |
| 8 | Energy supply data / optional storages / process control | XYZ ~ f (time) |

### 3. Energy conversion efficiency – lose or use the "losses"?

Every energy conversion is associated with an increase in entropy and decrease in exergy, respectively. In practice this means "losses", if the amount of input energy at the beginning (e. g. in Fig. 1: Electricity) of the process chain is compared with the main energy "product" at the end (e. g. in Fig. 1: energy content of E-Methane). But energy doesn't get lost, we find the difference in other types of energy, often waste-heat, bio-sludge etc.

A part of energetic transformation "losses" in the power-to E-Methane process chain is not avoidable because of laws of thermodynamics. For instance, the theoretical heat release of the methanation process is 17 % of the energy content of input hydrogen:

$$4H_{2_{(g)}} + CO_{2(g)} \rightarrow CH_{4_{(g)}} + 2H_2O_{(g)} \qquad \text{Eq. 1}$$

$$\Delta H_R^0 = -165\,kJ/mol$$

But in practice the conversion efficiency is less than theoretical values, depending on process designs. State of the art electrolysis converts at minimum 30 % of input electricity into "waste" heat. Further on, there are "byproducts" due to material transformation, e. g. in electrolysis (0.5 Nm³ $O_2$/Nm³ $H_2$) and methanation (1.6 l $H_2O$/Nm³ $CH_4$).

Two strategies in process design are most important in commercial use cases to maximise the overall process chain efficiency as well as the economic profitability:

(1) Minimising avoidable losses
(2) Beneficial use of waste heat and byproducts

The beneficial reintegration of "losses" requires a thorough analysis of the site situation, including the often predefined framework of upstream and downstream requirements such as system pressure of electrolysis and gas systems, temperature of heat sinks and time-dependent availability of renewable electricity as well as time-dependent requirements on the demand side.

The general system parameters used (p, T) must not impede the operational flexibility of the biological methanation process. This means, every step in the conversion chain must be considered under dynamic load changes and the resulting changes in material flows and heat demand. This may make various intermediate storages an option if lower operating costs compensate for higher investment costs.

Overall system simulation capabilities (e. g. development and use of digital twins) are very helpful for the design processes. The main objective of this integrated engineering approach is to minimize stand-by and optimize energy consumption within a flexible load environment, ensuring stable product quality.

### 4. Examples for optimal process design for maximising process efficiency

*Example1: Pressure levels*

The least changeable site parameters are pressure levels of the gas product demand and the hydrogen source. A combination of standard storage systems with 45 barg and matching electrolyser output pressure is the most efficient option, regardless of downstream pressures. Though differences in energy consumption exist among electrolysers the pressure dependency is neglectable [1-4]. The transfer point pressure for local gas application and the $CO_2$-source pressure are competing priorities in terms of system pressure definition. The closer these levels are, the smaller the energy losses of the process chain. The transfer point determines the required gas product pressure. For example, for the pressurization of a biological methanation of 10 bar, theoretically 133 Wh/Nm³ are required for biogas compression if the reactor obtains the carbon dioxide from a low pressure source. Exceedance of transfer point pressure levels leads to non-recoverable loss of compression work (Fig. 2). Likewise, pressure reduction from a $CO_2$-source and methanation at ambient levels followed by pressurization to the transfer point level leads to a comparable amount of work loss.

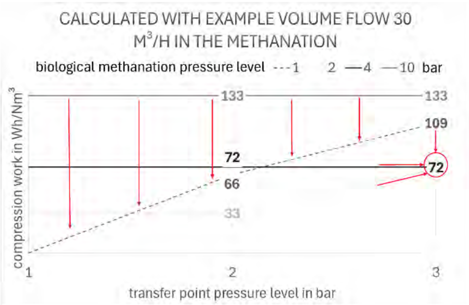


*Figure 2. specific compression work for operational pressures of biological methanation and different transfer point pressures (in bar abs).*

Nevertheless, the volume-specific energy required to compress biogas is lower than that required for methane. For instance, using a transfer point pressure of 3 bar, it is more efficient to operate the biological methanation at 4 bar instead of 1 bar. Alternatively, operating the biological methanation at 2 bar, compressing the methane afterwards to 3 bar, leads to the same additional energy consumption (Fig. 2).

The biological system has limitations regarding both negative and positive pressure gradients. This leads to the conclusion that ensuring a feasible pressure window is crucial for a stable process, which must be achieved for any non-ambient-pressure methanation without energy consumption to avoid losses.

*Example 2: Heat recovery*

State-of-the-art process chains of methanation processes (inclusive electrolysis) convert more than 45 % of the electrical energy input into thermal energy. The more of this energy potential can be recovered and used, the better the overall process efficiency, especially if the heat can be directly applied to a demand side and avoid there an additional energy consumption from high exergetic sources. Obviously this topic will be a key factor of site specific engineering of the energy system. Because of the low temperature level, the possible applications of recoverable waste heat are limited to the heating of other biological processes or buildings. But these demands occur at wastewater treatment and biogas plants, therefore, regularly exists a significant potential for using the synergies at such sites. Apparently small differences in process design – e. g. hyperthermophilic conditions instead of thermophilic in the biological methanation – may significantly improve the options with respect to heat recovery.

## 5. Conclusions – Advantages of TBR System

The economic competitiveness of a power-to-methane technology is largely determined by the following criteria

(1) Flexibility in relation to fluctuating supplies of renewable electricity
(2) Flexibility in adapting to site-specific infrastructure and
(3) High energy efficiency of the overall process chain.

During the development of the GICON® TBR technology, these criteria were taken into account comprehensively and tested in long-term practical operation on test systems. The technology is robust against load changes, has a low internal energy requirement and can be designed for different operating pressures between 1 and 10 bar [6].

Moreover, the operation under hyperthermophilic conditions has been identified as advantageous, with respect to the process stability as well as efficiency and options for heat recovery.

## 6. Next Project with application of GICON®-TBR-Technology

The large-scale demonstration project WeMetBio2 is currently in the planning phase and will be realised at the Nordhackstedt site in 2026 (Fig. 3, [7]).
The direct utilisation in BioCNG/BioLNG-powered vehicles, in particular agricultural vehicles such as tractors, is alternatively planned as special topic for the long term at this site.

*Figure 3. View on the project site of the Nissen Biogas GmbH & CO.KG in Nordhackstedt with the image GICON®-TBR-demonstration plant*

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[7] https://www.wemetbio2.de/

# Industrial Scale $CO_2$ Methanation – The Harjavalta Project

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## 1. Introduction

The global energy transition is gaining unprecedented momentum, driven by the urgent need to combat climate change, growing geopolitical tensions, and increasing trade policy uncertainties. Clean hydrogen has emerged at the heart of this transformation, enabling the decarbonization of hard-to-abate sectors and reshaping future energy systems. Globally, over 1,000 hydrogen projects are underway, requiring €300 billion in investments by 2030, with the clean hydrogen market projected to reach €3 trillion in annual revenues by 2050.

Europe, facing high energy import dependency and ambitious climate targets, is expected to become one of the world's largest markets for clean hydrogen.

Finland is uniquely positioned to take a leading role in this emerging hydrogen economy. With its abundant renewable energy resources, strong industrial base, and strategic energy policy, Finland's hydrogen economy could generate €16–34 billion in annual revenue by 2035 — potentially accounting for up to 13% of the nation's GDP — and grow to €41–69 billion by 2045.

A milestone in this development is the commissioning of Finland's first industrial-scale eMethane production plant in Harjavalta. This pioneering facility marks a significant step forward in renewable energy production and the development of the hydrogen economy. eMethane — synthetic methane produced by combining renewable hydrogen with recycled carbon dioxide — enables the efficient storage, transport, and utilization of carbon-neutral energy within the existing natural gas infrastructure. With its high energy density and full compatibility with current distribution networks and end-use applications, eMethane provides a practical and scalable solution for replacing fossil fuels.

As the climate crisis accelerates and geopolitical risks reshape global trade structures, renewable energy solutions like eMethane play a crucial role not only in environmental sustainability but also in strengthening energy security and economic resilience. Moving away from fossil fuels is increasingly seen not only as a climate imperative but also as a strategic response to global uncertainties. The expansion of decentralized energy production — enabled by renewable hydrogen and synthetic fuels — enhances regional energy self-sufficiency, increases system flexibility, and reduces exposure to international market disruptions.

Europe's extensive existing gas infrastructure — with over 200,000 km of transmission pipelines and 1,100 TWh of storage capacity — offers a fast-track pathway for the large-scale deployment of eMethane without the need for costly infrastructure overhauls. For Finland, the development of eMethane production is a critical enabler for advancing its clean hydrogen strategy, supporting both climate targets and broader goals of energy independence, supply security, and competitiveness in a rapidly evolving global market.

## 2. Technology description

Q Power is a Finnish energy technology company offering patented, scalable solutions for replacing fossil fuels with renewable synthetic methane. Q Power's biocatalytic methanation technology uses microbes to convert $CO_2$ and green hydrogen into methane efficiently. These technologies have been successfully piloted in real industrial environments and are now deployed at industrial scale. Q Power also develops syngas fermentation solutions and delivers comprehensive Power-to-X (P2X) systems for multiple industries.

The company's synthetic methane process offers an effective way to store and distribute renewable energy, taking advantage of existing gas infrastructure and multiple industrial and transport applications.

## 3. First green hydrogen and synthetic methane production plants in Harjavalta

P2X Solutions and Q Power are spearheading a landmark project in Finland: the first industrial-scale production plants for green hydrogen and synthetic methane. P2X Solutions is the project owner, and Q Power is the technology provider for the methanation unit.

*Location - Harjavalta Industrial Park*

Harjavalta Industrial Park, a 300-hectare site along the Kokemäenjoki river, is home to companies specializing in metallurgy, the chemical industry, and process energy. The area provides an ideal ecosystem for industrial-scale green gas production and y

*Green hydrogen production*

The hydrogen plant, with a 20 MW capacity, uses electricity from renewable sources to produce green hydrogen. The process also yields valuable by-products such as oxygen and thermal energy, supporting industrial processes at the site. A portion of the green hydrogen is routed to the methanation plant for conversion into eMethane.

*Figure 1. The Harjavalta power-to-methane plant is a pioneering project in Finland's renewable energy sector.*

*Synthetic methane production*

The synthetic methane production facility in Harjavalta represents Finland's first industrial-scale methanation plant and a pioneering step toward a renewable gas economy. Delivered by Q Power, the methanation unit is integrated with P2X Solutions' green hydrogen production facility and is based on biocatalytic technology that converts green hydrogen and captured industrial $CO_2$ into renewable eMethane.

Construction of the methanation unit progressed rapidly throughout 2023 and early 2024. All 42 bioreactor modules—forming the core of the eMethane production system—were completed by the end of 2023 following an intensive manufacturing period by the Q Power team. On-site installations began in February 2024, starting with infrastructure preparations and the gradual arrival and assembly of the bioreactors. The methanation plant is built adjacent to the hydrogen plant.

By June 2024, mechanical completion of the unit was achieved—marking a significant engineering milestone and allowing the transition to the cold commissioning phase, during which all mechanical and electrical systems were thoroughly tested without process fluids. This stage ensured the readiness of the facility for biological activation.

*Current Status and Schedule*

As of early 2025, eMethane production has officially begun in Harjavalta. The microbes in Q Power's reactors are actively converting green hydrogen and $CO_2$ into methane, marking the start of full-scale renewable gas production in Finland. Ongoing commissioning and optimization work continues, with increasing microbial activity and methane output expected in the coming weeks.

This milestone reflects the successful collaboration between Q Power and P2X Solutions and underscores the viability of biocatalytic methanation at industrial scale.

## 4. Conclusions

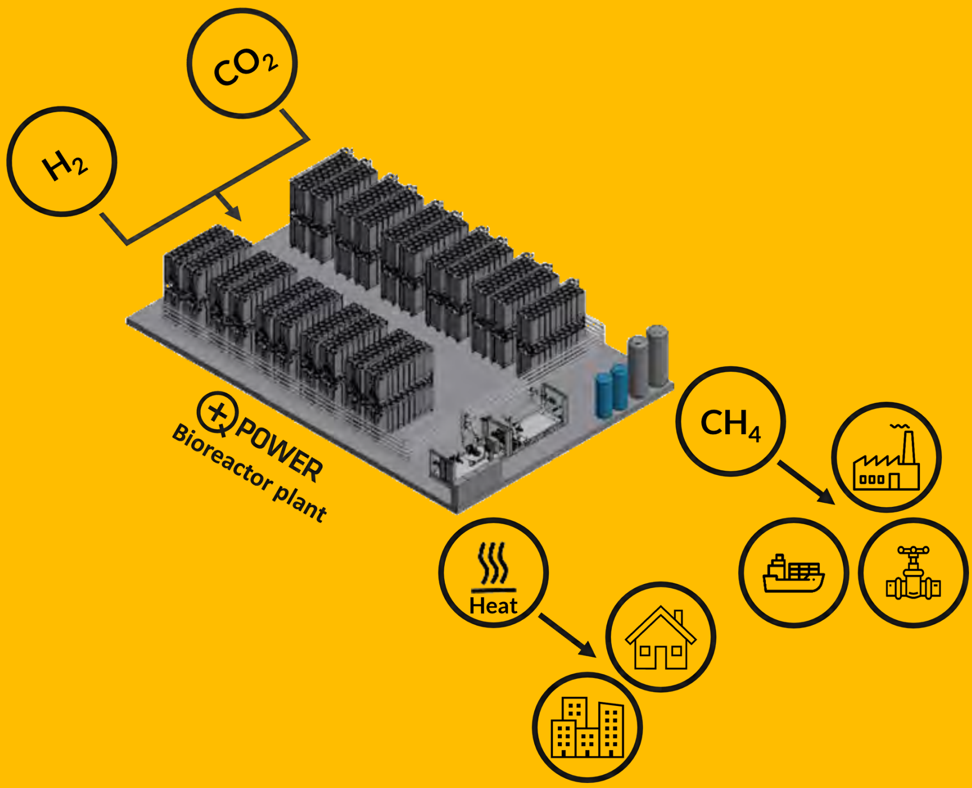
The start of eMethane production in Harjavalta marks a turning point in Finland's transition to a resilient, decentralized, and low-carbon energy future. This facility is not only Finland's first industrial-scale methanation plant, but also a demonstration of how innovation, collaboration, and strategic focus can accelerate the deployment of renewable gas technologies.

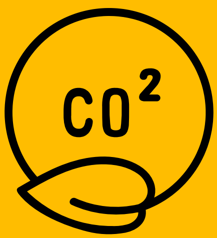
By transforming green hydrogen and $CO_2$ into a storable, transportable, and versatile fuel, the Harjavalta plant proves the viability of synthetic methane in decarbonizing existing energy systems. As geopolitical tensions and trade policy uncertainties reshape global energy dynamics, clean, local, and infrastructure-ready energy solutions like eMethane are gaining new strategic importance.

Harjavalta is more than a first step—it is a model for scalable, clean energy development. It showcases Finland's potential to lead the European hydrogen economy while reinforcing energy independence, climate targets, and industrial competitiveness.

# Q-Power-to-X

## Concrete solutions for fighting climate change




**Unique biological process**
Low energy losses and high process efficiency 82%.

**Scalability**
The modular design allows redundancy and easy capacity increase.

**Robustness**
Our methanation is tolerant to impurities, enabling broad range of input feeds.

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# Impact of operating parameters on biomethanation of syngas.

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## 1. Introduction

The use of microbial mixed cultures for the production of RNG from biomass, industrial wastes or other $CO_2$ emitting sources through biological processes is of great interest. It increases the stability of the processes, improves the resistance to both toxicants and microbial contamination, and brings a higher substrate flexibility. However, reported performances are heterogeneous and optimization is needed to increase the volumetric efficiency of those processes.

Operating parameters play a crucial role in the establishment and on the behaviour of those mixed cultures in trickle bed systems. Temperature, pressure, internal packing shape and composition, inoculum composition, can all have a great impact on the biomethanation [1]. Here is the evaluation of those parameters during syngas biomethanation on the process efficiency, microbial structure, reaction kinetics, among other indicators.

## 2. Methods

The biomethanation process occurred in two 40 litres trickle bed reactors (TBRs) (Bioengineering, Switzerland). They were fed with various synthetic gaseous feedstocks bottom-to-top, and the nutritious buffered media was constantly recirculated via a nozzle located above the packed bed, downward at countercurrent of the gas phase, top-to-bottom, as shown in Figure 1.

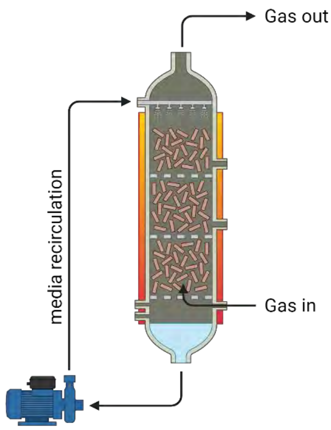


*Figure 1. Reactor design (BioRender.com)*

The stainless-steel reactors were packed randomly with plastic biorings (RVT Process Equipment, Germany) to create beds of 18 L (76 cm x 19 cm diameter; H/D ratio 4). As shown in Figure 2, two models were tested; HF25-7-PP, a 1" hiflow ring tower packing crafted from polypropylene (PP), known for its robust structural integrity and efficient mass transfer properties; and RKF 25L, a biological random packing made from PE-recycled material, designed to enhance microbial adhesion and gas exchange.


*Figure 2. Biorings tested*

The reactor temperatures were maintained at 36°C or 56°C using hot water jackets fed by thermostatic baths (Lauda-Brinkmann, United States). Pressure at reactors' bottom was maintained by backpressure control regulators (Linde Canada, Canada) at either 1.5 atm or 2.5 atm. The pH was monitored but not regulated.

The tests were done by stepwise approaches, ensuring the collection of useful information on a regular basis, allowing the comparison between selected parameters. The gaseous substrate was inserted continuously into the reactor, measured and controlled by thermal mass flow controllers (Alicat Scientific, United States) for bed gaseous hydraulic retention times (HRT) from 0.05 to 0.5.

The gaseous products were exhausted at the top of the reactor toward a gasmeter (Ritter Apparatus, Germany) and analyzed by gas chromatography (Agilent, United States). The gas phase was not recycled, the reactor being operated as a plug flow. All gas flows were sampled at regular time intervals, according to the HRT values.

## 3. Results

*Packing*

As shown in Figure 3, the biofilm that developed on the HF biorings can produce more $CH_4$ per $m^2$ than RFK for the same COD consumed. However, this apparent advantage is counterbalanced by the limitations imposed by the COD range that can be used and, more critically, by biomass retention of those HF biorings.

For the syngas tested, the TBR packed with HF could not convert more than the equivalent of 1.3 ± 0.0 gCOD/Lpbd, compared to 2.8 ± 0.1 gCOD/Lpbd with RKF, giving a volumetric efficiency more than twice lower.

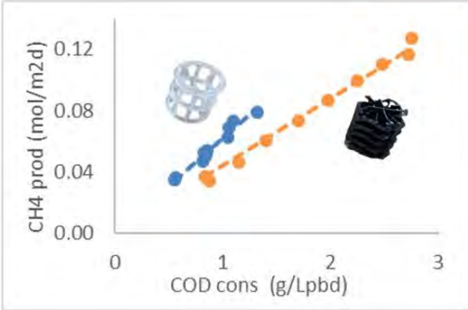


*Figure 3. $CH_4$ produced per surface function of COD consumed (Lpbd: litre of packed bed·day)*

Per bulk volume, HF has a surface area of 214 $m^2/m^3$, while RKF has one of 312 $m^2/m^3$, which represent almost 50% more. Due to this characteristic, RKF is able to retain more and better support the biofilm growth. As shown in Figure 4, RKF can maintain higher amounts of biomass compared to HF. Thus, despite having a less optimal biocatalyst than HF, the overall performance in terms of volumetric methane production is better with RKF due to its greater biocatalyst retention.

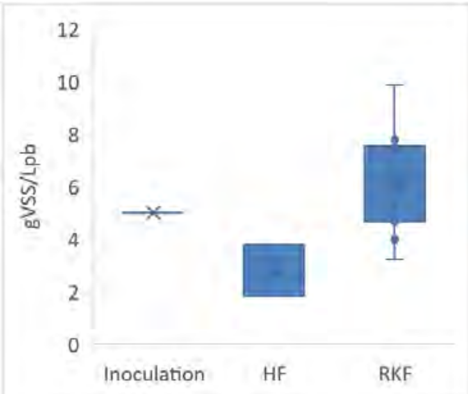


*Figure 4. Volumetric concentration of biomass on HF or RKF packed bed.*

*Pressure*

A higher operational pressure can greatly affect CAPEX and OPEX with its higher reactor design and operation complexity, even at lab scale. A comparative investigation was made at 1.5 atm and 2.5 atm, aiming to define trends, even at those relatively low pressures.

Globally, there were no major differences between biofilm growth and reactor performances (range of COD consumed, quantity of biogas produced, methanogenic yields), which validates, in one way, the good efficiency of TBR system for mass transfer, even at low pressure (nearly atmospheric). The same biodiversity was observed for both pressures.

However, two potentially harmful trends were observed at higher pressure. First, higher CO and $H_2$ partial pressures affects more methanogens. This sensitivity brings some instability in the process, with increased time for reaching steady states at every parameter change. Second, a higher $CO_2$ partial pressure tends to lower the pH, which can also negatively impact methanogenesis. This problem was, in our case, addressed by using the power-to-gas option, *i.e.*, adding an external source of $H_2$ in the syngas used, to increase $CO_2$ capture and then lower its partial pressure.

*Temperature*

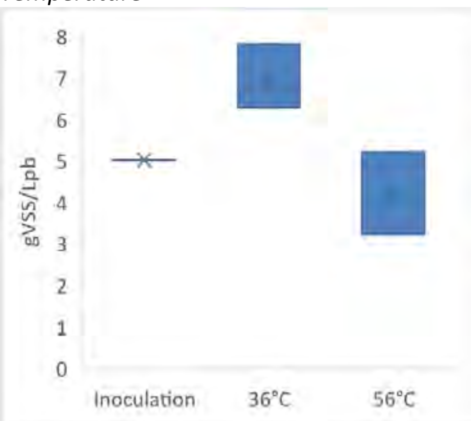


*Figure 5. Biomass density (grams of VSS per litre of RKF packed bed, mesophilic and thermophilic experiments).*

Two reactors operating at 36°C and 56°C respectively were inoculated with the same biocatalyst mixture, composed of a mesophilic and thermophilic inocula mixed in equal proportion. The results obtained, after tests carried out at different flows and syngas compositions, show a better growth and respectively a better formation of biofilm in mesophilic conditions, as shown in Figure 5.

*Table 1. Experimental results from mesophilic and thermophilic experiments*

| | **36°C** | **56°C** |
|---|---|---|
| CO-specific activity (mmol/gVSSd) | 11.5 ± 0.7 | 23.0 ± 5.0 |
| Reactor, max CO activity observed (mmol/Lpbd) | 132 ± 2 | 137 ± 1 |
| H2-specific activity (mmol/gVSSd) | 330 ± 10 | 560 ± 10 |
| Reactor, max H2 activity observed (mmol/Lpbd) | 88 ± 0 | 87 ± 1 |
| pH | 6.3 ± 0.1 | 6.6 ± 0.1 |
| Volatile fatty acids (VFAs) (Eq. gCOD/L) | 0.0 ± 0.0 | 1.4 ± 0.7 |

Despite having different biomass quantities, the maximum conversion rates (CO and $H_2$) were the same for both temperatures tested, explained by the fact of having a biomass nearly twice more active at 56°C than 36°C (Table 1). Higher activity leading to diffusive limitations through the biofilm [2] may explain this outcome of having less biomass into the thermophilic process, as well as slower growth rates.

Even if there was a continuous presence of VFAs (mostly acetate and propionate) at thermophilic operation, the pH measurements were always higher than those at mesophilic temperature, probably due to the CO2 solubility differences.

The VFAs presence may be a sign of a different variety of metabolic pathways between both temperatures, and whatsoever those pathways might be, the thermophilic population exhibits higher CO consumption efficiency than the mesophilic for almost all phases (Figure 6a)

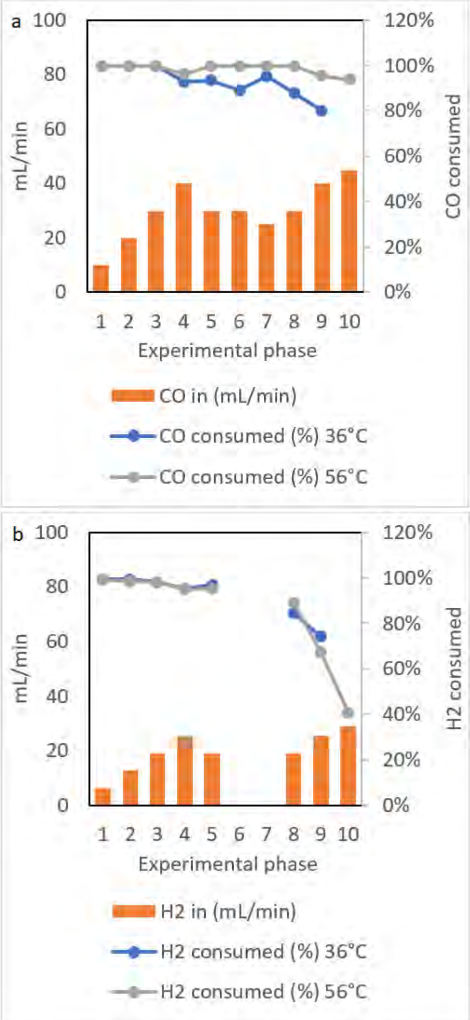


*Figure 6. Flowrates and efficiency during mesophilic and thermophilic phases (a: CO, b: $H_2$).*

Both TBRs demonstrated similar efficiency for $H_2$ consumption, as shown in Figure 7, but to be noted: the drop of efficiency to convert $H_2$ in the last phases. This high sensitivity to H2 excess, contrary to the robustness to CO excess, has already been observed [2].

The $H_2$ excess can cause thermodynamic imbalances during CO conversion, and this may alter the overall redox environment. Adding this to the complexity of the mass transfer into the biofilm, which can be quite high into TBR, this situation may lead to the failure of the methanogens, and then to the overall system.

## 4. Conclusions

- It is beneficial for the overall volumetric efficiency to favour high biomass retention by choosing biorings with a large surface area, even if the conversion rates per unit of biofilm growing on them are lower.
- More pressurized TBR systems don’t seem to bring much more valuable efficiency compared to less pressurized systems, and even bring countereffects of increased CO and $H_2$ sensitivity, on top of pH management.
- Thermophilic operations are promising due to significatively higher conversion rates shown by the biocatalysts, despite the thermodynamics challenges, and how to protect the biofilm against its sensitivity to H2 excess scenarios.

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# Design and performance of a novel 3D-printed dual function methanation and in-situ tar co-reforming reactor.

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## 1. Introduction

Tar is a by-product of biomass gasification which is created during the breakdown of large aromatic structures like lignin [1]. Tar-laden syngas can cause severe problems in a synthetic natural gas (SNG) process chain, with tar components condensing or even crystallizing at lower temperatures. This can lead to blocked piping or other downstream issues. If the syngas is used as a feed gas for catalytic methanation, carbon formation can rapidly deteriorate the catalyst [2,3]. In state-of-the-art processes such as GoBiGas, extensive gas cleaning is a major cost factor [4,5]. With the newly emerging advances of the additive manufacturing process (3D-printing), the design of catalytic reactors can be adapted to the requirements of the reactions, as the shapes are not limited to conventional manufacturing constraints.

In the Horizon Europe project CarbonNeutralLNG, the advantages of additive manufacturing were therefore used to conceive a catalytic methanation reactor design with the ability to reform tars in-situ, omitting the need of extensive gas-cleaning. Several factors are relevant for the in-situ co-reforming of tars. High temperatures and a high steam content promote the endothermic tar reforming reactions, whereas a high hydrogen content helps to prevent carbon formation, as precursors of permanent forms of carbon are removed faster than they accumulate [2,3]. The concentration of sulfur components in the syngas still needs to be reduced with a less elaborate hot gas cleaning step to prevent catalyst poisoning. At smaller scale, the catalyst can be considered as a consumable to some extent, if the CAPEX needed for extensive gas cleaning are saved instead.

## 2. Technology description

The novel ADDmeth3 reactor (see ref. [6]) is based on an existing heat pipe cooled additively manufactured reactor design (see refs. [7,8,9]), which was then adapted for the in-situ co-reforming of tar. Several design changes were made in comparison with the previous ADDmeth1 reactor. The heat pipes were downsized and moved to the centre of the reaction channel instead of wrapping around the outer wall of the reaction channel. These changes aimed at an increased catalyst volume and higher local residence time in the inlet section due to a better usage of the space in the triangular unit-cells. The main goal was to create a suitable hot spot with high temperatures of up to 600 °C in which the tar components can be reformed. Another target was to improve the feed gas input of the reactor for the specific conditions of the CarbonNeutralLNG process.

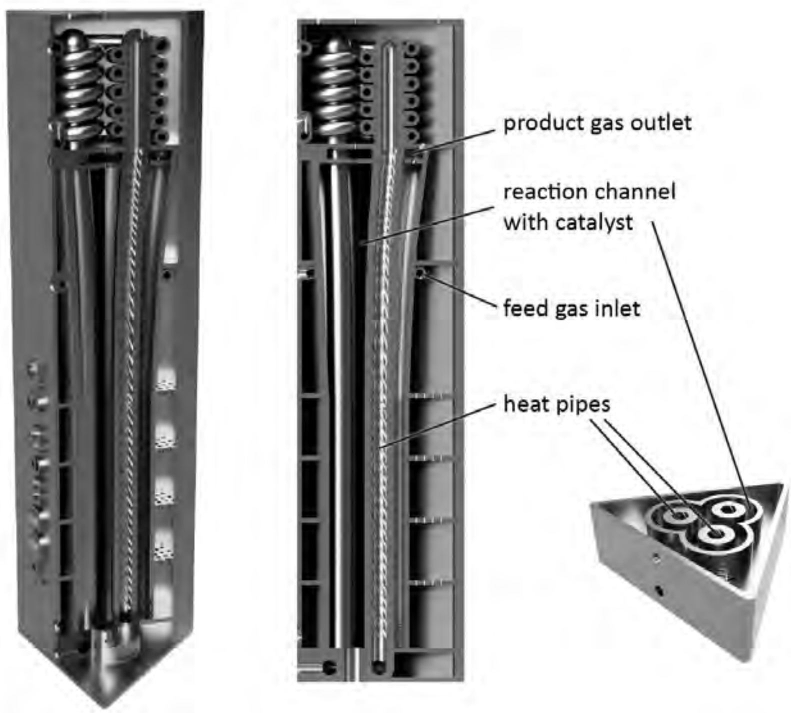


*Figure 1. Additively manufactured ADDmeth3 reactor in a cross-sectional view*

## 3. Methodology

The ADDmeth3 reactor was subject to an experimental campaign in which all of the relevant parameters were varied first in benchmark experiments and then under the conditions of the in-situ co-reforming of tar. The hydrogen-rich syngas composition from the sorption-enhanced CarbonNeutralLNG gasifier is shown in Table 1, together with the tar content using benzene, toluene and indene as representative tar components. A high tar content was chosen, in order to test the ability of the reactor to reform tar at even at very high tar contents. The experiments were conducted under ambient pressure, since a compression of tar-laden syngas might lead to issues in the compressor.

*Table 1. Gas composition.*

| | **CarbonNeutralLNG Syngas** |
|---|---|
| CO [%-vol] | 10 |
| $H_2$ [%-vol] | 70 |
| $CO_2$ [%-vol] | 7 |
| $CH_4$ [%-vol] | 13 |
| Benzene [g/Nm$^3$] | 23 – 26 |
| Toluene [g/Nm$^3$] | 1.4 |
| Indene [g/Nm$^3$] | 0.9 – 1.0 |

## 4. Results

The results of the experiments indicate that ADDmeth3 is suitable for the in-situ co-reforming of tar. The benzene content was very efficiently reduced, with 95 to 97 % removal. The toluene content was reduced by 35 to 64 % and the indene content was completely removed, but in some samples up to 70 % of the initial indene were present as hydrogenated indane. In the benchmark experiments, an almost fivefold increase in feed gas power was achieved from the 2.1 kW in ADDmeth1 to over 10.1 kW in ADDmeth3 while still operating under stable conditions. Water cooling was used with steam being produced by the reactor cooling. After operation with a high tar load for multiple hours and an addition of short hydrocarbons (2 vol.-% of $CH_4$ were replaced by a mixture of 50 % ethylene, 40 % ethane and 1 % acetylene), carbon formation was visible in the reactor and the hot spot moved slightly away from the inlet section, indicating some minor catalyst deactivation taking place. During an addition of sulfur components (1.2 ppm $H_2S$, 0.5 ppm mercaptans and 0.5 ppm thiophene), a clear catalyst deactivation took place, with the hot spot shifting upwards by almost 10 mm over the course of an hour. The transient behavior of the reactor was satisfactory. Load shifts resulted in a comparatively fast return to stable operation over the course of less than 20 minutes with the heat pipe pressure – which indicates the heat pipe's wall temperature - being the slowest parameter to adjust.

## 5. Discussion and Upscale

The reactor performed well in all the design goals specified in ref. [6]. The reactor is suitable for the in-situ co-reforming of tar. However, even better tar reduction capabilities might be reached with an increase in hot spot temperatures to well above 500 °C. During the experiments, the highest temperature measured was 505 °C. A further increase is expected to improve the tar reforming performance further. Several measures in the operation of the reactor are examined in order to determine possible ways to improve the hot spot temperature. These mostly focus on a different operation of the heat pipes with a reduced cooling of the hot spot.

In the course of the CarbonNeutralLNG project, an upscale of the reactor is being developed, with multiple of the ADDmeth3 unit cells joined together and operated in parallel. The triangular footprint of the unit cells can be extended in a honeycomb pattern. Some minor changes resulting from experiences of the experimental campaign will also be made in the design.

## 6. Conclusions

The additive manufacturing process was used to conceive a novel methanation reactor design optimized for the in-situ co-reforming of tar. A lab-scale reactor was printed using stainless steel (AISI 316L) and characterized in an extensive experimental campaign. The experiments confirmed the effectiveness of the design changes and the tar content was effectively reduced by the reactor. Future considerations include an upscale of the reactor and an optimization of operating parameters, mainly focussing on the heat pipe in order to further improve the tar co-reforming capabilities.

**Funding:** The work carried out was funded by the European Union within the project entitled "CarbonNeutralLNG: Truly Carbon Neutral electricity enhanced Synthesis of Liquefied Natural Gas (LNG) from biomass", Grant Agreement No. 101084066 (www.carbonneutrallng.eu). This paper reflects only the author's views and the European Commission is not responsible for any use that may be made of the information contained herein.

## 7. References

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[4] H. Thunman, C. Gustavsson, A. Larsson, I. Gunnarsson, and F. Tengberg, “Economic assessment of advanced biofuel production via gasification using cost data from the GoBiGas plant,” *Energy Sci Eng*, vol. 7, no. 1, pp. 217–229, Feb. 2019, doi: 10.1002/ese3.271.
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[9] A. Hauser, A. Feldner, P. Treiber, F. Grimm, and J. Karl, “Utilization of Synthetic Steel Gases in an Additively Manufactured Reactor for Catalytic Methanation,” *Sustainability (Switzerland)*, vol. 15, no. 9, May 2023, doi: 10.3390/su15097652.

# BioLNG production – lessons learned after the first 20 plants

Patrick Dumpe[1]

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## 1. Introduction

Stirling Cryogenics is a turnkey supplier for the production of decentralised Bio-LNG (or liquid biomethane) on a farm scale. The company was founded over 70 years ago and has built over 4,000 liquefaction projects for various types of gas.

In recent years, Stirling Cryogenics has been building liquefaction plants for biomethane. There are currently more than 20 projects in operation, producing biomethane on existing biogas plants in Sweden, Norway, Italy and Germany. In total, the plants built will produce more than 170 tonnes per day of Bio-LNG (liquid biomethane).

## 2. Technology description

Stirling Cryogenic is offering the technology to upgrade the biogas to biomethane through a membrane system. The produced biomethane will be liquefied with the Stirling Cryocooler, who can cool down the biomethane to -150°C at 2bar or lower in a close circle without further operating materials or operating resources. The system is scalable and with redundancy, to optimize the yearly production and minimize the downtime.

The central element in all equipment of Stirling Cryogenics is the Stirling Cycle Cryogenerator. The Stirling Cycle is remarkable because it is a closed cycle in which the Cryogenerator's internal working gas (He) never comes into contact with the fluid to be cooled; they connect only by flow of heat through the heat-exchanger wall. This concept eliminates contamination of the customer's process as well as of the Stirling Cycle working gas, resulting in long continuous operating periods and longevity.

The Stirling Cycle alternately compresses and expands a fixed quantity of helium in a closed cycle. The compression takes place at room temperature to facilitate the discharge of heat caused by compression, whereas the expansion is performed at the cryogenic temperature required by the application

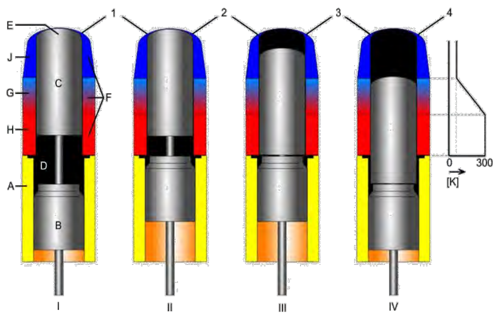


***Figure 1****. The Four stages of the Stirling cooling cycle.*

For the purpose of explanation, the process may be split up into four distinct piston positions illustrated in Figure 1. In position I, all helium is at room temperature in space D. Going to position II, this gas is compressed by piston B increasing the gas temperature to about 80°C, refer to Figure 2, column 1. When the displacer C moves down from position II to III, the gas is displaced from space D to space E, forcing it first through the cooler H where the compression heat is dissipated into the cooling water, reducing the gas temperature to about 15°C (column 2). Next, the helium flows through regenerator G. Using the cold which was stored in the regenerator by the previous cycle, the helium gas is cooled to almost the final working temperature when arriving in space E (column 3). The final and main action is the displacer and piston moving down to position IV, expanding the helium gas. This expansion creates the actual cooling power in the cold heat exchanger J (column 4), cooling the customer's process.

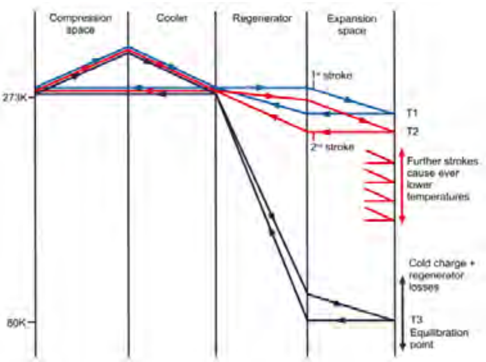


***Figure 2**. Temperature gradient in a single stage cycle.*

## 3. Mass and energy balances

To liquefy the biomethane and produce Bio-LNG at -150°C @2bar, you will have an electrical consumption of 0.98kWh/kg Bio-LNG. To produce biomethane using the membrane liquefaction process, you need 0.31kWh/Nm³ of biogas. This is slightly higher than the consumption of the membrane system that will feed the biomethane into the grid (0.27kWh/Nm³ biogas), but you will need to take back some recycle gas from the liquefaction in the upgrading process. These figures are average annual consumptions based on some fixed parameters such as ambient temperature (15°C), pressure of biogas and Bio-LNG and composition of biogas.

## 4. Results

Based on more than 70 years of experience in liquefaction, Stirling Cryogenic can provide a stable liquefaction unit to produce Bio-LNG on a decentralised basis, without the need for a gas grid. Based on more than 20 projects and more than 170 tonnes of Bio-LNG produced per day, the quality of the liquefied biomethane will be higher than 99,5% $CH_4$ at a temperature of -150°C (@2bar). If required, Stirling can also add a sub-cooling system to provide the Bio-LNG at a temperature of -160°C.
The construction is a solid system that can be easily operated by the biogas plant operator. With remote control support, customers throughout Europe will be able to operate the plant as expected with high availability.

## 5. Conclusions

Stirling Cryogenics products fit perfectly into the biogas market in terms of small-scale liquefaction units. It is possible to start with a 2tpd plant, with is around a 500kW (el.) biogas plant and is a scalable system, up to 18tpd.

## 6. References

| | | |
|---|---|---|
| 2 ton/day | Central Sweden | May 22 |
| 20 ton/day | North East Italy | May 22 |
| 12 ton/day | North East Italy | September 22 |
| 9 ton/day | South Italy | January 23 |
| 5 ton/day | East France | September 21 |
| 5 ton/day | West France | October 22 |
| 6 ton/day | North Italy | January 23 |
| 6 ton/day | South Italy | February 23 |
| 8 ton/day | North East Italy | May 23 |
| 7 ton/day | Italy | November 23 |

| | | |
|---|---|---|
| 7 ton/day | Italy | November 23 |
| 5 ton/day | South Germany | October 23 |
| 12 ton/day | North Germany | September 24 |
| 6 ton/day | South Germany | December 24 |
| 5 ton/day | South Germany | May 25 |
| 8 ton/day | Central Sweden | Febuary 25 |
| 5 ton/day | Central Sweden | November 24 |
| 12 ton/day | Nortn East Italy | January 24 |
| 7 ton/day | Sardinia | 2025 |
| 11 ton/day | North East Italy | 2025 |
| 7 ton/day | South Italy | 2025 |
| 7 ton/day | Norway | 2026 |



# Virtual liquefaction of biomethane

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## 1. Introduction

The International Sustainability and Carbon Certification (ISCC) is a globally recognized system that verifies the sustainability of biomass and bioenergy production. Within this framework, ISCC EU specifically addresses compliance with the European Union's Renewable Energy Directive[1] (RED II), providing certification for biofuels, bioliquids, and biomass fuels. This encompasses biogas, biomethane, and bioLNG, ensuring that these renewable gases meet stringent sustainability and traceability criteria throughout their value chains.

## 2. Process description

The biomethane value chain begins with the sourcing of biomass from farms and plantations, as well as the collection of waste and residues from various points of origin. These feedstocks are processed in biogas plants through anaerobic digestion, producing biogas primarily composed of methane and carbon dioxide. Subsequent upgrading processes refine biogas into biomethane by removing impurities and adjusting the methane content to meet pipeline specifications.

Within the ISCC EU certification framework, each transfer of biomethane between parties in the value chain must be accompanied by a Proof of Sustainability (PoS) document. This document verifies the sustainability attributes of the biomethane and ensures that the transfer is linked to a corresponding quantity of sustainable material. The ISCC guidelines stipulate that the transfer of a PoS must always be accompanied by the transfer of ownership of a respective quantity of sustainable material.

Once upgraded, biomethane can be injected into the EU interconnected gas grid, a network that spans multiple EU countries. Defined in Implementing Regulation 2022/996[2] (IR 2022/996), this grid functions as a single mass-balancing system, governed by physical infrastructure and regulatory oversight. It effectively acts as a large, integrated storage and transmission system, allowing seamless transfers of gas among producers, traders, and end-users. Each biomethane transfer through this network is accompanied by its corresponding PoS, preserving the link between the sustainability attributes and the physical material flow. Certified LNG terminals are integral to this network, equipped to handle both the liquefaction and regasification of natural gas and its renewable counterparts while maintaining the required PoS documentation.

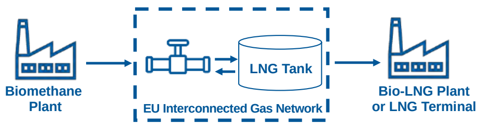


*Figure 1. Mass-balanced or Virtual biomethane liquefaction scheme*

According to the ISCC 203 System Document[3], sustainability characteristics can be transferred from biomethane to Bio-LNG under mass balance principles in the EU interconnected gas network, provided that conversion factors, losses and GHG emissions equivalent to an actual liquefaction process are applied. This approach—often referred to as "Mass-Balanced Liquefaction" or "Virtual Liquefaction"—enables recognition of Bio-LNG production without physically liquefying biomethane at an LNG facility. It relies on the mass-balance system, a chain of custody method that tracks the amount and sustainability characteristics of biomethane through the supply chain, ensuring that each unit of biomethane is traceable and linked to a transaction within the gas network. This allows for flexibility and efficiency in managing biomethane supplies while maintaining the integrity of sustainability claims.

## 3. Conclusions

The concept of virtual liquefaction offers a practical and flexible method for recognizing Bio-LNG production under mass-balance principles. By allowing sustainability characteristics to be transferred from biomethane to Bio-LNG within the EU interconnected gas network—while applying appropriate conversion factors and equivalent GHG emissions—this approach preserves the integrity of sustainability claims without requiring physical liquefaction at every step. When combined with the EU interconnected gas grid, certified LNG terminals, and the mandatory PoS documentation, virtual liquefaction ensures traceability and compliance throughout the supply chain. Ultimately, this framework supports greater market access for renewable gases, promotes efficient use of existing infrastructure, and reinforces the overarching goal of decarbonizing Europe's energy landscape.

## 4. References


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[2] Commission Implementing Regulation (EU) 2022/996 of 14 June 2022 on rules to verify sustainability and greenhouse gas emissions saving criteria and low indirect land-use change-risk criteria

[3] ISCC EU 203 Traceability and Chain of Custody. Version 4.1 Valid from: 01 January 2024

# Small scale bioLNG - case study Renzenhof plant.

Gennaro Formisano[1]

[1] Business Development Manager LNG – SIAD Macchine Impianti SPA (ITALY)

## 1. Introduction

The definition of small scale LNG is very large and don't take in account that the technology used for liquefaction have a direct impact on the efficiency and final cost of LNG. Among the commercially viable technologies, Direct Expansion (Linde-Hampson cycle), Turbo-Brayton, and Single Mixed Refrigerant (SMR) are preeminent. While SMR and Turbo-Brayton demonstrate comparable operational expenditure (OpEx) above 15 tonnes per day (TPD), Direct Expansion proves more competitive in terms of efficiency below this threshold. Both Turbo-Brayton and Direct Expansion technologies are integral to the SIAD portfolio. This analysis will focus on the principal technical aspects of a Bio-LNG plant situated in Renzenhof, Germany, utilizing SIAD Macchine Impianti's Turbo-Brayton cycle.

## 2. Technology state of the art

The Turbo-Brayton technology employs nitrogen as a refrigerant within a closed-loop system. The requisite refrigeration for bio-methane liquefaction is achieved through the expansion of nitrogen across a turbo-expander, enabling the attainment of exceptionally low liquefaction temperatures, down to -175°C [1]. Plant efficiency is directly proportional to scale; thus, while efficiency commences at 0.9 kWh/kg of LNG for 20 TPD, it can achieve 0.5 kWh/kg at 200 TPD. The Renzenhof facility utilizes this technology to liquefy 140 TPD, and is also equipped with an amine polishing system, dual storage tanks, and a truck loading system.

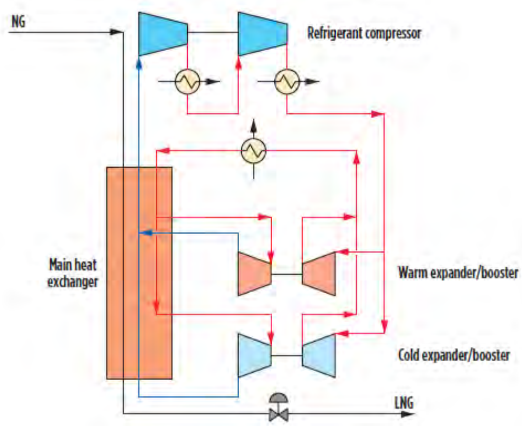


*Figure 1. Turbo-Brayton – Process Flow Diagram*

## 3. Technology Description – State of the Project

The Turbo-Brayton cycle ensures optimal energy efficiency for capacities exceeding 15 TPD, attributable to the enhanced efficiency of centrifugal machinery compared to reciprocating compressors, and the utilization of a turbo-expander in lieu of a Joule-Thomson valve. The Renzenhof plant is in its concluding phase and is projected to achieve full operational capacity by July 2025. Complementing its high energy efficiency, the plant has been engineered to be the most ecologically sustainable LNG production facility in Bavaria, incorporating a closed-loop water system and achieving methane slip below 0.1%. Furthermore, all boil-off gas (BOG) is internally recirculated to minimize atmospheric emissions. A distinctive feature of this plant is its fully automated, unmanned operation.

*Figure 2. Renzenhof Bio-LNG liquefaction plant.*

## 4. Conclusions

The Renzenhof plant represents a significant LNG production installation within Europe, and its strategic location positions it as a vital LNG truck loading hub for central Europe. The plant's high degree of customization and minimal atmospheric emissions represent an exemplary approach to the LNG sector, wherein technological efficiency, plant capacity, location, and environmental impact are accorded commensurate importance in business case evaluations.

## 5. References

[1] SIAD MI – Technical specification – SMAR TB – LNG Plant. 2017

# Efficient hydrogen removal/recovery for biological and catalytic eLBG/eLNG production.

Magnus Folkelid[1] and Lars-Evert Karlsson[1]

[1] Wärtsilä Gas Solutions, Sweden

## 1. Introduction

The Hydrogen economy is coming into the market of Biomethane with the e-fuels conversion of CO2 and H2 into e-methane. When being liquified into eLNG it is to use the existing LNG infrastructure due to it's 100% blend able mix with LNG. That requires handling of excess hydrogen in the LNG infrastructure in a new efficient way.

## 2. Technology system description

Biological or Catalytic methanation technologies producing e-methane from conversion of Carbon Dioxide and Hydrogen to methane is into early commercial introduction with pilot and demo plants operational today.

*Gas quality standards*

Looking at the transport sector there is in the standard EN 16723-2 a Hydrogen concentration set to max 2 mol-%. LBG/LNG distributers want the liquified methane in the distribution chain as close to zero mol-% as possible.

Solutions are needed to manage efficient Hydrogen removal/recovery in production facilities for liquefaction of methane.

## 3. Results

Compared to removal of Hydrogen with separation technologies before the liquefaction process a solution for downstream removal after the liquefaction process have been developed.

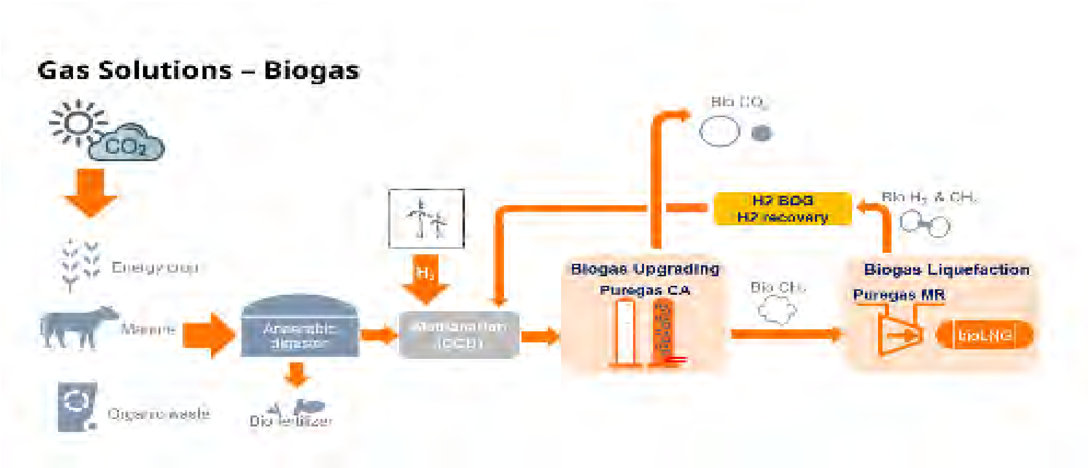


*Figure 1. Example Biogas/biomethane system layout with methanation*

# REGATEC 2026

*Bringing science, technology and industry together*


The 12th and final International Conference on Renewable Energy Gas Technology, REGATEC 2026 takes place 19-20 May 2026 at Scandic Star hotel in Lund, Sweden.

REGATEC 2026 puts an end to a long and successful series of annual conferences bringing the biogas, biomass gasification and power-to-gas sectors together.

One of the speakers in the opening session will be Mattias Goldmann, named the most powerful in sustainability in Sweden and dubbed a knight by the French government for his efforts in the environmental field.

**WARM WELCOME TO A MEMORABLE FINAL CONFERENCE!**

# How to build a lucrative business model for heavy duty transport with biogenic energy gases.

Johan Laurell[1]

[1]The Swedish Gas Association, Saltmätargatan 5, SE-113 59 Stockholm, Sweden

## 1. Introduction

Emissions from domestic transport account for one-third of Sweden's total greenhouse gas emissions. In 2023, the transport sector's emissions amounted to approximately 13.9 million tons of carbon dioxide equivalents, which is 28 percent lower than in 1990. The majority of emissions come from road traffic, mainly from passenger cars and heavy vehicles. Sweden has set a goal to reduce greenhouse gas emissions from domestic transport by at least 70 percent by 2030 compared to 2010 [1].

Emissions from heavy vehicles (over 3.5 tons) account for about one-third of road traffic's climate emissions. In total, this means that trucks and buses account for about 6.5 percent of Sweden's climate emissions. Freight transport with heavy trucks emitted approximately 2.78 tons of carbon dioxide equivalents in 2023, which corresponds to one-fifth of the transport sector's emissions.

Many efforts are being made to increase the proportion of heavy trucks powered by fossil-free fuels or electricity to achieve these goals, and the importance of this transition is often highlighted by both politicians and the public. Despite this, many transport companies in Sweden find it difficult to compete with fossil fuels as fossil-free alternatives of both vehicles and fuels often result in increased total costs, and the willingness to pay seems to be lacking among many transport buyers. Therefore, a challenge is to create a lucrative business model along the entire value chain which includes the end consumer.

## 2. The challenge

It is often a challenge for transport companies that take the lead and invest in vehicles with fossil-free powertrains or battery-electric vehicles to argue for the opportunities and competitive advantages this can provide for their customers, the transport buyers. It is not uncommon for this to result in a number: the difference in additional costs for a large number of transports over a specified contract period. This is often negotiated between the transport company and a few people at their counterpart, the transport buyer.

This often gives a misleading impression that the transport buyer is purchasing identical transports from point A to point B, when it is in fact two completely different services, one fossil free and the other not. For the transport buyer, the value of the fossil-free transport can sometimes be shown in an annual report or an environmental reporting, but it often ends there. The full value of the fossil-free transport is then not utilized.

## 3. The method – an example

By breaking down the additional cost for a fossil free transport and providing specific examples, the possibilities for getting acceptance for an extra cost across the entire value chain can be increased.

An example can illustrate this:
A domestic transport by truck from the harbour in Gothenburg to the city of Sundsvall is approx. 720 km.

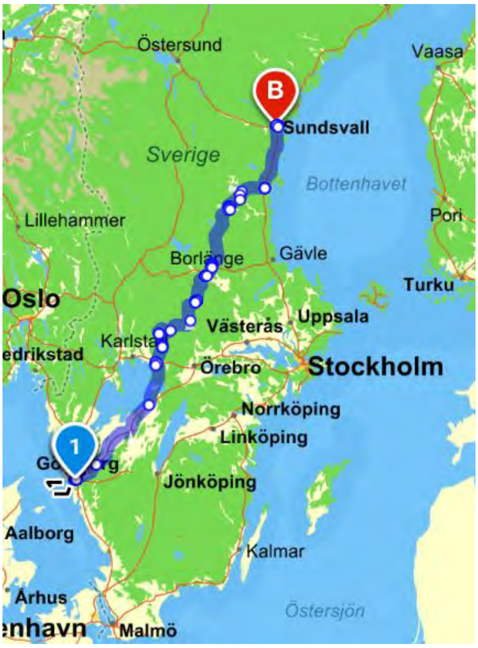


*Figure 1. Transport by road Gothenburg to Sundsvall, appr. 720 km*

The total cost for operations, including the investment in vehicle, fuel etc., in Sweden for a 720 km transport with liquified biomethane, bio-LNG, is today approx. 50 euro extra compared to diesel.

A fully loaded truck with trailer can carry approx. 33 000 pair of shoes. The extra cost for a 720 km fossil free transport is therefore roughly 0.15 cent for a pair of shoes.

## 4. Conclusions

By illustrating the extra cost in this way, the cost vs. benefit might become more clear and manageable, and the possibilities for using the choice of transport in advertising to attract more customers.

## 5. References


[1] https://fossilfrittsverige.se

# The role of the Liquid Gas Industry in the energy transition.

Alison Abbott[1]

[1] Communications Director, World Liquid Gas Association, 182 avenue Charles de Gaulle, 92200 Neuilly-sur-Seine, FRANCE

## 1. Introduction

The World Liquid Gas Association (WLGA) is the authoritative voice of the global Liquid Gas industry representing the full Liquid Gas value chain. The primary goal of the Association is to add value to the sector by driving premium demand for Liquid Gas, while also promoting compliance to good business and safety practices. This presentation addresses the role of the Liquid Gas industry in the energy transition.

## 2. Change is on the Horizon

What net zero commitments is the industry facing, what opportunities to these changes bring, and how is WLGA approaching these challenges for the global industry?

## 3. Renewable Liquid Gas Production and Pathways

A short dive into the Renewable Liquid Gas production, pathways (see Fig. 1) and global projects. What projects are currently active to help integrate renewable fuels into the supply chain. We look at the top six pathways currently being commercialised.

## 4. Reaching Renewable Targets

To reach stretch targets requires continued action and innovation from the WLGA and the industry it serves.

| Pathway | Production Type | 2030 Outlook | 2030 Est. Volume | Carbon Intensity (gCO2e/MJ) | Challenge |
|---|---|---|---|---|---|
| Alcohol to rLG | Byproduct | ~10 Plants | ~ 1,200 kTPA | 10-20 | Feedstock Competition |
| Biogas to rLG | On-Purpose | ~60 Plants | ~600 kTPA | 5-80 | Feedstock in Volume |
| Gasification to rLG | Byproduct (rLPG)<br>On-Purpose (rDME) | ~25 Plants | ~2,250 kTPA | 5-30 | Novel Process & Technology |
| H2/CO2 to rLG | Byproduct | ~30 Plants | ~3,750 kTPA | 0-20 | H2 Production Costs |
| Pyrolysis to rLG | Byproduct | ~15 Plants | ~800 kTPA | 5-30 | Low rLG Yield (<5%) |

***Figure 1***. *Renewable Liquid Gas Production Pathways*

## 4. Reaching Renewable Targets

To reach stretch targets requires continued action and innovation from the WLGA and the industry it serves.

## 5. Conclusions

The WLGA sees a confident future for traditional and renewable Liquid Gases but must unite to achieve this. We will have a major focus on this during our flagship event, Liquid Gas Week, in Rio de Janeiro, $22^{nd}$ – $26^{th}$ September 2025.

# Poster presentations

# Application of Hollow Fiber Membranes for Enhanced $CO_2$ Biomethanation at Pilot Scale

Irene Bonato[1], Arianna Catenacci[1] and Francesca Malpei[1]

[1] Department of Civil and Environmental Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, Milano, 20133, IT

## 1. Introduction

Biological Power-to-Methane technology employs anaerobic microorganisms to convert C1 gases (CO, $CO_2$) and green$H_2$ into biomethane while also storing excess renewable energy. Biomethane production is often limited by inefficient, energy-demanding gas-to-liquid mass transfer. To address this, hollow fiber membranes are used to deliver substrates directly to a biofilm on their outer surface, which improves mass transfer efficiency while keeping energy requirements low. The Membrane Biofilm Reactor (MBfR) builds on this approach by using gas-permeable membranes to supply dissolved gaseous substrates to the methanogenic biofilm [2], [3].

## 2. Technology description

Enhanced $CO_2$ biomethanation was achieved at the pilot scale (90 L) designing a MBfR (Figure 1).

***Figure 1**. Pilot scale MBfR.*

Gaseous substrates can be supplied in two ways: either by delivering only hydrogen through the membrane (Figure 2A) while $CO_2$ is provided via conventional microbubble diffusers, or by transferring both $H_2$ and $CO_2$ through the membrane (Figure 2B).

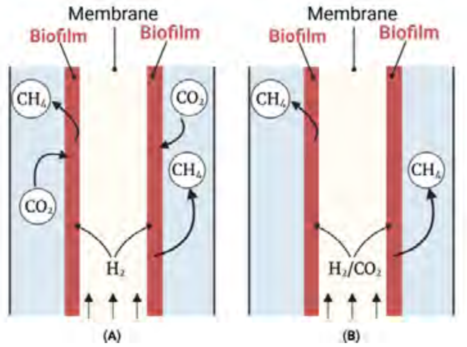


***Figure 2**. Membrane-based mass transfer.*

The monitoring plan of the pilot is designed to obtain the key parameters necessary for both optimizing and engineering the innovative process under varying membrane feeding conditions (dead-end, flow-through, and venting) and different $H_2/CO_2$ feeding ratios. Specifically, it focuses on characterizing hydrogen transfer yields and conversion efficiencies, critical metrics for process optimization and scale-up. Additionally, the data collected will enable precise estimation of the kinetic parameters associated with the metabolic pathways involved, thereby supporting the development of robust and accurate process models.

## 3. Results

Preliminary results are available for the pilot-scale reactor. Regarding gas transfer efficiencies, the dead-end mode maximizes gas transfer but allows for greater back-diffusion of dissolved gases in the lumen, which reduces the partial pressure of $H_2$ and thus its availability to the microorganisms. The flow-through mode proves to be the best for minimizing this back-diffusion effect, but it results in a lower gas transfer efficiency than the previous. The venting mode emerges as the best compromise, maximizing transfer while simultaneously minimizing back-diffusion (Table 1). Back-diffusion was quantified by measuring the gas composition within the membrane's lumen.

***Table 1****. Average hydrogen transfer efficiency as a function of feeding mode.*

| Feeding Mode | $H_2$ transfer efficiency |
|---|---|
| Dead-end | 85% |
| Flow Through | 61% |
| Venting | 74% |

For the latter operating mode, hydrogen to methane conversion efficiency remains in average above 90%.

## 4. Conclusions and future developments

The outcome of this research will provide a comprehensive understanding of the innovative membrane biofilm reactor for enhancing gas-liquid mass transfer rates of gases with low solubility, such as $H_2$.

Moreover, the same membrane process will be applied at the laboratory scale to study the biomethanation of carbon monoxide (CO) first, followed by the biomethanation of syngas. By ultimately optimizing the conversion of $CO_2$ and CO into $CH_4$, this technology could play a pivotal role in the energy transition, supporting the broader adoption of renewable energy and aiding in carbon emission reduction.


## 5. Acknowledgement

This work was supported by EU BIOMETHAVERSE.


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[3] B. E. Rittmann et al. A framework for good biofilm reactor modelling practice (GBRMP). Water Science & Technology (2018).

# The Potential Use of Digestate-Based Products in the Horticultural Industry.

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## 1. Introduction

In Germany, the majority of biogas residues is being used in agriculture. However, nutrient surpluses in regions with a high level of livestock farming and provisions in legislative regulations make this increasingly difficult. Biogas plants therefore need to develop alternative markets.

Due to their fibrous and nutrient contents, digestates have great potential to be used as input material for replacing peat in potting soil or as organic fertilizers. Market development is further supported by the climate protection plan 2050 of the German government, which aims at substantially reducing the use of peat both in hobby gardening as well as in professional gardening and landscaping (BMUB, 2016).

There a number of studies on the decision-making of private gardeners with regard to the choice of substrates or fertilisers and the acceptance of digestate-based products. This is lacking for the horticulture industry.

## 2. Aims

In order to close this gap, the authors conducted a qualitative interview study among professional gardeners in order to gain insights into:

- the way horticultural businesses take decisions about fertilisers and substrates and what the influencing factors are;
- the attitudes of professional gardeners towards digestated-based products.

## 3. Methods

Between February and August 2023, 23 guideline-based qualitative interviews were conducted with professional gardeners and consultants from the southwestern German state of Baden-Württemberg. The aim was to have as much diversity in the sample as possible. Therefore, we chose interviewees from the sectors of cemetery maintenance, gardening and landscaping, municipal services, floristry, fruit-, wine- and vegetable-growing as well as gardening services for private customers. Furthermore, there were substantial differences in business structures and size.

The interview guideline was based on the Diffusion of Innovations theory by Rogers (2003). It included the following topics:

- Decision-making process with regard to the use of fertilisers and substrates
- Level of knowledge on digestate-based products in potting soils and fertilisers
- Attitudes towards and assessment of digestates and substrates
- Attitudes on innovations and future perspectives

The analysis was done in accordance with Mayring's qualitative content analysis method (2022) using the MAXQDA software.

## 4. Results

Professional horticulturalists:

- Are very loyal with regard to the substrates and fertilisers they use;

- Feel the need to reduce their peat usage in view of the climate protection strategy of the German government;
- Find it important to do their own testing before using new products;
- Do not want to take any risks due to the high importance of reliability and safety of potting soil and fertilisers

Product quality and reliability, good handling and compatibility with existing technology are important decision criteria. Other influencing factors include:

- Social influence: talks with other professional gardeners were the most frequently mentioned factor, publications range far behind that and consultants play, other than for agricultural businesses, almost no role
- Knowledge: knowledge on how to apply biogas residues in the horticultural sector is rather limited

Professional horticulturalists perceive digestate-based products to potentially have the following advantages:

- Support of the regional circular economy
- Potential cost reduction
- Soil improvement, building humus, improvements in the hydrological balance

Perceived disadvantages include:

- No availability at local level, no experience yet
- More effort and time necessary with regard to usage and transport, especially when nutrient content is low
- Less reliable and slower fertilising effects
- Risk of contamination with e.g. herbicide residues in the digestate

While cemetery gardeners, ornamental horticulturalists and vegetable farmers consider the potential use of biogas residues to be rather low, nursery gardeners, fruit-growers, wine-growers, (municipal) gardeners as well as landscapers consider the prospects to be medium/high.

## 5. Discussion and Conclusions

In conclusion, we can say that scepticism and uncertainty prevail among horticulturalists due to a lack of knowledge on and experience with substrates and fertilisers based on digestates. Therefore, substantial effort is necessary to build up general knowledge on the products' virtues. When launching new products, one has to ensure that they can be extensively tested.

Primary target groups should include gardeners and landscapers, municipal and nursery gardeners as well as fruit- and wine-growers. Gardeners and landscapers are in direct contact with end customers. This fosters customer involvement and could subsequently create higher demand, because end customers may like the idea of eco-friendly peat-free substrates. Besides, substrate costs are a negligible position when contracting a gardener or landscaper. Among municipal gardeners, there is no direct competition, so they may be more willing to try out new materials and take more risks than entrepreneurs who are directly affected in the case of a failure of new materials. Furthermore, municipalities may want to publicly present themselves as eco-friendly. For wine-growers, fertilisers based on digestates may be attractive because pellets can be more easily applied in steep slopes.

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[3] Mayring, Philipp. Qualitative Inhaltsanalyse: Grundlagen und Techniken. 13. Auflage. Weinheim Basel: Beltz, 2022.

# Methanation Catalyst Performance on CO with Power to Gas

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## 1. Introduction

Renewable natural gas (RNG) can be produced from biomass based carbon monoxide with hydrogen provided from electrical power, i.e. power to gas. Carbon monoxide can be converted into methane with the addition of hydrogen following the methanation reaction (1) using a (Ni/Ru/MgO) catalyst previously developed [1] and patented [2] to promote the reaction:

$$CO + 3 H_2 \leftrightarrow CH_4 + H_2O \qquad (1)$$

To determine the performance of the methanation catalyst to reform CO into $CH_4$ with power to gas, experiments were performed over a range of $H_2$/CO ratios in (Table 1) and temperature from 250 to 450 ºC. The results are compared with the chemical equilibrium composition.

*Table 1. Gas compositions (v%) for the study of the catalytic methanation of CO with $H_2$.*

| H/C=$H_2$/CO | $H_2$ | CO | $N_2$ |
|---|---|---|---|
| 4.0 | 54.9% | 13.7% | 31.4% |
| 3.0 | 51.5% | 17.1% | 31.4% |
| 2.0 | 45.7% | 22.9% | 31.4% |
| 1.5 | 41.2% | 27.4% | 31.4% |

## 2. Experimental Technique

The methanation of CO with additional hydrogen was conducted in a temperature-controlled fixed-bed methanation flow reactor developed in a previous work [3], and shown in **Fel! Hittar inte referenskälla.**. The flow reactor contained either 250 mg or 375 mg of the catalyst on a Sasol Puralox 300/200 alumina support (290 micron diameter, impregnated surface area 106 $m^2/g$) and mixed with 5.0 g of (1.5 mm) quartz chips in a quartz tube with a 10-mm ID. The flow rate was 400 sccm with the weight hourly space velocity (WHSV) of 96,000 or 64,000 scc/h/g with the two catalyst loadings. Methanation product gas composition was measured with a micro gas chromatograph, Agilent 990.

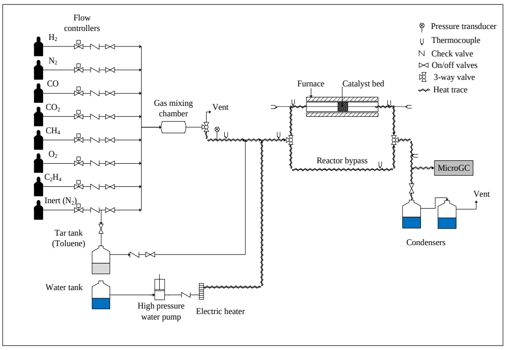


*Figure 1. Fixed-bed flow reactor schematic for the production of renewable natural gas from methanation of CO.*

## 3. Results

The measured methane yield, $[CH4]/[CO]_{inlet}$, at increasing hydrogen/carbon ratio (H/C) and WHSVs of 96,000 and 64,000 scc/h/g is presented in *Figure 2.* For both catalyst loadings the methane yield is below equilibrium but approaches at the higher temperatures. Below 300ºC the methanation catalyst activity falls off substantially.

At the highest H/C ratio (4.0), the highest catalyst loading 1.5X (lowest WHSV=64,000 scc/h/g) significantly improved methanation performance. The methanation highest yield was 93.6% at 400°C. The chemical equilibrium methane yield is 98.4%

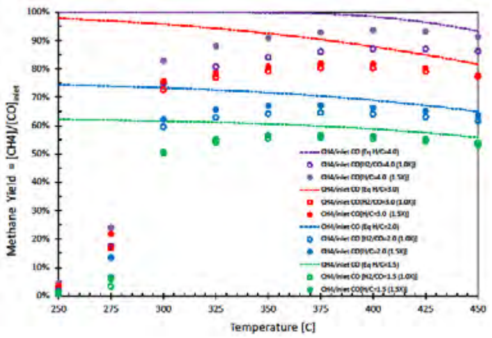


*Figure 2. Methane yield as a function of H/C ratio, temperature, and equilibrium.*

The $CO_2$ product mole fraction with increasing ratio (H/C) and WHSVs of 96,000 and 64,000 scc/hr/g is presented in *Figure 3*. The $CO_2$ production results from the water gas shift reaction (2) with $H_2O$ provided by the methanation reaction (1).

$$CO + H_2O \leftrightarrow H_2 + CO_2 \qquad (2)$$

The minimum $CO_2$ production (0.65%) is at the lowest level at H/C=4.0 at 400 °C. Below the stoichiometric ratio H/C=3.0 the $CO_2$ product mole fraction is above equilibrium. Above the stoichiometric H/C ratio, the $CO_2$ product mole fraction is below equilibrium.

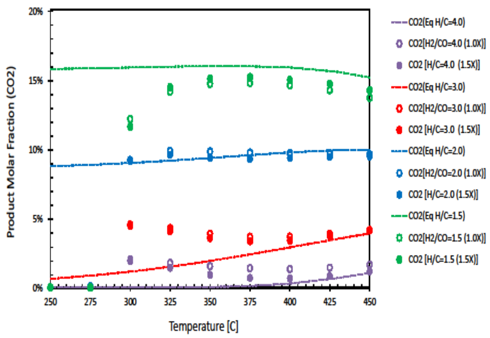


*Figure 3. $CO_2$ mole fraction in product gas by H/C ratio, temperature, and equilibrium.*

The CO product mole fraction as a function of H/C ratio and temperature is presented in *Figure 4*. The lowest level of CO product mole fraction 0.05% was obtained at WHSV=64,000 scc/h/g at the highest hydrogen carbon ratio (H/C=4.0) at 350 °C.

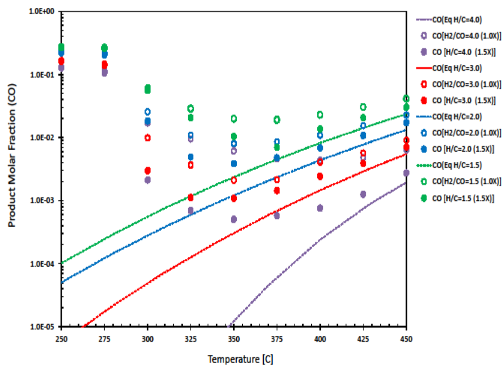


*Figure 4. CO mole fraction in product gas by H/C ratio, temperature, and equilibrium.*

## 4. Conclusions

(1) Improvement in the methanation of CO by a Ni/Ru/MgO catalyst with additional hydrogen was demonstrated for power-to-gas application. (2) The maximum methane yield (93.6%) was at H/C=4.0 at 400°C for WHSV=64,000 scc/h/g) and near to equilibrium (98.4%) at the higher catalyst loading.(3)Maximum conversion of CO (99.95%) occurred at 350°C and H/C=4.0 for the highest catalyst loading WHSV= 64,000 scc/hr/g. (4) The minimum $CO_2$ production (0.65%) was at (H/C=4.0) at 400°C for the highest catalyst loading WHSV=64,000 scc/hr/g. (5) Higher catalyst loading and lower WHSV can be used to improve performance.

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# Particle mass flow measurements in a combined bubbling and circulating fluidized bed reactor for sorbent-enhanced Power-to-X applications.

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## 1. Introduction

A combined bubbling and circulating fluidized bed reactor [1] is a novel approach for various sorption-enhanced Power-to-X applications, for instance yield increased methanation processes. This concept integrates a large particle-sized catalyst bubbling fluidized bed reactor (BFB) with a small particle-sized sorbent circulating fluidized bed reactor (CFB) to facilitate continuous in-situ water removal. The sorbent particles are continuously transported out of the reactor at high reactive gas velocities while the catalyst particles remain in the reactor within the bubbling fluidized regime, enabling high catalyst hold-up and effective heat and mass transfer. The removed sorbent particles are regenerated and reintroduced into the reactor in a circulating loop.

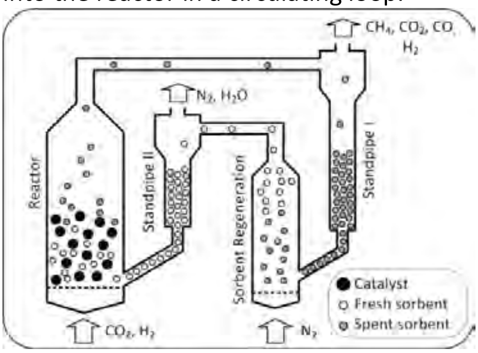


***Figure 1**. Concept of the combined reactor*

## 2. Cold flow Model

A cold flow model was developed to study the fluid dynamics of the combined reactor. It employs alumina particles (AlOx) as a sorbent replacement and quartz sand as a catalyst replacement. Figure 2 illustrates the mean particle size of the materials used and the corresponding minimum fluidization velocity.

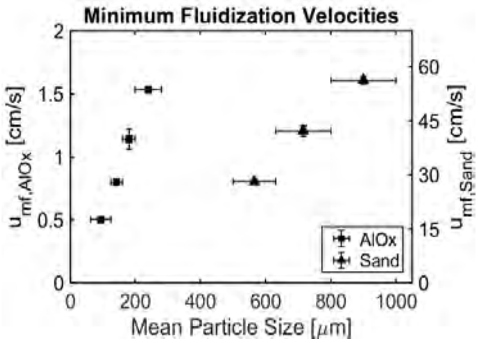


***Figure 2**. Minimum fluidization velocity of the used particles in the cold flow model.*

A stable operation could be achieved with the cold flow model, as it ran for several hours without clogging or flow collapse, proving the concept's hydrodynamics feasibility.

## 3. Microwave Doppler Sensor

Measuring the particle mass flow is challenging, and previous researchers have employed various techniques [2]. One feasible method involves inducing a microwave field that the particles must cross in a pipe. A receiver measures the resulting Doppler frequency shift, which directly depends on the particle's velocity.

The MF3000 of the manufacturer *Mütec Instruments GmbH* is a commercially available sensor for in situ mass flow measurements using microwave Doppler techniques.

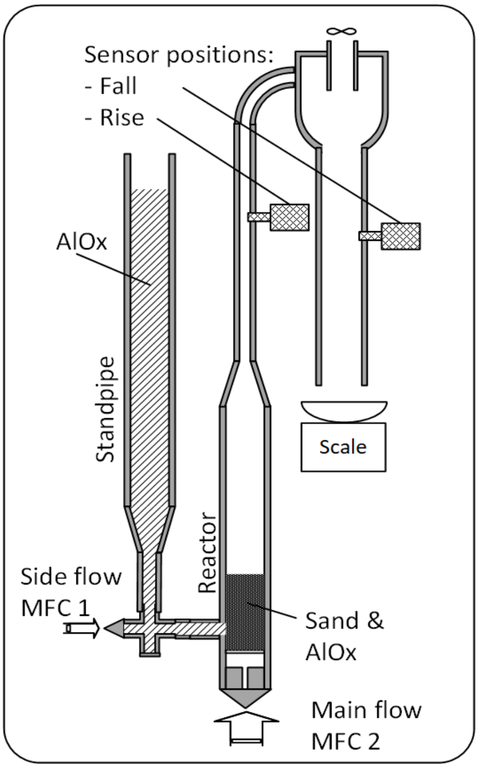


***Figure 3**. Setup for the microwave Doppler sensor tests in the cold flow model*

The sensor was utilized in the cold flow model to measure the particle mass flow at two positions, as depicted in Figure 2.
At position *Rise*, the sensor detects the particles after the reactor column, where they are transported via pneumatic conveying and in the presence of abrasive particles. At position *Fall*, the particles are measured in free-falling conditions without abrasive particles, as they are removed along with the reactive gas.

## 4. Results

Figure 4 illustrates the error in the measured particle mass flows. The best results were obtained with a large split in the AlOx – Sand particle diameters at the *Fall* position. A smaller gap between the particle sizes slightly increased the error but remained within an acceptable range. The *Rise* position exhibited the most significant error (the digital value is more significant than the analogous one), as particle velocities are more widely distributed in pneumatic conveying than under free-falling conditions. Additionally, abrasion particles caused substantial measurement errors at small particle flows.

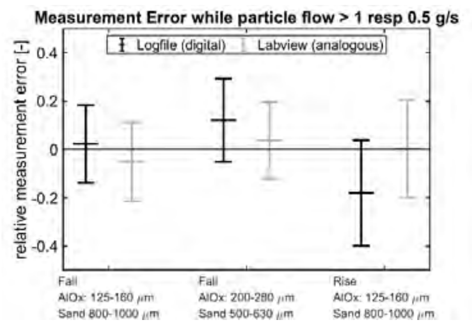


***Figure 4**. Results of the MF3000 measurements with an analogous and digital data processing*

## 5. Conclusions

A stable, running cold flow model could demonstrate the fluid dynamical feasibility of a combined BFB and CFB reactor. Microwave Doppler sensors can be employed for flow measurements and system control in this reactor.

## 6. References

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# Levelised cost of offshore produced eLNG.

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## 1. Introduction

With the ongoing energy transition, the demand for renewable energy, including green LNG, is increasing to ensure a stable energy supply. In addition to imports, local production in Germany is essential. As part of the $H_2$Mare research project, the offshore production of green LNG is being investigated. By directly coupling an LNG plant to a wind farm, conversion losses are avoided. The need for a grid connection to the shore can be eliminated. As a result, the costs for DC cable and transformers are dispensed. This approach not only enhances energy independence but also makes efficient use of the high offshore wind potential.

## 2. Process description

The LNG process chain is shown in Figure 1. In a first step, the concept for offshore LNG production is designed for a 100 MW electrolyser. To optimise methane production, the offshore wind farm (OWF) is sized to generate 15 % more power than the electrolysis capacity. Due to wake effects and other loses an installed capacity of 180 MW is required to reach a power output of 115 MW. The hydrogen generated by a proton exchange membrane (PEM) electrolyser is either fed directly into the methanation process or stored in a compressed hydrogen tank (maximum pressure of 350 bar). Methane is then produced in a two-stage methanation process with a honeycomb reactor in the first stage, while the required $CO_2$ is delivered by ship. The methanation unit is sized to accommodate the full hydrogen output from the electrolysis process at maximum capacity and operates at a capacity of 49 MW (referring to the methane output in relation to lower heating value LHV). The resulting green methane is liquefied using a two staged Stirling liquefaction unit. The produced LNG is stored in LNG tanks until it is transported to shore by ship. Due to the transient electricity profile of the wind farm and the missing grid connection, the plants need to operate at flexible loads. Therefore, to buffer high load changes and to ensure power supply during doldrums a battery and combined heat and power plant (CHP) is integrated on the offshore platform.

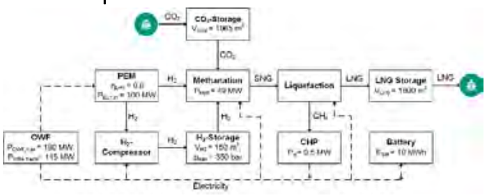


*Figure 1*: *LNG process chain*

## 3. Technical optimisation

To maximise LNG yield and minimise production costs, the plant dimensions must be optimised. The following focuses on optimising the annual methane production depending on the hydrogen storage capacity and the methanation capacity (see Fig. 2). With a methanation capacity of 49 MW (referring to the methane output in relation to LHV), the maximum methane output of 18.5 kt/a (257 GWh) is achieved. A smaller methanation unit would suffice on annual average, but the required hydrogen storage capacity would need to increase significantly to reach maximum production again. Determining the optimal plant configuration requires an economic assessment.

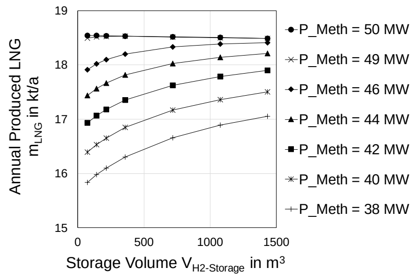


***Figure 2:*** *LNG produced as a function of $H_2$ storage volume and methanation capacity*

## 4. Cost calculation

The levelised costs of LNG for the process chain in Figure 1 are calculated using the annuity method, based on our own expertise, literature data, and stakeholder interviews with industry and research partners. The levelised costs of LNG amount to 0.23 €/kWh - 0.41 €/kWh (LHV) (see Fig. 3). Transport costs for $CO_2$ and LNG as well as personnel costs have not yet been considered in the costs.

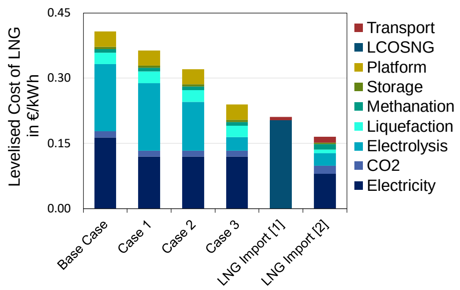


***Figure 3****: Levelised cost of LNG for different cases compared to literature [1,2]*

Methanation and hydrogen storage at 49 MW and 150 m³ represent only 2 % of the levelised cost. Therefore, the produced methane quantity is the key determining factor. The highest share of the costs is allocated to the electricity cost, accounting for 33 %(Case 1)- 50 % (Case 3) The levelised cost of energy (LCOE) are assumed to 54 (Case 1-3) / 74 €/MWh (Base Case/ Case 1-3) with no curtailment. Because 7 % of the power must be curtailed over the year, the effective electricity price is 78 €/MWh (Base Case). Besides electricity costs, the CAPEX of the PEM has a significant impact on the levelised costs, which were calculated with a CAPEX of 2500 €/kW (Base Case, Case 1), 1000 €/kW (Case 2) or 470 €/kW (Case 3). The costs for the base case are higher than in the literature [1, 2]. On the one hand, this is due to the currently high investment costs for PEM and the high electricity generation costs in the German Bight. With comparable electricity costs and CAPEX for PEM (Case 2), the additional costs are mainly due to platform costs. The platform is a jacket structure, and its costs is determined by the topside weight [3].

## 5. Conclusions

Volatile power generation without grid connection requires an adapted process chain design and the integration of storage facilities. Offshore eLNG can be produced at 0.23 €/kWh - 0.41 €/kWh (LHV). With competitive PEM and LCOE, the levelised cost of LNG are close to imported LNG (0.17 €/kWh - 0.21 €/kWh ) and can be a viable alternative. Additional costs compared to onshore production are mainly due to platform costs. The aim is to maximise the methane yield while minimising curtailment, which has a significant impact on electricity costs (LCOE). The next step is to optimise the production costs. Therefore, the effect of the battery size, the CHP and the OWF will be analysed in detail.

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[3] DNV Denmark: Cost and performance data for offshore hydrogen production, Report, (2023)

# The WeMetBio2 project - Construction, operation and evaluation of a pilot plant for biological methanation in northern Germany

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## 1. Introduction

As part of the "WeMetBio" project, a feasibility study was conducted on the integration of biological methanation as an additional process in a biogas plant for a specific location in the federal state of Schleswig-Holstein in northern Germany [1]. As a result of the technical feasibility and prospective economic and ecological viability, the realisation of a pilot plant in the following project is in progress.

The "WeMetBio2"project started in 2024 and involves the construction, operation, and evaluation of a plant in Nordhackstedt, Schleswig-Holstein in Germany for the supply of e-methane and heat [2]. This pilot plant will operate a trickle bed reactor with a working volume of $50\,\mathrm{m}^3$, which will initially produce $20\,\mathrm{m}_\mathrm{n}^3$ of e-methane per hour.

***Figure 1**. local setting of wind-, PV-, biogas plant, local underground gas- and heat grid*

The reaction partner is "green" hydrogen, produced by electrolysis and renewable energy from wind or PV plants that currently cannot be stored. In addition to $H_2$, the second reaction partner of the process is $CO_2$, which is supplied via biogas from the biogas plant in Nordhackstedt. The $CO_2$ originates from biomass and is utilised in biomethanation, instead of being seperated. This circular flow prevents additional GHG emissions. A by-product of the process is heat, which can be used to supply local district heating to neighbouring communities and a nearby dairy.

The produced "green" methane is chemically comparable to natural gas and, unlike short-term storage systems such as batteries, it enables long-term energy storage via the existing gas network infrastructure. This gas reserve can be used independently off the season, even in times of so-called dark doldrums. Alternatively, its direct use in bioCNG or bioLNG-powered vehicles, such as agricultural tractors, is planned. The project also includes an economic and ecological evaluation of the integration into the local energy grid.

The results and experiences, gained during plant construction or the approval process, are of particular interest to heat, electricity, and gas network operators, operators of PV and wind power plants, hydrogen and biogas producers, $CO_2$ emitters and developers of post-Renewable Energy Act concepts.

## 2. Description of Technology and Planning Criteria

The biological methanation is achieved using the patented GICON®-trickle bed process in which the reactants $H_2$ and $CO_2$ are converted biocatalytically into $CH_4$:

$$4H_{2(g)} + CO_{2(g)} \rightarrow CH_{4(g)} + 2H_2O_{(g)}$$
$$\Delta H_R^0 = -165\,KJ/mol$$

Theoretical aspects, process conditions and advantages of the trickle bed methanation, its performance and the limitations, have been published multiple times [3-5]. Concluded investigations in GICON®'s large-scale laboratory have resulted in process describing parameters and the development of a process model. This model is part of the basis for reactor dimensioning, plant design and detailed engineering, aiming for a practical, industry-relevant scale at the potential site in Nordhackstedt.


***Figure 2.*** *simulation of GICON®trickle bed process [6]*

The local boundary conditions such as the available energy from nearby wind turbines and the biogas volume flow are already considered during the conceptualisation and planning phase. Process characteristics like thermophilic conditions, fluctuating availability of reactants and the heat dissipated have an additional influence on the reactor design, equipment and material selection.

Clogging of the fixed bed, due to the biofilm formation and filtration effects, needs to be avoided. For long-term operation of the pilot plant, a specific flushing concept was developed and incorporated into the plant design.

## 3. Summary

The WeMetBio2 project involves the construction of a pilot plant for biological methanation with a multiplier effect. Its purpose is to demonstrate the technical feasibility of providing e-methane and heat on a practical scale. The outcome is a decentralised supply with green energy and harmonisation between the supply and demand of renewable energy through a long-term storage solution. In this way, the energy transition has been thought through to the end.

**Funding notice**

The authors would like to thank the BMEL and the FNR for funding FKZ 2222NR051

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# Advanced zeolite membranes for the selective separation of $H_2$ and $CO_2$ from $CH_4$ in renewable gas systems.

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## 1. Introduction

In the context of renewable energy, methane ($CH_4$) has emerged as a vital energy carrier. The separation of hydrogen ($H_2$) and carbon dioxide ($CO_2$) from $CH_4$ is essential to optimize its use in various applications, including energy production and biogas upgrading. One promising approach to achieve this selective separation is the use of zeolite membranes, which have attracted attention due to their selectivity, stability, and high efficiency in gas separation based on molecular size and adsorption properties. High-silica CHA (Chabazite) membranes have shown great potential in selective gas separation due to their well-defined pore structure and exceptional thermal and chemical stability [1]. This study investigates the application of high-silica CHA membranes for the separation of $H_2$ and $CO_2$ from $CH_4$ and emphasizes their potential in renewable gas systems, especially for biogas upgrading and gas cleaning.

## 2. Experimental procedure

According to Figure 1, zeolite membranes were fabricated using the secondary seeded growth method, which improves the possibility of controlled synthesis of high-quality zeolite films with gas separation properties [2].

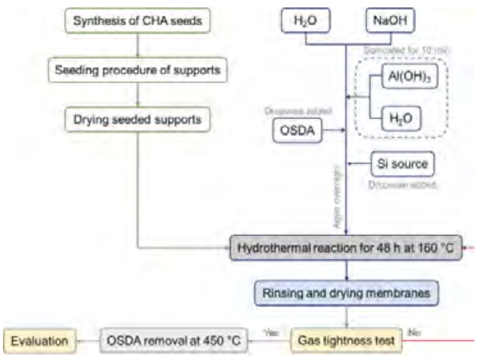


***Figure 1**. Preparation procedure of CHA membranes via secondary seeded growth approach*

## 3. Evaluation of membranes

The performance of the membranes is evaluated through single gas (He, $H_2$, $CO_2$, $N_2$, $CH_4$ and $SF_6$) and mixed gas ($CO_2$-$CH_4$ and $H_2$-$CH_4$) permeation measurements, with an emphasis on understanding the effects of the presence of water vapor on membrane performance [3].

## 4. Results

According to Figure 2 (a), the high-silica CHA membranes demonstrate high performance in the selective separation of $H_2$ and $CO_2$ from $CH_4$. The performance remains stable under both single and mixed gas conditions (Figure 2 (b)), with slight reductions in permeance observed in the mixed gas permeation experiments, likely due to competitive adsorption effects. However, even in the presence of water vapor (Figure 2 (c)), which is typically known to influence gas permeability, the membranes maintain a high degree of separation efficiency.

## 5. Conclusions

It was found that the membranes had remarkable $H_2$ and $CO_2$ permeance, as well as high selectivity over $CH_4$, making them ideal candidates for industrial applications.

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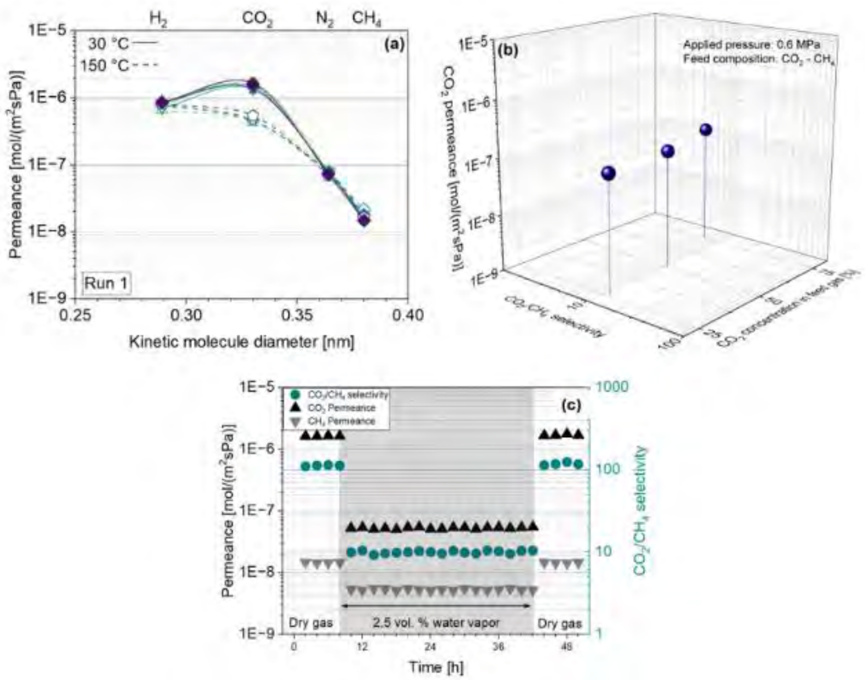


***Figure 2**. Evaluation of fabricated membranes with (a) single and (b) mixed gas permeation measurement and (c) in presence of water vapor.*

# The HyFuelUp Project.

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## 1. Introduction

As the rising prices of fossil natural gas make evident, the need to increase renewable gas capacity is undeniable and goes hand in hand with solving bottlenecks that current biomethane production technologies cannot effectively address. The HYFUELUP project aims to demonstrate a flexible and hybrid pathway for the efficient and cost-effective production of biomethane through thermochemical technologies combined with renewable hydrogen. A complete deployment value chain, including biomethane off-take and distribution, will also be demonstrated to contribute to the market penetration of biomethane in key sectors. The achievement of HYFUELUL tasks will contribute to the European effort for decarbonisation of the energy and transport systems. Thanks to the broad composition of the consortium, the project blends market knowledge with advanced academic and industrial perspectives to demonstrate the production of biomethane at scale.

## 2. Approach

There are three major challenges to increasing the European renewable gas capacity and establishing biomethane as a cornerstone of EU decarbonisation.

1. The need to diversify the available technologies for biomethane production, removing the focus from anaerobic digestion at a wider scale
2. The need to use sustainable biomass and biogenic waste feedstocks and improve supply chains
3. The market penetration of biomethane production technologies

Biogas upgrading after anaerobic digestion (AD) is the current technological choice for biomethane production but faces two major limitations: operational problems due to biogas process instability and inhibition and feedstock limitations, as the conversion of woody biomass or lignocellulosic feedstocks is not yet technically feasible. For this reason, in HYFUELUP project, an alternative biomethane production pathway will be demonstrated. This pathway includes the flexible conversion of low-grade feedstocks via sorption-enhanced gasification coupled with syngas or flue gas clean-up, followed by fluidised-bed methanation of either syngas or flue gas with the dynamic addition of hydrogen. Since this pathway is validated then both technologies will be integrated into a plant to produce biomethane at demonstration scale.

Regarding the required feedstock, the Recent European legislation, such as Directive 2018/2001/EU (RED II), has reinforced the need to use waste feedstocks to produce renewable gaseous fuels. Since the AD industry is growing across Europe, this results in a respective increase in sludge digestate production. On the other hand, there is a similar increase in the lignocellulosic wastes derived in Europe. HYFUELUP estimated the potential of those types of wastes in the countries participating in the project consortium. The results of this estimation are drafted in two separate deliverables. Also, reliable supply chains of those feedstock must be established to ensure the reliable supply of biomethane plants. Those supply chains are also studied within the context of HYFUELUP.

Finally, market penetration of biomethane production technologies needs to increase and their associated production costs need to be reduced. Costs can be reduced by widening the technological market and developing experience through learning-by-doing. The questions faced by these technologies can be addressed by industrial scale first-of-a-kind plants, as the one developed in HYFUELUP. This will bridge the gap to commercialisation and then, in the long run, establish a commercial framework that leads to more widespread activities and full deployment

## 3. Results

*The feedstock availability in the participating countries*

The feedstock availability in the participating countries (DE, GR, PL, ES and CH) has been estimated and the biomethane production potential has been calculated, as shown in Table 1.

*Table 1. Biomethane potential from lignocellulosic feedstock in participant countries*

| FEEDSTOCK TYPE | GREECE TWh | PORTUGAL TWh | GERMANY TWh | SWITZERLAND TWh | SPAIN TWh |
|---|---|---|---|---|---|
| CEREALS | 1.49 | 2.57 | 20.39 | 0.00 | 2.43 |
| TREE PRUNING | 1.22 | 7.83 | 0.96 | | 2.38 |
| FOREST RESIDUES | 0.00 | 5.73 | 10.15 | 7.40 | 1.22 |
| LANDSCAPE CARE | 0.96 | 4.51 | 4.53 | 1.23 | |
| WASTE WOOD | 0.67 | 0.00 | 0.00 | 2.63 | |
| **TOTAL** | **4.35** | **20.64** | **36.04** | **11.26** | **6.03** |

The data on the current availability of lignocellulosic feedstock originates mainly from national resources in the participating countries and is provided by the respective partners. Data are based on official facts and figures if existing, such is the case of DE, PL, ES and CH. Whenever data is not exactly straightforward, like in GR, where national data on the lignocellulosic biomass availability is not available, the figures are calculated from raw data based on the agricultural production per crop type, as they are reported on official facts and figures.

Accordingly, the digestate potential of the participant countries was calculated. The calculation was based on a special AD mass balance calculation model and on data regarding the feedstock used in each country's AD plants, shown in Table 2.

*Table 2. Digestate potential in the participant countries*

| TYPE OF FEEDSTOCK | GREECE | PORTUGAL | GERMANY | SPAIN | SWITZERLAND |
|---|---|---|---|---|---|
| Agricultural waste, tons/y | 349,915 - 562,861 | 12,525 | 43,683,537 – 48,671,719 | 204,440 - 227,842 | 196,756 – 177,340 |
| Sewage sludge, tons/y | 364,863 | 85,254 | 6,633,865 | 426,271 | 545,626 |
| **TOTAL, tons/y** | **699,829 – 912,776** | **97,780** | **50,317,402 – 55,305,584** | **630,711 – 654,112** | **722,966 - 742,382** |

## 4. Conclusions

The need for increased biomethane production highlights the necessity to investigate diverse methods of production from the, so far, dominating method of upgrading biogas produced from AD. HYFUELUP addressed this necessity by developing an alternative biomethane production pathway that can valorise lignocellulosic agricultural wastes and digestate from AD plants. The work that has been completed up to now shows that there is significant potential for those two types of feedstocks in the participant countries and that there will be enough feedstock to support the biomethane production. Of course, reliable supply chains have to be established in order to ensure that this feedstock can reach the production plant, and this is part of the investigation that is ongoing now in the project.

# Valorisation of Landfill Gas Using a Spinning Fluids Reactor

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## 1. Introduction

Landfill gas (LFG) is a complex by-product of anaerobic degradation of municipal solid waste. It typically contains a significant fraction of methane ($CH_4$), but in many cases - particularly in mature landfills - the methane concentration drops below 40%, making the gas unsuitable for direct use in engines or combustion without enrichment. Conventional technologies like flaring or direct combustion are no longer viable under such conditions, leading to underutilization of a valuable energy source and uncontrolled methane emissions.

Within the Interreg South Baltic project Low Calorific Gas for Green Power Production (LoCaGas), a new approach to LFG valorisation is being developed. The Spinning Fluids Reactor (SFR) has been identified as a promising technology capable of enhancing gas-liquid interactions, thereby enabling the removal of $CO_2$ and other undesired components from low-calorific biogas and increasing its energy content. The project involves cross-border collaboration among partners from Poland, Lithuania, Sweden, and Germany, with a focus on advancing decentralized and sustainable energy production solutions.

## 2. Technology Overview

The SFR (Figure 1) is a high-efficiency contactor designed for intensified gas-liquid mass transfer. It utilizes rotational flow patterns induced by tangential liquid injection and vortex-forming geometries. The gas phase is introduced radially through a porous element, resulting in highly turbulent conditions that:

- Maximize interfacial surface area,
- Promote rapid mixing,
- Shorten diffusion paths.

These characteristics allow the SFR to operate with high efficiency at low pressure drops (6–8 kPa), making it ideal for integration into low-pressure biogas systems.

In the LoCaGas context, the SFR is coupled with chemical absorption processes, such as $CO_2$ removal using diglycolamine (DGA) solutions. Its compact and modular design makes it particularly attractive for decentralized applications at landfill or agricultural biogas sites.

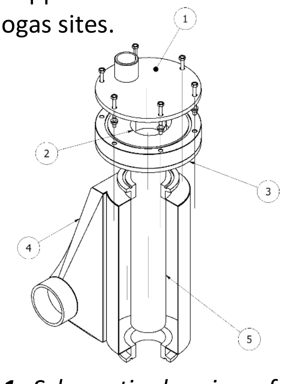


***Figure 1.*** *Schematic drawing of SFR working principle. 1 - SFR head cover, 2 - pattern generating the vortex motion, 3 - head base, 4 - SFR housing, 5 - porous tube.*

## 3. Semi-Industrial Demonstration and Results

The industrial applicability of the SFR was evaluated through the construction and operation of a semi-technical scale biogas upgrading plant in Międzyrzec Podlaski, Poland. The facility consisted of a four-section absorber battery (see Figure 2), each equipped with four SFR units.

*Table 1. Key process data from a representative test campaign:*

| | |
|---|---|
| Raw biogas flow rate: | 100 $Nm^3/h$ |
| Raw biogas composition (in): | $CH_4$ – 59%,<br>$CO_2$ – 41%,<br>$H_2S$ – 490 ppm |
| Valorised biogas composition (out) | $CH_4$ – 98%,<br>$CO_2$ – 2%,<br>$H_2S$ – 8 ppm |
| Absorbent: | 60% aqueous DGA solution |
| Operating temperatures: | Absorption – 40°C;<br>Desorption – 120°C |

The test campaign confirmed the effectiveness of SFR modules in significantly reducing $CO_2$ and $H_2S$ content while enriching the methane fraction to a quality suitable for energy generation. The reactors operated reliably and maintained process stability over the duration of the tests.

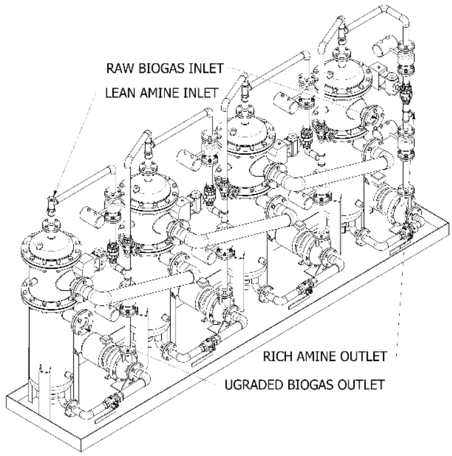


***Figure 2.*** *View of the biogas enrichment system based on the SFR.*

## 4. Industrial Relevance and Advantages

The pilot installation (see Figure 3) demonstrated the key strengths of the SFR technology:

- Compact footprint, enabling retrofitting or integration into constrained industrial spaces,
- Low operational energy demand due to minimal pressure drop,
- High flexibility and modularity, allowing adaptation to variable gas flows,
- Effective operation with low-quality gas streams, such as landfill gas with <40% $CH_4$.

***Figure 3.*** *View of the biogas enrichment system based on the SFR.*

The system's design also allows for scalability, either by increasing the number of parallel SFR units or by extending the number of absorption stages.

## 5. Conclusions and Outlook

The results of the semi-industrial demonstration plant validate the technical feasibility and scalability of the Spinning Fluids Reactor for gas upgrading processes. The technology offers a novel solution for enhancing the quality and usability of landfill gas and low-calorific biogas in a decentralized, resource-efficient manner.

Within the LoCaGas project, further development will focus on:

- Integrating the SFR system with combined heat and power (CHP) units,
- Expanding the use of SFR in real landfill sites across the South Baltic region,
- Supporting circular economy and emission reduction strategies through improved gas recovery.

The SFR thus represents a practical step forward in the valorisation of challenging biogenic gas resources and contributes to the broader goals of sustainable waste-to-energy transformation.

# LoCaGas – Dual fuel engine technology

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## 1. Introduction

LoCaGas stands for Low Calorific Gas for Green Power Production and is an Interreg South Baltic project coordinated by the Gdansk University of Technology (PL). The other project partners are, Eco-Construction Ltd. (PL), Klaipeda University (LT), Lithuanian Energy Institute (LT), NSR AB (SE), Rostock University (DE), UAB Addeco (LT) and Baltic Energy Innovation Centre (SE).
The 3-year project started on the 1st of July 2024.

The project revolves around power production using low calorific gases such as landfill gas with low methane content (<40%).

Within the project, three different solu-tions will be investigated.

1) Dual fuel engine technology able to use landfill gas with methane content down to ~10%.
2) Oxygen-enriched combustion in combination with a conventional gas engine.
3) Spinning Fluids Rector (SFR) to increase the heating value of the landfill gas by removal of carbon dioxide.

## 2. Background

Deponigas ApS (DK) has been running dual engines on landfill gas with low methane content and fossil diesel as pilot fuel at several landfills in Denmark. To guarantee a good-quality combustion and sufficient cooling of the pilot fuel injectors, Deponigas ApS injects fossil diesel corresponding to approx. 15% of the supplied fuel on an energy basis.

***Figure 1.*** *Ole Elmose, CEO Deponigas ApS besides a Volvo Penta engine modified to operate in dual fuel mode at the landfill in Hedeland, Denmark.*
*Photo: Jörgen Held*

Baltic Energy Innovation Centre conducted a paper study[1] under Swedish conditions using data from Deponigas ApS but with RME as a pilot fuel. It was found that the main cost for producing electricity was related to the cost for the renewable pilot fuel. As much as 70% of the production cost was associated with the cost of the pilot fuel. It would be optimal to find a cheaper pilot fuel with a lower heating value. In this way the same amount of pilot fuel can be injected for cooling the injectors but the cost per kWh injected pilot fuel will be lower. Such a fuel was identified in the paper study, namely pyrolysis oil.

## 3. Experimental testing

Within the LoCaGas project pyrolysis oil and/or blends of pyrolysis oil and HVO or RME will be tested in a combustion engine laboratory.

Project partner NSR AB will produce the pyrolysis oil in its pilot scale pyrolysis unit at RecoPark – a competence centre for biocoal. Pyrolysis oil is taken out in the condenser and at two subsequent oil traps. Figure 2 shows mixtures of the pyrolysis oil taken at the three different points and Diesel, HVO and RME.

The pyrolysis oil from the condenser contains most of the water released by the feedstock (pelletised wood) during the pyrolysis process. In the third bottle from the left in Figure 2, it is clearly visible that the pyrolysis from the condenser and Diesel are not miscible. The Diesel is on top of the pyrolysis oil.

At first, a reference case with HVO or RME as pilot fuel will be used with a model gas (20% methane and 80% carbon dioxide) resembling landfill gas with low methane content.
Next step involves mixtures of filtered pyrolysis oil and HVO or RME. Depending on how easy it is to obtain compression ignition of the mixture, pre-heating of the pilot fuel may be necessary.

## 4. Case studies and decision support tool

The results from the experimental testing with the dual fuel will be used together with results from the other two solutions; oxygen enriched combustion and the Spinning Fluids Rector, to make case studies based on existing landfills in the participating countries.

Finally, a decision support tool will be developed to support landfill operators in the South Baltic Sea region to continue produce green power (and heat) even if the methane content declines and conventional spark ignited gas engines, which requires a methane content of ~40%, no longer is an option.

## 5. Acknowledgement

The LoCaGas project is co-financed from the Interreg South Baltic Programme 2021-2027 through the European Regional Development Fund.

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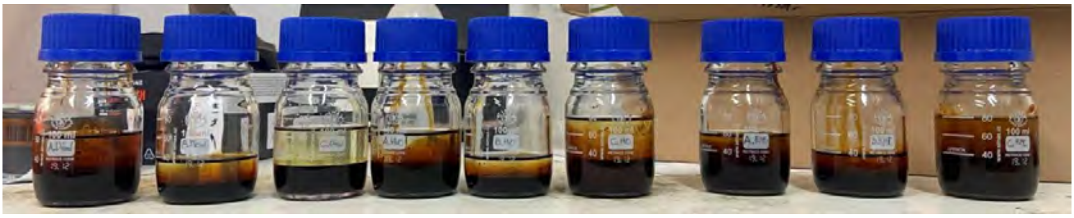

***Figure 2**. Pyrolysis oil from oil trap 1, oil trap 2 and the condenser mixed with Diesel (left), HVO (middle) and RME (right), respectively. Photo: Marcus Lundgren, Lund University.*

**CarbonNeutralLNG**, https://www.carbonneutrallng.eu, is a three-year Horizon Europe project coordinated by the Friedrich-Alexander-Universität Erlangen-Nürnberg.

**Project partners are**: National Technical University of Athens
University of Natural Resources and Life Sciences
Electrochaea GmbH
RINA Consulting S.p.A.
University of Graz
Ludwig-Maximilians Universität München
BEST – Bioenergy and Sustainable Technologies GmbH
Diffenbacher Energy
Baltic Energy innovation Centre
KN Energies
University of Calgary

The project revolves around liquefied methane (green LNG) produced through sorption enhanced e-gasification of woody biomass, catalytic and biological methanation followed by liquefaction.

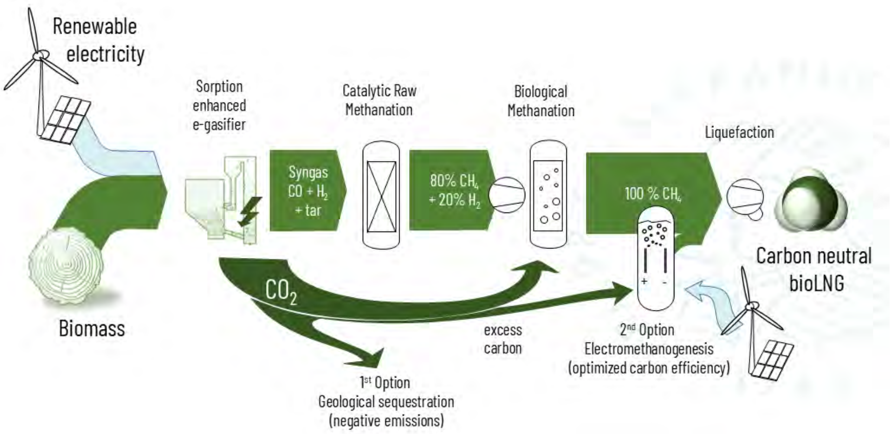


***Figure 1***. *Process scheme. Source FAU*

Within the project two Symposia will be organised in collaboration with International Conference on Renewable Energy Gas Technology, REGATEC.

The 1st Symposium, on biomass gasification, took place on the 16th of May at REGATEC 2024 in Lund, Sweden and the 2nd Symposium takes place 21st of May at REGATEC 2025 in Weimar, Germany.

# Baltic Energy Innovation Centre

*Innovative energy technology for a sustainable future*

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The Baltic Energy Innovation Centre (BEIC) is a non-profit Association participating in regional, national and international R&D activities with focus on innovative energy technology in general, and renewable methane related development in particular.

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  - Simulations (PetraSim, Ansys, etc.)
  - Measurements (3D-LDV, Raman scattering spectrometer, etc.)
  - Fuel characterization - ultimate and proximate analysis
- Independent evaluations (scientific quality, technology and economic aspects)
- Conferences, seminars and expert presentations
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