Final report

1. Project details

Project title	ZeroWastePilot
File no.	64020-2082
Name of the funding scheme	EUDP
Project managing company / institution	Aarhus University
CVR number (central business register)	31119003
Project partners	BioWaste2Gas ApS, Dansk Gødning og Biofiber A/S
Submission date	

2. Summary

Biowaste2Gas ApS has developed their gasifier technology for use in the circular bio-economics of the future, by optimizing the possibilities for utilizing both the energy content and the fertilizer value of agricultural and industrial waste products, for example – the used fiber fraction from biogas plants. The gasification of fibers and other biomasses, produces a solid fraction of biochar and a syngas containing hydrogen, carbon monoxide, methane, and CO_2. The produced biochar will retain not only nutrients for plants, but also carbon in a recalcitrant form. Sequestering carbon as biochar will reduce its susceptibility to degradation and hereby reduce CO_2 emissions normally associated with the degradation of such biomasses.

During the ZeroWastePilot project a 100 kWgas pilot gasifier was constructed based on the gasifier design and work of Dan Christiansen (CEO in Biowaste2Gas). The scale-up was based on a small 10 kW prototype gasification plant - the Combi-gasifier - previously constructed, and tested.

The main activities of ZeroWastePilot included the construction and test of the 100 kW_{gas} gasifier. Tests were conducted on biomasses from the production plant of "Dansk Biofiber og Gødning (DBG)", which produces biomass pellets based on degassed fibers from biogas plants. After deployment at the production facilities of DBG, the pilot-scale gasifier was operated under different operational settings with pelleted fibers as feedstock. Wear and abrasions of the gasifier was tested at the end of test period. In parallel, experiments were conducted by Aarhus University to document the possibilities for microbial methanation of syngas (H_2, CO)

like that produced via gasification. As final part of the project, the business potential of deploying the gasifier at DBG was evaluated.

Resumé (dansk):

Biowaste2Gas har videreudviklet deres forgasser-teknologi, til anvendelse i fremtidens cirkulære bioøkonomi, ved at optimere mulighederne for at nyttiggøre både energiindhold og gødningsværdi i restprodukter fra både landbrug og industri, som f.eks., afgassede fibre fra biogasanlæg. Forgasning af fibre og andet biomasse, producerer en biochar samt en pyrolysegas der indeholder brint, kulmonoxid, metan og CO_2. Den producerede biochar vil indeholde næringsstoffer til planter, samt kulstof i en stabil form der nedbrydes meget langsomt. Binding af kulstof som biochar, vil således øge kulstoffets robusthed imod at blive omsat, hvilket vil reducere den CO_2 udledningen der normalt foregår når biologisk materiale nedbrydes. I projektet er der konstrueret og fremstillet et 100 kW_{gas} forgasser-anlæg baseret på Dan Christiansens (CTO i Biowaste2Gas) forgasser-design. Denne opskalering tog udgangspunkt i en mindre prototype forgasningsanlæg - Kombi-forgasseren - som tidligere er udviklet og testet. Test af anlægget blev gennemført med biomasse fra ”Dansk Gødning og Biofiber (DBG)” der pelleterer afgasset fiber fra biogasanlæg. Efter idriftsættelse af Kombi-forgasseren, blev der gennemført flere levetidstests og forsøg med forskellige indstillinger og driftsparametre. Sideløbende blev der gennemført en række forsøg på Aarhus Universitet for at dokumentere mulighederne for omdannelse af pyrolysegassens indhold af brint og kulmonoxid til biometan via bioreaktorer. Afslutningsvis blev der gennemført beregninger på forretningspotentialet ved at anvende Kombi-forgasseren som en del af DBG’s proceslinje.

3. Project objectives

The purpose of the current project has been to up-scale the gasifier technology by a factor of 10, producing a 100-kW Combi-gasifier pilot plant, which can be a key steppingstone for building a commercial full-scale plant. With the completed design, manufacture, and operation of the 100-kW plant, this project has generated technical and operational know-how that will enable BioWaste2Gas ApS to build a commercial plant in the size 1 – 1.5 MW.

In the project, experiments have also been carried out with the aim of uncovering a possible future use of pyrolysis gas. Here, experiments were carried out to investigate if bioreactors could be used to convert the syngas to methane. Such conversion could open completely new business opportunities for the use of the technology. As even large biogas plants only convert about half of the energy supplied into biomethane, there is thus a significant energy potential tied up in the residual product. With a possible conversion of the produced pyrolysis gas to a methane-containing biogas, the biogas plant's biomethane production can thus be boosted with an add-on gasification and methanation plant. Use of gasification will further have the advantage that the current wet residual product from biogas production can be converted into a dry storage-stable concentrated biochar.

4. Project implementation

The project did evolve as planned albeit with some challenges. The factor 10 upscaling of the plant was implemented, and the technology proved reliable at bigger scale. Gas samples were produced from both the small prototype and later the pilot plant (Figure 1), and Aarhus University used this gas samples in a long series of experiments. All four milestones were implemented during the project.

Almost finish plant in workshop - lacks control

The finish plant installed in Nibe - Denmark

Figure 1. Designed and constructed Combi-gasifier in workshop at Biowaste2Gas (left) and installed at Dansk Biofiber og Gødning (right).

The main risks associated with conducting the project were mainly linked to the technology's inability to scale up, and the inability of experimental bioreactors to convert pyrolysis gases into biomethane. Both risks proved unfounded. In addition, the produced biochar showed a composition as expected with a significant content of carbon bound in a solid stable form. The produced pyrolysis gas had a calorific value that made it possible to burn in a flare without a supporting flame, which proves that the energy content of the produced pyrolysis gas was at a level where it can easily be used as fuel in a gas engine or be used as feed-gas for production of chemicals like biomethane or other fuels.

Project implementation progressed reasonably as planned. Delays from contractors, however, required some adjustments of the time schedule. The delays of the major subcontractors, who designed and constructed the gasifier plant's main control, caused the testing phase to be postponed for almost three months. The reason for this accumulated delay has been a series of unforeseen events, including challenges with supply of components and lack of the necessary manpower to deliver the main control on time.

Delays were furthermore caused by a fire at the plant host DBG A/S, which put their main production line out of service. This has caused this company not to be staffed 24 hours a day but only in the daytime where working hours mainly were spent on rebuilding the affected production line. As a result, we could not man the pilot plant around the clock as expected and therefore only ran the plant during the daytime. Since the pilot plant cannot run completely unmanned and BioWaste2Gas does not have the crew for 3 shifts, it has been necessary to start up the plant every morning and run for approx. 8 hours daily. This fact, combined with the delay in the delivery of the plant's control, has meant that it has not been possible to operate the plant as much as expected.

Of course, the reduced number of operating hours has also had an impact on plant wear and tear and degradation. On the other hand, it is to be expected that the many starts and stops have caused an increased wear and tear on the components, compared to stable operation - especially due to corrosion in the hot sections of the plant. As the B2G7 work package deals with the degeneration of the plant components, attention has therefore also been focused on wear and tear specifically caused by frequent heating/cooling, in addition to normal wear and tear accumulated during operation. To uncover the level and extent of wear, the entire plant was disassembled after the test course.

As later described, the experimental bioreactors at Aarhus University showed the ability to convert syngas into methane, which opens great prospects for the future spread of the technology. By adding the gasification technology to a biogas plant, pyrolysis of the degassed fibre fraction will produce a gas that can be converted to methane and CO_2, thereby boosting the production of biomethane.

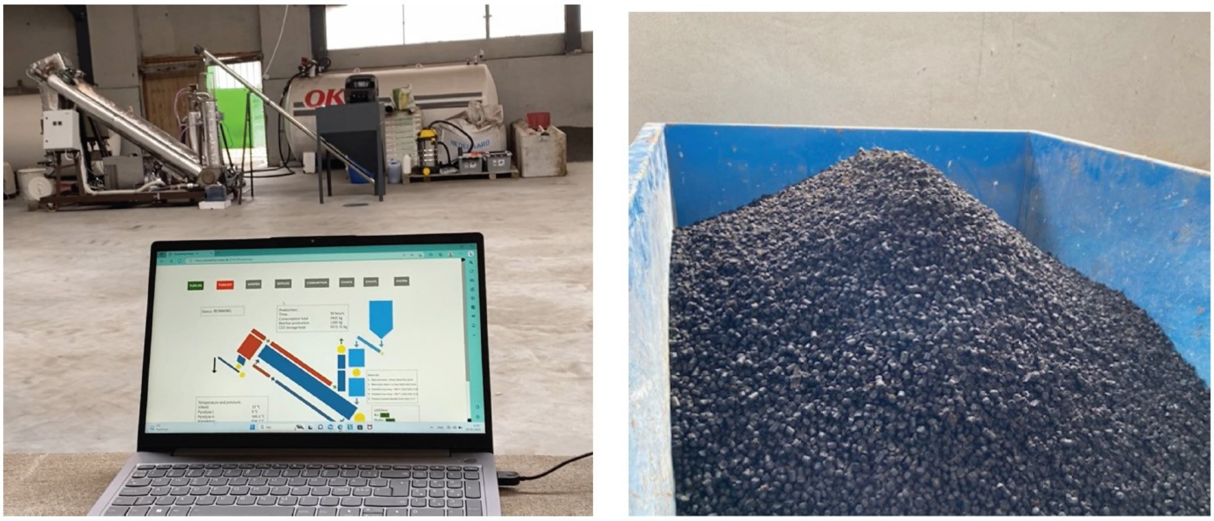
5. Project results

Was the original objective of the project obtained?
The objectives of the project were obtained, and milestones completed. The 100 kW Combi-gasifier was constructed and built by BW2G. The test course and the degeneration test were conducted by BW2G together with DBG. The reactor- and biomethanation experiments were also conducted at Aarhus University. All technical and commercial milestones, from M1 to M4, and CM1, were completed as planned.

Construction and operation of gasifier

M1: Pilot-anlæg færdigt
M2: Anlæg i kontinuert drift

Describe the obtained technological results. Did the project produce results not expected?
It was demonstrated that the technology could be scaled up and that it was possible to construct a controller that allowed remote control of the plant and logging of operational data via the Internet.



Control of plant via internet

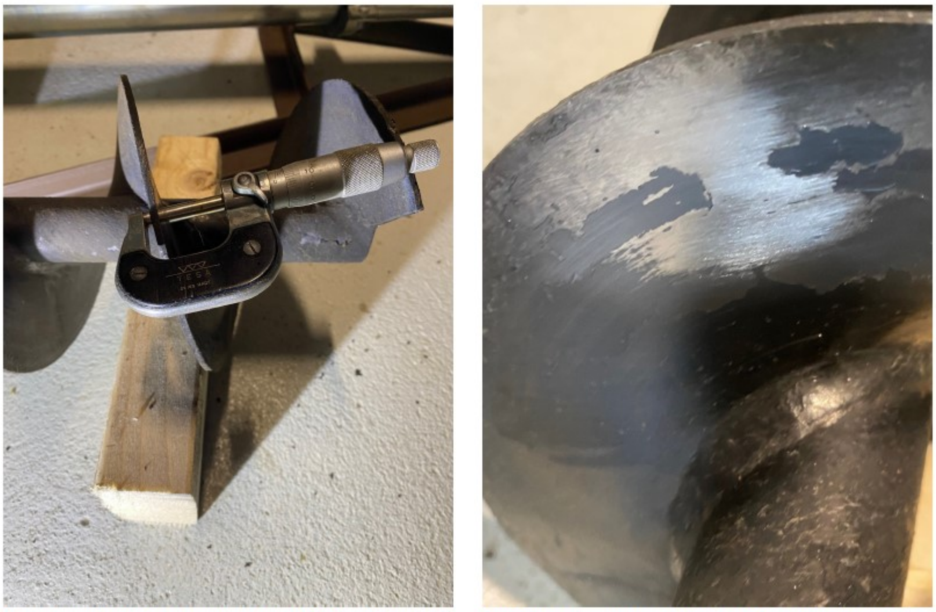
Biochar produced in Nibe

Figure 2. Operation and control of gasifier at Dansk Biofiber og Gødning, producing biochar from pelleted biofibers.

The plant lived up to the expected performance and production. Due to a high moisture content of 13% in the fiber fraction, the calorific value of the pyrolysis gas produced was reduced. This is because a disproportionate amount of gas had to be consumed for the maintenance of the temperature of the plant's hot section. This is necessary to convert all the tar compounds. In addition, it was not possible to produce a gas that was completely free of oxygen, which may also be related to the high moisture content of infeed. This made it difficult to use gas samples from the plant directly as feed gas to the experimental methanation reactors at Aarhus University.

The reason for the high moisture content of the infeed material lies in the fact that the material has been stored for about 1 year in the open air, increasing the moisture content from the original 9% to 13% due to the surrounding humidity in the air. The reason for the long storage is that the DBG production line has been out of service for a long time due to the fire. Therefore, it was not possible to produce new dry material during the experimental period. Thus, the infeed had an abnormally high moisture content. Normally, pelleted biomass will have a moisture content of between 8 – 10%. This will mean that the plant will be able to produce a pyrolysis gas with 40 – 45% combustible components, divided into 20 – 22% CO, 22% H_2 and 1 – 2% CH_4, with remaining part being nitrogen (N_2) and CO_2. This was demonstrated with the original prototype, which has the same operating parameters as the 100-kW plant in terms of residence time and operating temperatures. However, the gas produced during the test was of a quality that can be used in a gas engine, hereby enabling the production of electricity and heat.

Despite challenges with the moisture and obtaining stable long-term operation, the wear, and abrasions of the gasifier during its approximate 200 hours of operation could still be evaluated. All parts that have had contact with the product gas were assessed for coatings and corrosion. The entire water system was also separated for examination of deposits and accumulations of sludge. In addition, the hot section as well as the coke reduction zone were separated for the assessment of special the refractory. Since the pyrolysis auger is a highly loaded component, it was removed from the plant and examined thoroughly for wear and corrosion. It was expected that there would be signs of corrosion at the top of the pyrolysis tube/conveyor, but none were found. This means that the choice of materials was appropriate, lending the necessary robustness to these parts of the pyrolysis system. The plant components showed no serious signs of wear, in fact only signs of normal use. Special attention was paid to the heat exchanger and its cleaning coil. Even though 600 degrees C gas flows into the top, the coil showed no sign of degeneration. In fact, the exchanger turned out to be surprisingly clean on the inside. The accumulation of sediment in the washing system was at a very low level and will not give rise to necessary constructive changes. On future larger plants, it will be advantageous with a simple water cleaning system, with suction from the bottom of the tank, filter the water and return this to the tank. This will allow the washing system to run continuously for months. In addition, in appendix 1 - 4 there are several images that deal with work package B2G7.



Measurement of thickness of auger windings. No loss of material

Auger winding after spot cleaing. No corrosion detected

[redacted]

Figure 3. Evaluation of conveyor corrosion.

Conversion of syngas to Methane.

M3: Afslutning metaniserings forsøg

The biological conversion of syngas to methane was an overall success. After selecting an artificial gas (CO:20%, H_2: 23%, CH_4:7% and CO_2:50%) with a composition close to the expected syngas produced by the gasification pilot plant (CO:22%, H_2: 22%, CH_4:1.5% and CO_2:55.5), two main experiments were conducted to (i) determine whether biomethanation of CO was possible and (ii) whether the process could be optimized. The conditions of the experiment were furthermore determined to run on a continuous gas stream of syngas at thermophilic temperatures (55°C) as literature and previous studies pointed towards biomethanation being more pronounced and selective at higher temperatures. To optimize gas transfer, packed-bed reactors were the choice of reactors, and digestate from an anaerobic digester was used as inoculum.

The first experiment showed that after a short adaptation phase of 27 days, a fast consumption of CO and H_2 at 9.3±1.9 and 11.9±1.5 $\text{mmol}\cdot L_{bed}^{-1}\cdot h^{-1}$ respectively was reached, comparable to those found in literature (**Figure 4**).

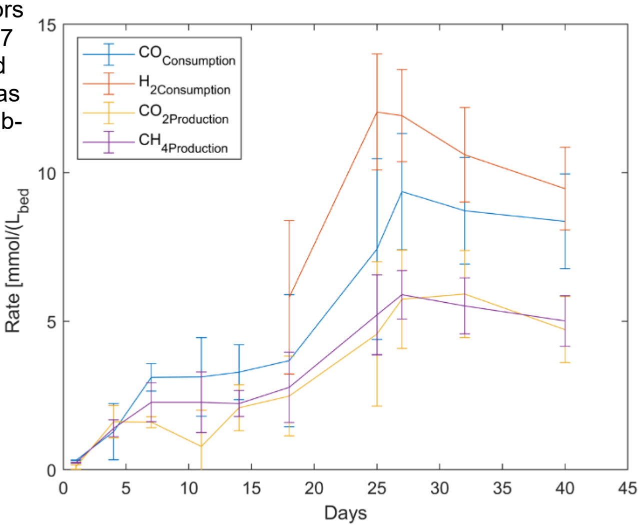


Figure 4. Mean conversion and production rates of the reactors during 40 days of continuous syngas exposure. From day 0-27 the reactors were operated at a syngas flow of 10 mL/min and increased to 30 mL/min from day 27-40. At day 14 the flow was increased transiently to 140 mL/min for 24 hours to test for substrate limitation.

The reactor furthermore had a high selectivity towards CH_4 production as close to 100% of the consumed CO and H_2 ended as CH_4, confirming the high potential for biomethanation of syngas.

The plateau in conversion rates at 27 days after inoculation (**Figure 4**), can be caused by either biological limitations where the capacity of the biology is limited or due to the barrier of supplying feed gasses fast enough to the microorganisms. Further experiments, increasing the gas pressure of the reactors from 1 bar to 1.6 bar, showed an increase in conversion rates of CO by 58%. This showed that the biological potential for faster conversion of CO was present and that the reactions therefore were limited not by biology but be ability to supply CO to the microorganisms (**Table 1**).

Table 1. Increase of gas pressure and its influence on the mean conversion rate of H_2 and CO and production rate of CH_4 on day 47. The rates were determined at 1 bar and then at 1.6 bar on the same 3 reactors.

	Rate at 1 Bar	Rate at 1.6 Bar	Rate increase	Rate increase	Pressure increase
	mmol/Lbed·h	mmol/Lbed·h	mmol/Lbed·h	%	%
H_2	6.6±2.52	9.65±2.93	3.05±0.55	49±13	
CO	7.87±4.2	10.66±4.34	2.79±0.64	41±21	58±1
CH_4	3.59±1.71	5.94±2.27	2.35±0.69	72±29	

Having validated the microbial systems capability to convert syngas, an inhibition study showing which microbial pathways were used for CO conversion to CH_4, was initiated to possibly identify which microbial groups were responsible for the conversion. The conversion of CO, H_2 and CO_2 can follow several pathways. Insights into these processes and their predominance could form the basis for future system optimizations. . The pathway studies carried out on the packed bed reactors showed that that methanogens could be responsible for 42±2% of the CO conversion, while bacteria converted 65±8% of the CO (**Figure 5**). This showed that both microbial groups are active in the CO conversion.

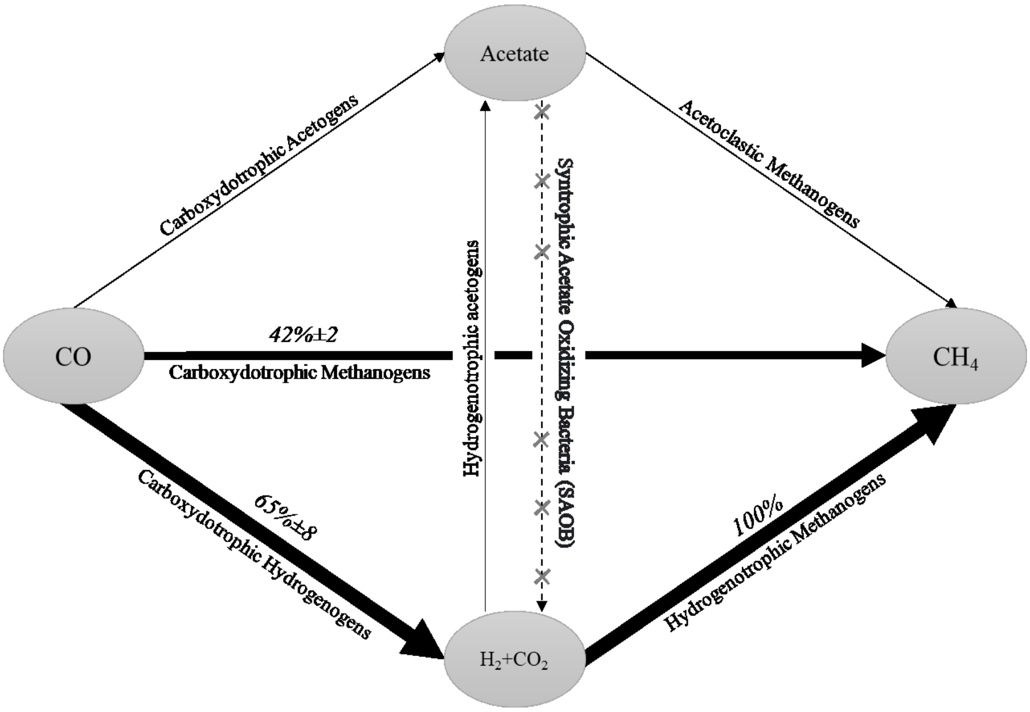


Figure 5. The three major hypothesized pathways for biomethanation of CO. Acetogenesis coupled with acetoclastic methanogenesis (Top); Carboxydotrophic methanogenesis (Middle), Hydrogen formation coupled followed by hydrogenotrophic methanogenesis (Bottom).

A second set of experiments were performed to decrease start-up times for the bioreactor by adding specialized bacteria capable of converting CO. After addition, the reactors which were bioaugmented showed a faster adaptation phase and a slightly higher CO consumption rate. The second experiment further showed all reactors to have a high consumption rate of CO and H_2 at 32±8 $mmol \cdot L_{bed}^{-1} \cdot h^{-1}$ and 24.6±5.4 $mmol \cdot L_{bed}^{-1} \cdot h^{-1}$ respectively. After stable operation for 20 days, a robustness evaluation of the microbes and reactors to different impurities was conducted. A starvation period where no gas was supplied to the reactors for 3 days showed the CO consumption rate to be highly affected the first days, but quickly recovering.

Real syngas with 2% O_2 from the BW2G lab-scale gasifier, scrubbed with water, was then supplied to the reactor, resulting in a pronounced reduction in H_2 consumption rates and CH_4 production – a negative effect which was attributed to the presence of O_2 in the syngas. After a long phase of recovery, another addition of syngas from the lab-scale gasifier was supplied to the reactors this time with no cleaning of the gas and no O_2 present. This addition showed a negative impact on the reactors ability to convert untreated syngas and concludes that biomethanation of syngas from a gasifier will need some degree of cleaning. Literature suggests that cleaning and subsequent biomethanation is possible, but will require extensive treatment to remove inhibitory compounds. Future studies should therefore investigate different technical options for low-cost gas cleaning to reach a composition acceptable in bioreactors.

Although the experiments showed the necessity of gas cleaning of raw syngas, they also showed the technical feasibility of syngas biomethanation. To evaluate the economic aspects of syngas biomethanation, three overall possibilities for the gas were considered in relation the project activities (Figure 6). Conventional gas scrubbing to remove CO_2 was not considered here.
A key figure for biomethanation is the composition of the gas since the composition of syngas is strongly dependent on that. With more CH_4, CO and H_2 present in the feed gas, more CH_4 can be obtained in the product gas. As the pilot plant built by Bio2Waste could not produce a gas with CO and H_2 content as predicted due to the large water content in the fiber pellets, the gas had a very low potential for CH_4. The expected syngas could theoretically be converted to a gas with 17% CH_4 and 83% CO_2, while the actual produced gas

only had a theoretical potential of 5% CH_4 and 95% CO_2. As such, it will therefore require extensive cost to upgrade by either gas scrubbing of the CO_2, or through further methanation by addition of additional H_2 to the bioreactor. Based on the pilot plant's production of 60 m^3 syngas $\cdot h^{-1}$, it would require more than 200 m^3 H_2 $\cdot h^{-1}$ to convert it into $60m^3 \cdot h^{-1}$ of CH_4. With hydrogen prices of 2-4 DKK m^3, the price of H_2 alone would add a cost of 8-16 DKK per m^3 of CH_4. Although renewable hydrogen production is a large focus area in Denmark, burning of the syngas for heat and power is evaluated as being the most optimal approach in this case. Adjusting the production of syngas to increase the content of CO and H_2 in the gas would also improve the methane content of the gas after methanation.

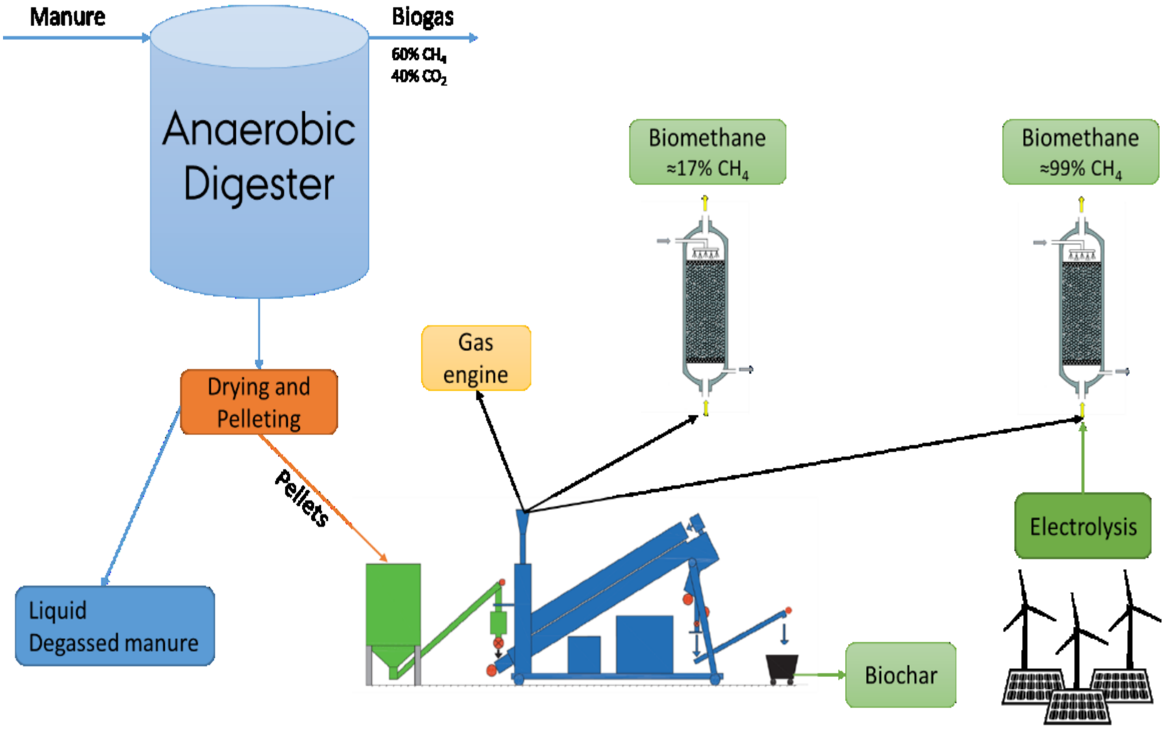


Figure 6. The concept of pelleting and gasifying the fiber fraction of biogas plants, with three subsequent possibilities for the gas. I) Burning for heat and power, II) biomethanation of the gas, III) biomethanation of the syngas with additional addition of H_2 to reach pure biomethane.

Economic Analysis

CM1: Analyse og projektering tilendebragt

M4: Projektafslutning

Describe the obtained commercial results. Did the project produce results not expected?

At this stage of development, there are no commercial results yet. The sketch below shows how a commercial pyrolysis plant in the size of 1 MW could contribute to the existing production line at DBG. It should be noted that it is the commercial end-use that finally determines the performance and capacity of any future plants. If biological residues with high calorific value are used, the capacity of the high temperature section of the pyrolysis plant must be adjusted to have sufficient capacity. For example, if dried sewage sludge is used, the relative content of mineral material is large, and the calorific value is therefore low. This will have an impact on the plant's dimensioning and gas production. The heat demand for the operation of the pyrolysis section would higher, as the mineral material primarily functions as thermal heat capacity without contributing to the process. If dried fiber fraction is instead sourced from biogas plants, the calorific value is significantly higher and therefore the high temperature section must be dimensioned to process the increased gas flow. The black lines indicate the current production line, and green lines indicate the addition of a pyrolysis plant.

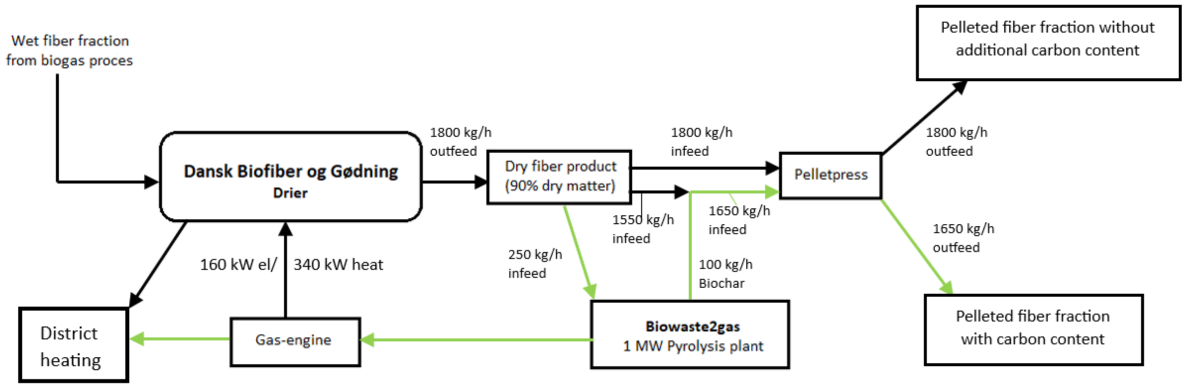


Figure 7. Diagram of pyrolysis plant integrated with existing production lines at DBG

As can be seen, the pyrolysis plant will consume about 250 kg of fiber per hour. The energy of this material will partially supply a gas engine with fuel, thereby producing about 160 kW of electric power, which corresponds to the pellet press' consumption at full capacity. Likewise, the gas engine will be able to contribute more than 300 kW of heat to the drying process, which corresponds to approx. 10% of the drying plant`s total heat consumption. Likewise, the biochar produced will be added before the pellet press, thereby enabling DBG to produce carbon-containing fertilizer pellets.

As there is currently very high interest in biochar, but the business case is still not clear and, the product value of biochar is therefore still uncertain. This means, of course, that it is difficult to establish a valid business model and calculate a payback period for the above initiatives. However, the calculations below are based on an Investment of DKK 4.5 million for a 1 MW plant, and a current electricity price of an estimated DKK 1/kWh:

Investment: 4.5 mio.kr.
Duty: 8,000 h/year.
Production of pelleted fertilizers: 1.8 ton/h
Electric contribution to pellet-press: 125 kW (self-Consumption Pyrolysis Plant: 35 kW – total 160 kW)
Heat contribution to drying systems is conservatively valued at: 0.1 kr./kWh (340 kW from gas engine)
Positive economic contribution per unit of carbon pelleted fiber produced: 50 kr./ton.
Cost of dried fiber consumed: 20 kr./ton.
Service cost pyrolysis plant estimated at: 250,000 kr./year.

Income from displaced electricity and heat consumption at existing drying plants:
(8,000 h/year x 125 kW x 1 kr./kWh) + (8,000 h/year x 340 kW x 0.1 kr./kWh) = 1,272,000 kr./year.

Income due to increased earnings on carbon-containing fertilizer product:
8,000 h/year x 1.65 ton/h x 50 kr./ton. = 660,000 kr./year

Total revenue: 1,272,000 kr. + 660,000 kr. = 1,932,000 kr./year

Pyrolysis plant operating cost incl. service:

(8,000 h/year x 0.25 ton/h x 20 kr./ton.) + 250,000 kr./year = 290,000 kr./year

Simple payback period:
4,500,000 kr. / (1,932,000 kr./year – 290,000 kr./year) = 2.7 year

In the above calculation, financing is not considered. Likewise, it is assumed that existing DBG operating personnel can monitor and look after the pyrolysis plant.

As can be seen in appendix 5 – 6 and 7 - 8, most of the inorganic compounds are up-concentrated in the biochar compared to the infeed material. The average increase in concentration for all compounds is 2.9 times, which could be used as marker for the reduction in organic material as part of the pyrolysis. Phosphorus, zinc, lead, and nickel aligns with this average increase in concentration However, increase in concentrations deviate from 2.9 for some of the other compounds.

Concentrating the sub-components throughout the process;

(See results of analyses - see Appendix 5 - 6)

Type:	**Infeed:** (mg/kg dm.)	**Biochar:** (mg/kg dm.)	**Increase in concentration:**
Phosphorus	9.500	26.000	2,7
Potassium	18.000	38.000	2,1
Sulfur	7.400	6.100	0,8
Cobber	30	190	6,3
Zinc	120	330	2,8
Chrom	10	47	4,7
Lead	below 2	5	3,0
Cadmium	0,074	0,062	0,8
Nickel	19	55	2,9

Potassium: reduced slightly in the process compared to the 2.9 increase.
Sulphur: Reduced in concentration, released in either gas stream or through washing water.
Copper: The amount in the biochar suggests contamination in the process, probably from copper coil in drying plant before the pyrolysis tube. (The coil will be changed to a stainless-steel quality)
Chromium: Evidence suggests that metal from pyrolysis tubes and auger contaminates the material. Acid-resistant steel contains chromium.
Cadmium: Drastically reduced. Potentially transported out of the system via the washing water.

Phosphorus: goes through the process seemingly unaffected.
Zinc: goes through the process seemingly unaffected.
Lead: goes through the process seemingly unaffected.
Nickel: goes through the process seemingly unaffected.

As can be seen from appendix 7 - 8, the carbon content increases slightly throughout the process. It must be assumed that the 51% TC in the Biochar is bonded in a hard shape due to the thermal process that the material has undergone.
Since the plant also supplies a significant amount of condensate, approx. 4-5 l/h, we have analyzed this to determine whether this contains a valuable component that can contribute to our earnings. The analysis is presented in appendix 9 -10. As can be seen, the liquid contains several higher carbon compounds components, but, unfortunately, in smaller quantities. Most interesting are methanol, benzene, and the light hydrocarbons. With boiling points between 65 °C and 80 °C, these volatile flammable components can be separated relatively easily from the liquid by evaporation. With a content of about 2,500,000 µg/l and a specific gravity of 0.79 (methanol), the condensate contains about; 2,500,000 µg/l / 0.79 x 10^{-6} = 4 ml of bio methanol per liter - or the equivalent of 0.4 vol.%. If a 1 MW pyrolysis plant, with 90 % DM in infeed, produces about 50 L of condensate per hour, then the potential for by-production of bio methanol is approx. 0.2 l/h or just under 5 l/day, which makes it difficult to make a business out of so little. It is likely that the condensate produced can be disposed of through the public sewage system. The rules to be complied with are first and foremost the rules for the disposal of condensate from condensing wood chips fired heating plants. In addition, an individual wastewater permit must be applied for from the local utility company in the case of industrial wastewater, as in this case. Biowaste2Gas ApS has been in dialogue with consultants within water treatment and has evaluated that the current level of carbon compounds is not expected to be problematic. This is why it is our expectation that the condensate can be disposed of after normal filtration and neutralization.

Target group and added value for users: Who should the solutions/technologies be sold to (target group)? Describe for each solutions/technology if several.

The gasifier technology is primarily targeted at residual product from agriculture. In addition, we see it as obvious to connect pyrolysis with the existing biogas plants, to increase the production of biomethane. Likewise, we see the wastewater industry as an obvious business area. Since our technology are built specifically to embrace several different residual products, hence the name Combi-gasifier, only adjustment of control parameters is required to switch between different types of infeed. Common to the end users is the obvious opportunity to reduce the residues to a dry layer of stable fertilizer and at the same time utilize a lot of the residual energy found in the product. An additional added value for the end user is of course the sequestering of carbon– which is bound in the produced biochar. Based on a full-scale 1 MW pyrolysis plant, which will produce around 100 kg biochar/h, 45 – 50 kg of carbon will typically be sequestered in a stable form. This means that such a plant will be able to produce around 400 tons of pure carbon annually. With a CO_2 carbon equivalent of 3.66, a 1 MW pyrolysis plant will be able to reduce emissions corresponding to 1.400 – 1.500 tons of CO_2 annually. This is equivalent to the CO2 emissions from burning more than 600.000 liters of petrol. (1 liter of petrol emits 2,38 kg/CO2 when burned)

Where and how have the project results been disseminated? Specify which conferences, journals, etc. where the project has been disseminated.

The results of biomethanation as led to the one article is submitted and in the reviewing phase with the title **Bio-methanation of syngas in Packed Bed Reactors: A study of Adaption and Microbial Pathways in a Thermophilic Mixed Consortium.** Another article presenting bioaugmentation and the robustness of the reactors when exposed to syngas and O_2 is expected to be submitted.

6. Utilisation of project result

Describe how the obtained technological results will be utilised in the future and by whom.

The company Biowaste2Gas ApS will build on the results achieved in this project. We will begin design of another scaled-up version of the Combi-gasifier, this time in the size of 1.5 MW. With the technical solutions tested as part of the 100-kW system, the way is paved for the final upscaling of plant size. The addition of a pyrolysis plant could be seen as a future investment for biogas plants for either heat production or for use in a company comparable to DBG, where the pyrolysis plant is integrated into the production line or as direct heating.

Describe how the obtained commercial results will be utilised in the future and by whom the results will be commercialised.

At this stage of development, there is no commercial result yet.

Did the project so far lead to increased turnover, exports, employment, and additional private investments? Do the project partners expect that the project results in increased turnover, exports, employment, and additional private investments?

At this stage of the development process, there are not yet sales activities in BW2G. However, the completed project has shown that the technology has been developed to a level where the next natural step is commercialization. This will lead to increased turnover and employment in the company.

Describe the competitive situation in the market you expect to enter.

There are a few competitive technologies comparable to our technology. The company *AquaGreen* pursues a technology that makes it possible to convert wet biomass into biochar. The energy to be used for drying in the process is supplied from the pyrolysis gas produced. The technology is thus partly self-sufficient in energy. The only product is the biochar produced. If in-feed contains sulfur, the plant will emit sulfur dioxide, which is an environmental challenge. Another technology is from *Stiesdal* a/s called *Skyclean*. This technology can best be compared to a simple pyrolysis process, where the biomass is heated to approx. 600 C°, after which the tar residues are condensed from the gas into a so-called bio-oil. This oil contains a quantity of water, acetic acid, as well as other organic residues, and therefore requires extensive purification and cleaning. The technology thus produces biochar and oil-substance and in addition, a smaller part of waste heat. Our Combi-gasifier produces a flammable gas and biochar. The tar components are converted into gas inside the plant, making the pyrolysis gas clean and immediately usable. In addition, the condensate from the process is so clean that, after filtration, it can be directed to the public sewer.

Describe entry or sales barriers and how these are expected to be overcome.

There are still some barriers to overcome before the final commercial breakthrough for the pyrolysis technology. Firstly, it is crucial that there is a market for biochar. This will mean that there are partly outlets for the product and partly that there is a pricing that will make it possible to factor a stable income into the business model. This market is only now establishing itself as biochar recently has been approved for spreading on agricultural land. In addition, the upcoming CO_2-tax imposed on the agricultural industry will certainly boost the demand for biochar due to the obvious possibility of reducing the carbon footprint of the individual company.

How does the project results contribute to realise energy policy objectives?

There is no doubt that pyrolysis of residual products, from agriculture and wastewater, will be an important part of the overall transition to carbon-neutral circular bioeconomy. The possibility of converting residues into solid carbon, dry stock-stable fertilizer, and green gas could, contribute massively to the necessary transition towards a CO_2 neutral society. Virtually all biological waste products that we discard today could be dried and used as infeed in pyrolysis plants. The potential for the technology is therefore enormous globally.

7. Project conclusion and perspective

The conclusion of the project is first and foremost that it has been possible to scale up the technology without encountering complications regarding operation. On the contrary, it has been shown that the pilot plant in practice performs far better than the previously constructed small prototype. This can primarily be attributed to a more appropriate material distribution in the larger plant, as well as a smaller boundary effect internally in especially the hot zone of the plant, which has resulted in the temperature in the hot section being much easier to maintain than expected. This was even though the moisture content of infeed was measured at 13%, which is well above the 10% we have previously considered as the maximum limit. Thus, there has been a clear tendency that the increase in plant size has benefited the operation and process parameters. In addition, it was demonstrated that it is possible to extract a significant amount of energy that is still in the fiber after the biogas process. As shown by chemical analysis, the residual product from the plant, the biochar, contains a significant content of carbon sequestered in solid form. Similarly, it was demonstrated that pyrolysis gas can be upgraded to biomethane using bioreactors, but that the gas should be purified and not contain traces of oxygen, when coming from a gasifier. The composition of the syngas should also preferably contain as much H_2, CO and CH_4, to optimize the content of CH4 in the methane gas. This is very valuable knowledge for the further combination and integration of gasification technology with biogas plants, which means that the two technologies can complement each other and thus boost the overall plant's production of biomethane and convert the fiber fraction into a dry carbon-containing stock-stable fertilizer product.

The next step for the gasifier technology development will be to design an even larger plant. An upscaling of the pilot plant by a factor of 10 – 15 will bring the size up to a level that there, according to our research, will be a commercial market for. Such a plant will be able to produce 1-1.5 MW of gas and process around 6-10 tons of infeed per day. With a production of biochar of 3 – 4 tons per day, the CO_2 equivalents bound in the carbon will be in the size of 6 – 8 tons/day, or the equivalent of approx. 2.200 tons CO2 / year from a 1,5 MW size Pyrolysis plant. The end-user of such a pyrolysis plant will be biogas plants and wastewater treatment plants, where the significant energy content of the gaseous product along with the sequestration of carbon as biochar, can be obtained by using the developed gasifier technology.

The completed project uncovered few construction details which require further development. This concerns a sluice system where the biochar leaves the plant, which can advantageously be produced in a more temperature-resistant design. In addition, the hot biochar must go through a water trap before further transport to the collection container. Both points are something that can be easily incorporated into a future design. Besides this, no significant points requiring attention appeared.

With the completed project, a major and important step has been taken towards commercialization of our pyrolysis technology. It has been shown that the technology can be scaled up and that the plant can be started and run stable for long periods, and a homogeneous and stable biochar and pyrolysis gas can be produced. The next natural step is to build an actual commercial plant in the 1 - 1.5 MW size.

Appendices

- Add link to relevant documents, publications, home pages etc.
  Appendix no 1 – 2; (pictures of pilot plant during construction and operation)
  Appendix no 3 – 4; (pictures of pilot plant disassembly and assessment)
  Appendix no 5 – 10; (result of analyse of; infeed, biochar, and condensate)