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Jörgen Held
Baltic Energy Innovation Centre

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Skarpskyttevägen 10 D
SE-226 42 Lund
SWEDEN
info@renewtec.se

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Jörgen Held
Baltic Energy Innovation Centre

Postal address
Skarpskyttevägen 10 D
SE-226 42 LUND

Phone
+46 (0)723-182 582

Email
info@renewtec.se

Website
eng.renewtec.se

Preface

This report has been prepared in the framework of the project P2022-00570 *SynFerm – Efficient syngas fermentation of gasified woody biomass*.

The project was financed by the Swedish Energy Agency, Cortus AB, NSR AB, Q Power Oy, St1 Biokraft AB (former Biokraft International AB and Scandinavian Biogas Fuels AB) and Baltic Energy Innovation Center.

The project was carried out by Cortus AB, Linköping University, NSR AB, Q Power Oy, St1 Biokraft and Baltic Energy Innovation Center during the period 2023-01-01 – 2025-06-30 with Jörgen Held, Baltic Energy Innovation Centre as the project leader.

A large number of people have contributed directly or indirectly to this report, the author would like to thank the whole project team for their contribution and valuable input. A special thanks goes to Anna Karlsson, St1 Biokraft AB for improving the text of this report, Ragnar Stare, St1 Biokraft for all the interesting discussions, Q Power for hosting nice and fruitful study visits and meetings at the Qvidja Research Farm in Parainen, Marco Amovic, Cortus for providing technical details on the WoodRoll® gasifier, Anni Alitalo, Q Power for providing technical details on the biological methanation system, Marko Niskanen, Q Power for the contribution to the sensitivity analysis, Niclas Svensson for the environmental analysis and Staffan Hellsén, Cortus for hosting several good and fruitful meetings at the Cortus site in Höganäs. The author would also like to extend a special thanks to Dr. Ricardo Roque for the English proofreading

Summary

The project activities concern the development of efficient biological methanation of gasified woody biomass in a unique "solid-state" reactor, newly developed and patented by Q Power Oy.

Background

Through thermal gasification of forest residues/waste, demolition wood, park and garden waste etc., the carbon and hydrogen content of the lignocellulosic materials are made available to microbes and can thereby be biologically converted to methane. In this way, the raw material base for the production of biomethane is broadened. The Swedish potential for these materials has been estimated at 59 TWh/year.

Syngas fermentation enables cost-effective production even on a smaller scale, <20 MW, compared to catalytic methanation which takes place at elevated pressures and temperatures and involves extensive and costly gas cleaning, and expensive catalysts. Small scale production of biomethane brings several advantages:

- Easier to secure raw material supply and logistics become simpler
- Easier to match excess heat from the gasification and methanation processes with local heat and steam demands
- Lower economic risk

Expected outcomes and project goals

The project was expected to enable commercialization of the technique by 2030, and by that double the Swedish biogas production within 15 years and thus contribute to increased self-sufficiency. The project goals were to:

- Achieve a volumetric efficiency of 10 liters of methane per liter of reactor volume and day.
- Achieve an electricity consumption of less than 0.02 kWh per kWh of methane for the biological methanation.
- Achieve complete conversion of carbon monoxide.
- Achieve a level of residual hydrogen in the final product of less than 2%.

Results

Laboratory tests with model gas, with a gas composition corresponding to the synthesis gas produced with the WoodRoll® gasifier in Höganäs, showed that the microbes adapt quickly, and that carbon monoxide and water are converted into carbon dioxide and hydrogen via biological water-gas shift.

A mobile biological methanation plant with a total reactor volume of 750 liters was then transported from Q Power's facilities in Finland to Höganäs for tests on biological methanation of real synthesis gas from the WoodRoll® gasifier.

Experiments with four different gas flows of synthesis gas from the WoodRoll® gasifier were found to give rise to an unstable biological process. Addition of carbon

dioxide to the synthesis gas was however shown to stabilize it. A total of 10 experiments were carried out with synthesis gas plus carbon dioxide. The highest gas flow to the biological methanation reactor, 23.13 liters of synthesis gas and 4.47 liters of carbon dioxide, resulted in an output gas flow corresponding to 10.5 liters of methane per liter of reactor volume and day. At the same time, the remaining carbon monoxide and hydrogen content were 0.75 vol-% and 3.7 vol-%, respectively.

Six additional tests (not included in the application) were carried out with synthesis gas spiked with additional hydrogen from bottles. The lowest carbon monoxide and hydrogen content in the outgoing gas were, in these tests, measured to 0.06 vol-% and 0.20 vol-%, respectively. The electricity consumption based on multiple scaled-up "solid-state" reactors adapted for a synthesis gas flow equivalent to 6 MW was calculated to 59 kW excluding upgrading and compression of the produced bio-methane. This gives an electricity consumption for the biological methanation of 0.012 kWh/kWh methane. The figures are based partly on the present pilot-scale tests, partly on the industrial scale plant for biological methanation of CO_2 (3.3 MW biomethane) that Q Power delivered within the framework of the Harjavalta project[1].

The environmental analysis showed that emissions associated with harvesting and transporting wood chips constitute a major part of the emissions from the full process chain (from feedstock to biomethane). The produced biomethane contributed when replacing the fossil reference according to the Renewable Energy Directive (RED II), to a more than 85% reduction of CO_2 equivalents, 45 kg CO_2-eq/MWh versus 338 kg. CO_2-eq/MWh.

The techno-economic analysis, based on the same design as the existing 6 MW syngas WoodRoll® gasifier and multiple scaled-up "solid-state" reactors, showed that the production cost was too high to make the production profitable, regardless of whether investment support according to Klimatklivet was received or not, 13.2 and 17.5 SEK/Nm^3 biomethane respectively. It should be noted that the possibilities for optimization were limited since the approach was based on the existing construction and design of the WoodRoll® gasifier. Furthermore, the analysis concerns a so-called FOAK plant (First of a kind) and societal benefits, such as increased self-sufficiency of a high-quality and storable fuel and opportunities for regional development and new jobs, were not taken into account.

Within the framework of the project, an interesting business model was however developed. By using cheaper raw materials and co-producing biochar and bio-methane, the production cost could be more or less halved, 6.7 SEK/Nm^3 biomethane including investment support via Klimatklivet, despite increased investment costs in the form of a sorting plant that removes metal, stones and soil from low-quality raw materials (park and garden waste, recycled wood and demolition wood), rebuilding of the drying and pyrolysis reactors and the steam system, increased personnel and maintenance cost as well as less annual operating hours.

In summary, the project has achieved the set goals, but continued development, scaling up and long-term tests are required before the technology can become commercial. Unfortunately, Cortus went bankrupt during the Spring of 2025 and the future fate of the company and the WoodRoll® technology is therefore uncertain.

Abbreviations and expressions used in this report

CAPEX	Capital expenses
CO_2-eq.	Carbon dioxide equivalent. a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP) by converting amounts of other gases to the equivalent amount of carbon dioxide with the same GWP.
CO_2 methanation	$CO_2 + 4\ H_2O \rightarrow CH_4 + 2H_2O$
EAC	Equivalent Annual Cost
FOAK	First of its kind
GWh	Giga watt hour, 1 GWh = 1,000 MWh
kWh	kilo watt hour
kW_{el}	kilo watt electricity
kW_{th}	kilo watt thermal capacity
L	liter
normal L	liter of gas at a temperature of 0 °C and a pressure of 1.01325 bar
MWh	Mega watt hour, 1 MWh = 1,000 kWh
OPEX	Operational expenses
Syngas	or synthesis gas, a synthetically produced gas free of nitrogen, mainly consisting of hydrogen (H_2) and carbon monoxide (CO)
TWh	Terra watt hour, 1 TWh = 1,000 GWh
WGS	Water-gas shift ($CO + H_2O \rightarrow CO_2 + H_2$)

Content

1. Introduction

In this project, efficient biological methanation of gasified woody biomass in a unique "solid state" reactor, developed and patented by Q Power (FI) and fed with synthesis gas from the WoodRoll® gasifier in Höganäs (SE) was investigated.
Through thermal gasification of forest residues, demolition wood, park and garden waste, etc. the carbon and hydrogen content of the lignocellulosic material can be made available to microbes and thus biological conversion to methane. In this way, the raw material base is broadened. The Swedish potential for these materials has been estimated at 59 TWh/year[2].

Syngas fermentation enables cost-effective production on a smaller scale, <20 MW, which entails several advantages[3]:

- Easier to secure the feedstock supply and easier logistics.
- Easier to match excess heat from the gasification process with local heat and steam demand.
- Lower financial risk.

1.1 WoodRoll® gasification technology

WoodRoll® operates as a three-stage gasification process[4].

1. **Drying**: Wet biomass is dried to less than 5% humidity using indirect heating from flue gases.
2 **Pyrolysis**: Dry biomass undergoes pyrolysis at 400 °C, yielding solid char and pyrolysis gas. The pyrolysis gas serves as a vital heat source for the WoodRoll® process. The char is finely ground through grinding.
3 **Steam gasification**: Char powder is subject to steam gasification at high temperature (1,100 °C), resulting in the production of a syngas rich in H_2, along with CO, CO_2 and CH_4.

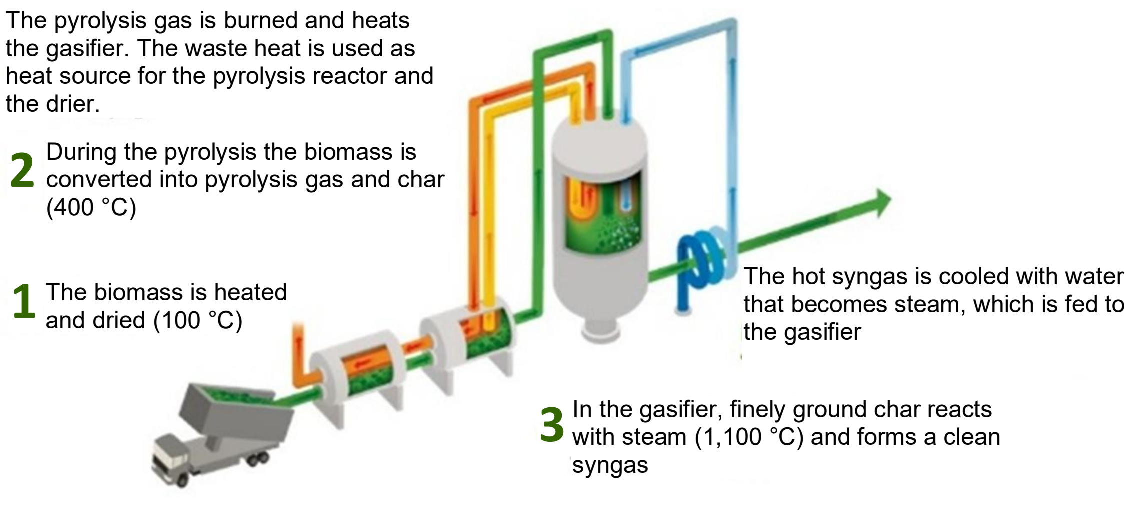

***Figure 1**. The WoodRoll® gasification process. Adopted from R. Ljunggren and M. Amovic, Proven Bio-Energy Solutions by Modular WoodRoll® Technology in Conference Proceedings 10th International Conference on Renewable Energy Gas Technology. ISBN 978-91-981149-9-7.*

1.2 Q Power "solid-state" biological methanation technology

Q Power Oy is a Finnish company that has developed and patented a unique so-called "solid-state" biological methanation technology able to convert syngas to methane. Q Power has revealed that it is not a trickle bed and not microbes suspended in a liquid, but no further details have been disclosed due to confidentiality.

The production site and laboratory are located at the premises of the Qvidja Research Farm in Parainen, Finland. The technology is a result of nearly two decades of research of cultures of microbes collected from the surrounding marsh-lands.

Figure 2. *Qvidja R&D center, Parainen, Finland. Source: https://qpower.fi.*

2. Methodology and limitations

The investigation of the “solid-state” biological methanation using a mixed culture has been performed in two stages:

- Testing of biological methanation in the Q Power laboratory with model gas resembling the composition of the syngas obtained in the WoodRoll® gasification plant in Höganäs, Sweden. The model gas contained H_2, CO, CO_2 and CH_4 from bottles but no contaminants or tar components normally found in biomass gasification derived syngas.

- Tests with syngas produced from the WoodRoll® gasifier using Q Power’s mobile pilot scale biological methanation system at site in Höganäs. To ensure a stable syngas flow a high-pressure storage was installed between the gasifier and the biological methanation system.

During the pilot scale tests in Höganäs an industrial-grade gas analysis setup equipped with a multi-gas analyzer, Rapidox 7100 Syngas Analyser, was used for the measurements of the gas compositions. The accuracy of the analyzer was $\pm$ 1% with a resolution of 0.1%.
If the sum of the measured vol-% of the different gas components in the feed-in gas and the gas coming from the different steps of the biological methanation system deviated from 100%, the values were normalized, i.e., modified so that the total of the normalized values equals 100%.

The environmental analysis was based on the general guidelines of ISO 14044 for life cycle assessment with the functional unit chosen as 1 MWh of biomethane. The result has been compared to the fossil reference according to the Renewable Energy Directive (RED II).

The capital expenses (CAPEX) in the techno-economic analysis were calculated using the annuity method with an internal interest rate of 7% and an operation period of 20 years. The techno-economic analysis for a commercial scale syngas fermentation plant was calculated using the existing design of the WoodRoll® gasifier while the business model was based on a modified WoodRoll® design allowing the use of low-quality feedstock and co-production of biomethane and bio-char. A currency exchange rate of 1 EUR = 10.9 SEK was used.

3. Project goals and objectives

The project goals were:

- Obtain a volumetric efficiency of 10 liter of methane per liter reactor volume and day.
- Obtain an electrical consumption less than 0.02 kWh per kWh methane for the syngas fermentation.
- Obtain complete conversion of CO
- Obtain a level of residual H_2 in the final product of less than 2%

The last project goal implies that the residual H_2 should be less than 1% after the biological methanation, since the outgoing gas stream contains approx. 50% CO_2, which will be removed before obtaining the final product, biomethane. The limit of 2% in the produced biomethane is a requirement to fulfill the *Swedish Standard SS-EN 16723-2:2017 Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network – Part 2: Automotive fuels specification*.

The project objectives were:

- Enable commercialization of syngas fermentation by 2030 based on the Cortus' WoodRoll® gasifier and Q Power's "solid-state" reactor for biological methanation.
- Double the Swedish production of renewable methane within a time span of 15 years and contribute to an increased self-sufficiency.
- Develop business models that, in addition to implementation in Sweden, provide the opportunity to export technology and know-how.

4. Test with model gas

The test was performed at Q Power's laboratory in Parainen, Finland using model gas from bottles.

4.1 Gas composition

The model gas composition was selected to resemble the real syngas in the WoodRoll® gasifier.

Table 1. *Typical syngas composition from the WoodRoll® gasifier.*

Syngas component	[%-vol]
H_2	58
CO	30
CO_2	10
CH_4	2

The high CO content is challenging due to the inhibitory effect of CO on the microorganisms involved in several anaerobic biological processes.

4.2 Experimental setup

The laboratory testing was performed with a gas flow of 10 liter/min and three 250-liter reactors in series (Figure 3).

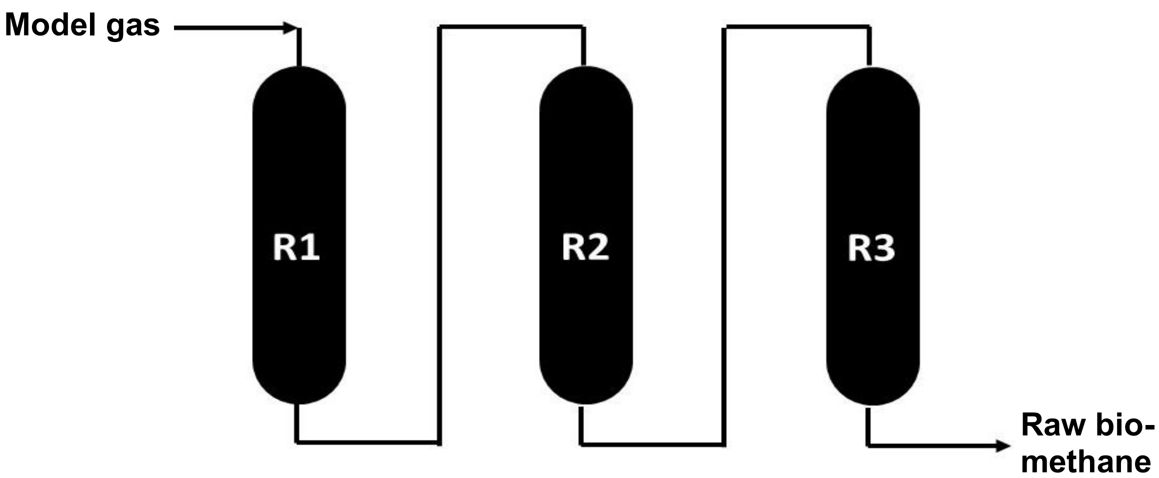

Figure 3. *Layout of the biological methanation laboratory setup.*

By having the reactors in series, the gas composition and other data of relevance could be measured after each reactor. A mixed culture of microbes, obtained from the marshlands surrounding the Q Power production site and laboratory, was used in the reactors.

4.3 Results

Due to problems with the micro-feeders, it was only possible to operate the laboratory setup for a week. The gas composition after each reactor is shown in Table 2. The values have been normalized to account for accuracy issues.

***Table 2**. The gas composition in the feed (model gas) and after each reactor, expressed as %-vol.*

	Feed-in gas measured	**Feed-in gas normalized**	**R1 normalized**	**R2 normalized**	**R3 normalized**
H_2	60.7	56.0	44.4	11.1	3.6
CO	33.1	30.5	20.7	7.8	0.0
CO_2	11.9	11.0	19.9	29.7	35.7
CH_4	2.7	2.5	15.1	51.4	60.7
SUM [%]	108.4	100.0			

It seems the CH_4 content after the last reactor, R3, is too high (and the CO_2 content too low), since the theoretical maximum CH_4 content, calculated with Eq.1 and 2, at full conversion of the feed-in gas is 54.8%. Even though there are question marks on the accuracy of the measurement, it is evident that the biological water-gas shift (WGS) reaction (Eq.1), converting CO and H_2O to CO_2 and H_2, took place during the laboratory testing.

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \textbf{Eq.1}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 4H_2O \qquad \textbf{Eq.2}$$

It is also evident that the microbes adapt rather quickly to gas streams containing CO. In fact, there was no CO measured in the gas stream after the last reactor, R3.

Despite the problems with the micro-feeders and the uncertainties regarding the accuracy of the measurements, the test gave promising results regarding the biological water-gas shift reaction and the prospect of complete CO conversion.

5. Tests with real syngas

The Q Power mobile biological methanation plant arrived to Höganäs at the end of January 2024 and the syngas fermentation tests were conducted between July 22 and August 13, 2024.
The pilot plant consists of three 250 L reactors in series.

***Figure 4**. Left: The WoodRoll® gasification plant. Source: Courtesy of Cortus. Right: The biological methanation plant is lifted in place. Photo: Jörgen Held*

5.1 Tests with only syngas

The test campaign was initiated with a setup in which only syngas was fed into the biological methanation reactors. The test began with a low feed rate which was successively increased. Tests with three different feed rates were recorded. After 48 hours, additional carbon dioxide was added to stabilize the process.

The syngas composition is shown in Table 3.

***Table 3**. Syngas composition, vol-%.*

	H_2	CO	CO_2	CH_4	SUM
Measured	53.40	30.30	9.12	1.92	94,74
Normalized	56,36	31.98	9,62	2,03	100,0

The tests with three different feed rates of syngas resulted in unstable operation of the biological process and high levels of unconverted CO in the outgoing gas after the last reactor.

The interaction of different microorganisms in the mixed culture and the syngas is very complex but it seems that the CO_2 was quickly converted to CH_4 with simultaneous H_2 consumption which increases the partial pressure of CO due to the strong volume contraction during methanation. When the CO_2 was depleted, it seems like the remaining H_2 preferred to react with the bicarbonate in the inoculum leading to a pH increase, which inhibited the activity of the CO consuming bacteria. Addition of CO_2 has the potential to counteract the pH increase.

5.2 Tests with syngas plus addition of CO_2

During these tests, additional carbon dioxide was fed along syngas, maintaining the feed gas mixture CO_2/CO ratio of approx. 1:1. The feed-in rate was increased step-wise.

Table 4. *Syngas + CO_2 composition, vol-%, the syngas flow was normalized to account for accuracy issues.*

H_2	CO	CO_2	CH_4
47.11	26.99	24.20	1.70

In total, 10 tests were conducted, ending with 23.1 L/min of syngas and 4.5 L/min of CO_2.

Table 5. *Measured outgoing gas composition, vol-%, for the case with 23.1 L/min of syngas and 4.5 L/min of CO_2, normalized to account for accuracy issues.*

	H_2	CO	CO_2	CH_4	SUM
Measured	3.74	0.76	57.30	38.99	100.79
Normal-ized	3.71	0.75	56.85	38.68	100.00

Once again, the CH_4 content seems too high (and the CO_2 content too low) since it is slightly higher than the theoretical maximum value of 36.25 vol-% at full conversion.

By assuming that the CO and H_2 levels were correct, it was possible to calculate backwards what the CH_4 and CO_2 levels should be using the chemical reactions of the water-gas shift and the CO_2 methanation. The result is shown in Table 6.

Table 6. *Recalculated values of the CH_4 and CO_2 content, vol-%.*

H_2	CO	CO_2	CH_4
3.71	0.75	59.83	35.71

With the lower, recalculated value of the CH_4 content, 10.5 normal liters of CH_4 per liter reactor volume and day were leaving the biological methanation reactor. Hence, the project goal of 10 normal liters of CH_4 per liter reactor volume and day was fulfilled. However, the project goals of complete conversion of CO and less than 2% of residual H_2 in the end product were not fulfilled

5.3 Tests with syngas plus addition of H_2

Even though it was not included in the project application, six tests with addition of hydrogen from bottles were conducted. Before starting the tests, the biological methanation reactors were initially fed with syngas prior to the addition of hydrogen. Six different levels of hydrogen addition were recorded. Throughout this period, the syngas fed to the process was maintained at 10 L/min

The lowest carbon monoxide and hydrogen content in the outgoing gas were measured to 0.06 vol-% and 0.20 vol-%, respectively, as an average value during the last 1 hour and 20 minutes of the test with a syngas feed of 10 L/min and 6 L/min of additional hydrogen. Hence, the project goal of less than 2% of residual H_2 in the end product were fulfilled. The carbon monoxide content was well below the accuracy of the gas analyzer and if one considers the possibility to separate remaining CO (and H_2) from the outgoing gas stream using membranes and return it to the feed-in gas stream, there will be no CO in the end product.

6. Environmental analysis

The environmental analysis was based on the general guidelines of ISO 14044 for life cycle assessment with the functional unit chosen as 1 MWh of biomethane. The result was compared to the fossil reference according to the Renewable Energy Directive (RED II).

The analysis was done for the existing 6 MW_{syngas} WoodRoll® gasification system in Höganäs, multiple up-scaled “solid-state” biological methanation reactors, gas conditioning and membrane upgrading, recycling of residual CO and H_2, delivering biomethane at 10 bar, meeting the requirements for grid injection or use as vehicle fuel according to the *Standard SS-EN 16723-2:2017 Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network – Part 2: Automotive fuels specification*.

The average wood chips transport distance was set to 300 km and the emission factor for the electricity was set according to the Swedish residual mix taking into account emissions from the Swedish power production minus issued Energy Attribute Certificates.

Table 7. *Emissions, expressed as kg CO_2-eq/MWh methane, for the harvesting, transport, gasification plant and biological methanation plant.*

	[kg CO_2-eq/MWh CH_4]
Harvesting	19.93
Wood chips transport (300 km)	13.74
WoodRoll®, construction material (steel, refractory, glass fibre, concrete etc.)	0.84
WoodRoll®, operation (water, electricity, nitrogen gas and natural gas)	8.87
Biological methanation, gas conditioning and upgrading, construction material	0.03
Biological methanation, gas conditioning and upgrading, operation (electricity, nutrients, methane slip)	1.23
TOTAL	**44.64**

The environmental analysis showed that emissions associated with harvesting and transporting of wood chips constituted a major part of the emissions from the full process chain (from feedstock to biomethane). The produced biomethane contributes to a more than 85% reduction compared to the fossil reference according to the Renewable Energy Directive (RED II), 45 kg CO_2-eq/MWh versus 338 kg CO_2-eq/MWh.
The low impact from the construction material of the gasification and biological methanation system is noteworthy.

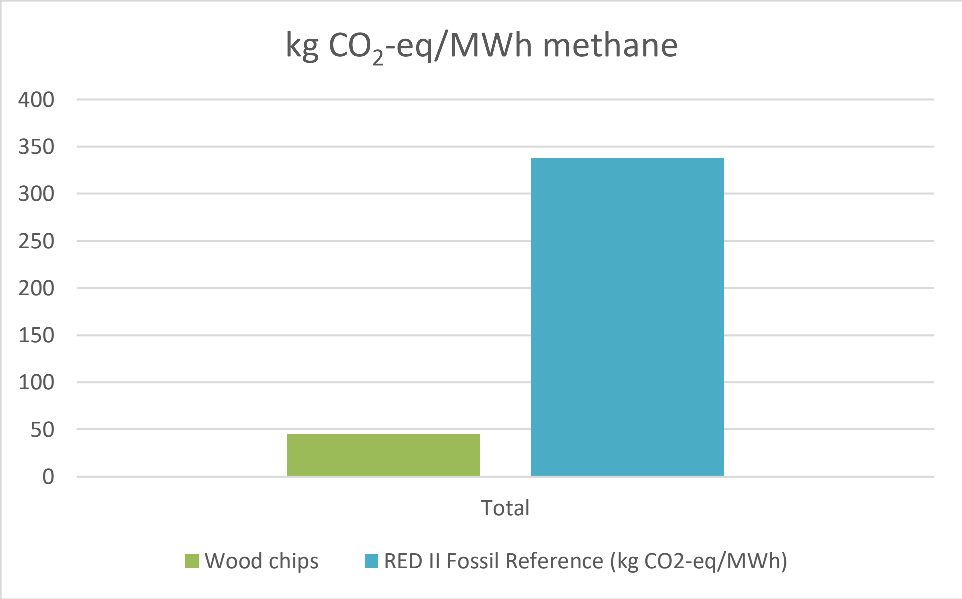

***Figure 5**. The total emissions, expressed as kg CO_2-eq/MWh methane, for produced biomethane using wood chips as feedstock, (green bar) compared to the fossil reference according to RED II (blue bar)*

7. Techno-economic analysis

The techno-economic analysis was based on the existing design of the WoodRoll® gasification plant and multiple upscaled "solid-state" biological methanation reactors with a capacity corresponding to a syngas flow of 6 MW. The analysis included compression, gas conditioning, upgrading and recycling of residual CO and H_2. The analysis took into account biomethane delivered at 10 barg and fulfilling the Swedish standard for grid injection and use as vehicle fuel.

The production cost expressed as SEK/Nm^3 of biomethane with a methane content of 97% was calculated, taking into account capital expenses (CAPEX) including start-up costs, operational expenses (OPEX), feedstock cost and revenues from sales of heat and biochar. The calculations were made with and without investment support through Klimatklivet, a Swedish instrument coordinated by the Swedish Environmental Protection Agency aimed at reducing the Swedish greenhouse gas emissions.

7.1 Investment costs

The annual investment cost was calculated using the annuity method. With an internal interest rate *i* of 7 % and an economic lifetime *n* of 20 years, the annuity factor (AF) became 11.23%, Eq.3.

$$AF = \frac{i}{1-(1+i)^{-n}} \qquad \textbf{Eq.3}$$

The investment cost was calculated as an equivalent annual cost (EAC), Eq.4.

$$EAC = AF * (Investment\ cost - investment\ support) \qquad \textbf{Eq.4}$$

A start-up cost of 5% of the total investment was included in the calculation of the CAPEX.

7.2 Operational costs

The operational costs included costs for personnel, maintenance, electricity, water, and nutrients. The electricity cost was set to 500 SEK/MWh (approx. 45.9 EUR/MWh)

7.3 Feedstock costs

The cost for wood chips was set to 300 SEK/MWh which is a little bit higher than the cost given by the Wood-chips FOB Baltic index[5] of approx. 25 EUR/MWh for the period March – May 2025 and a little bit lower than the estimated cost[6] of 330 SEK/MWh for contracted wood chips supply in Sweden for the heating season 2025/2026.

7.4 Revenues

It was estimated that 2 MW of heat @60 °C could be sold during 4,000 h per year at 30 EUR/MWh and that the carbon containing ash could be sold to metallurgical industry at 9 500 SEK/ton, approx. 865 EUR/ton.

7.5 Production cost

The production cost was calculated for 8,000 operational hours per year. It was estimated that part of the produced biomethane could be used to fuel the 50-kW flare during continuous operation. In case of startup, natural gas or stored biomethane from previous operation were assumed to be used.

***Table 8**. Biomethane production cost with and without investment support.*

	No investment support	Investment support
Investment cost [MEUR]	29.60	29.60
Start-up cost 5% of investment cost [MEUR]	1.48	1.48
Investment support, 45% [MEUR]	0.0	-13.986
EAC [MEUR]	3.49	1.92
OPEX/year [MEUR]	1.76	1.76
Wood chips cost/year [MEUR]	1.64	1.64
Revenues/year heat and ash [MEUR]	0.59	0.59
Biomethane production/year - flare [MWh]	38 032	38 032
Production cost EUR/MWh biomethane (100% CH_4)	166	125
Production cost EUR/Nm^3 biomethane (97% CH_4)	1.61	1.21
Production cost SEK/Nm^3 biomethane (97% CH_4)	17.5	13.2

The analysis showed that the production cost was too high to make the production profitable, regardless of whether investment support according to Klimatklivet is received or not, 13.2 and 17.5 SEK/Nm^3 biomethane respectively.

7.6 Sensitivity analysis

Q Power did the sensitivity analysis by calculating the production cost, expressed as EUR/MWh biomethane, by varying the investment cost and feedstock cost. Q Power used a slightly lower internal interest rate, 5% instead of 7%, that is why there is a small deviation compared to the numbers given in the previous chapter.
It is noteworthy, that even if the investment cost is set to zero the production cost is in the range of 80 EUR/MWh biomethane (see Figure 6). For the case with 45% investment support (see Figure 8), the feedstock cost needs to be 20 EUR/ton or lower to be economically interesting. 20 EUR/ton corresponds to approx. 6 EUR/MWh or 70 SEK/MWh.

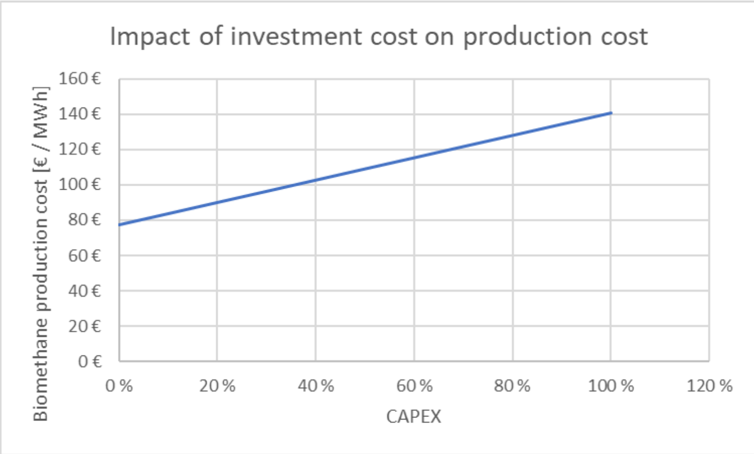

Figure 6. *Biomethane production cost as function of CAPEX.*

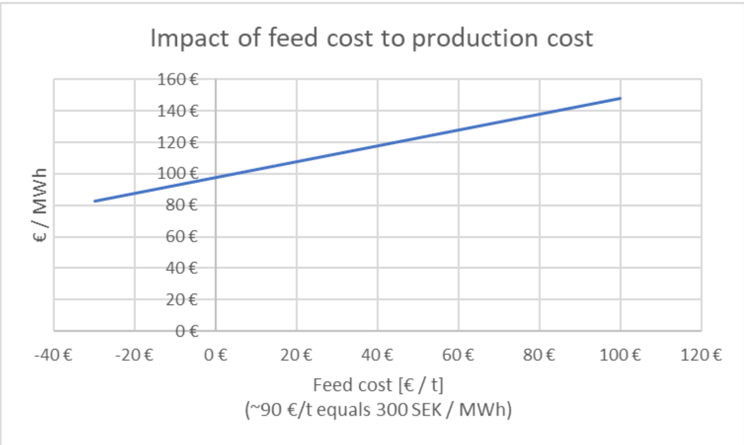

Figure 7. *Biomethane production cost as function of feedstock cost for the case without investment support. Note that the feedstock cost is expressed as EUR/ton.*

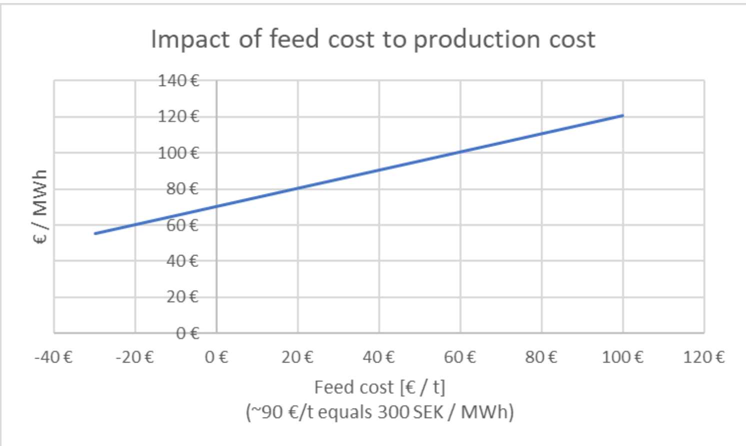

Figure 8. *Biomethane production cost as function of feedstock cost for the case with 45% investment support.*

8. Business model

From the techno-economic analysis it was evident that the production cost for biomethane through biological methanation was too high based on the existing design of the WoodRoll® gasification system. However, if one opt for cheaper feed-stock and co-production of biochar and biomethane the production cost was significantly reduced despite the increased investment costs in the form of a sorting plant that removes metal, stones and soil from low-quality raw materials (park and garden waste, recycled wood and demolition wood), rebuilding of the drying and pyrolysis reactors and the steam system, increased personnel and maintenance cost as well as less annual operating hours.

To produce an additional 200 kg/h of biochar, 1,100 kg/h of additional feedstock was required. The annual operational hours were reduced from 8,000 to 7,800 to take into account possible standstill due to issues with the sorting plant. The cost for low-quality wood chips was estimated to 200 SEK/MWh (approx. 18.34 EUR/MWh).
The personnel cost was increased with 12.5% and the maintenance cost with 20% due to the increased complexity with a sorting plant and the use of low-quality feed-stock. It was estimated that the biochar could be sold as soil amendment at a price of 1,500 EUR/ton including carbon credits.

Table 9. *Biomethane production cost with and without investment support for the case with co-production of biomethane and biochar.*

	No investment support	Investment support
Investment cost [MEUR]	30.83	30.83
Start-up cost 5% of investment cost [MEUR]	1.54	1.54
Investment support, 45% [MEUR]	0.0	-14.57
EAC [MEUR]	3.64	2,00
OPEX/year [MEUR]	1.93	1.93
Wood chips cost/year [MEUR]	1.57	1.57
Revenues/year heat and biochar + ash [MEUR]	1.93	1.93
Biomethane production/year - flare [MWh]	37 082	37 082
Production cost EUR/MWh biomethane (100% CH_4)	106.6	62.8
Production cost EUR/Nm^3 biomethane (97% CH_4)	1.03	0.61
Production cost SEK/Nm^3 biomethane (97% CH_4)	11.3	6.7

9. Conclusions

Conversion of syngas through gasification of woody biomass to biomethane has been demonstrated using “solid-state” biological methanation reactors.

The laboratory test with model gas showed that the mixed culture was able to convert CO through biological water-gas shift.

The tests with real syngas revealed that feeding only syngas resulted in an unstable biological process. This was circumvented by adding additional CO_2 to the feed-in gas. During the tests with syngas plus additional CO_2 the project goal of 10 normal L of methane per L reactor volume and day was achieved. This can be considered an excellent result for syngas fermentation since syngas fermentation is a more complex process compared to CO_2 methanation, involving multiple biochemical steps. As comparison, another project[7], co-financed by the Swedish Energy Agency, had a goal of reaching 1 normal L of methane per L reactor volume and day.

During tests with syngas plus additional H_2 the project goal of less than 2% of residual H_2 in the end product, biomethane, was achieved. The residual CO content was below the accuracy of the gas analyser indicating high CO conversion efficiency. In addition, during gas conditioning in a commercial scale facility, residual CO and H_2 will be removed and recycled back to the feed-in gas. In this way, no CO will leave the plant and thus the project goal of complete CO conversion can be considered fulfilled.

The addition of either CO_2 or H_2 resulted in a more stable biological process. This may be attributed to the lower partial pressure of CO when the syngas was diluted with CO_2 or H_2. In the case of CO_2 addition, it seemed like the influence on the pH level was beneficial for the biological process. However, the interaction of different microorganisms in the mixed culture and the syngas is very complex and further research to fully understand the process is needed.

The electricity consumption for the biological methanation, based partly on the pilot plant testing with real syngas in Höganäs, partly on Q Power’s 3.3 MW “solid-state” biological CO_2 methanation plant in Harjavalta, amounted to 0.012 kWh/kWh methane, which is well below the project goal of 0.02 kWh/kWh methane.

The environmental analysis showed a more than 85% emissions reduction compared to the fossil reference according to RED II.

The use of an industrial grade multi-gas analyzer inherently introduced some uncertainty into the results, particularly related to the measurement accuracy, e.g., in several tests, the methane content exceeded the theoretical maximum value based on the chemical reactions involved in the biological methanation of the syngas. Several other factors, besides accuracy issues, may explain this deviation. For one, it’s good to remember the gases’ water solubility. A portion of the generated CO_2 can dissolve into the reactor's aqueous phase depending on the process

conditions. This dissolution can lower the measured CO_2 concentration in the outlet gas stream and also affect the apparent concentrations of other gases. Biological methanation — where microorganisms convert CO_2 and H_2 into CH_4 — can sometimes yield methane at rates exceeding theoretical predictions. This is due to complex microbial interactions, metabolic versatility, and environmental conditions that can enhance methane formation. Similar phenomena are expected during syngas fermentation. Some methane may be produced from the microbial biomass itself. Mechanisms such as biomass degradation, syntrophic microbial interactions, and recycling of biomass-containing effluent can all contribute to methane formation beyond what would be expected from the feed-in gas alone.
It is important to note that a pilot-scale setup better reflects real-world operating conditions compared to laboratory-scale experiments and the pilot scale data provide more practical insights into how the process would perform under actual industrial conditions.

Since the measured results were associated with some uncertainties and the tests were conducted during a rather short period of time, the results should be regarded as qualitative and as a first step towards commercialisation. Future development would benefit from long term tests, upscaling and the use of high accuracy gas chromatographs.

10. Acknowledgement

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