Final report

1. Project details

Project title	ZeroWastePreStudy
File no.	64019-0586
Name of the funding scheme	EUDP
Project managing company / institution	Biowaste2Gas ApS Jeksen Dalvej 37 8362 Hørning
CVR number (central business register)	DK41164816
Project partners	Aarhus University Ea Energy Analyses A/S
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2. Summary

UK: ZeroWastePreStudy is a precursor project before the realisation of a 100 kW gasification plant. The existing laboratory scale model has been equipped with an energy recuperation system to reduce the electrical energy supplying heat to the pyrolysis section. In preparation for the pilot plant, a system controller has been developed and tested in a simulator to verify different system operations. The 3 gasifiers modules – pyrolysis, char reduction and hot section – have been simulated and the controller performs system start, running and shut-down.

The end results from the gasifier are a calorific rich gas and biochar. The gasifier gas and the hot section has been investigated in previous projects, so the char reduction zone has been the module subject to investigations. The plant availability of the phosphorus in the biochar has been measured and valuable input to operation parameters has been documented. The carbon and plant available phosphorus in the biochar are both function of the amount of air added to the biochar in the char reduction zone. This gives rise to a trade-off between the phosphorus plant availability and the amount of carbon desired in the biochar. Higher the temperature results in the less carbon present and less plant-available phosphorus.

The biochar has been investigated for heavy metal content, and the metals mainly remains in the biochar, following the increase in the boiling point of the metal. However, some heavy metal leave the biochar as dust and are sent though the hot section to be trapped in the gas filter system. Based on literature, microplastic and pharmaceutical agents will be decomposed during the pyrolysis process, reducing the environmental load of using biochar on agricultural land, as compared to the dewatered sludge typically used.

From a commercial perspective, the results in this project will be carried on by Biowaste2Gas in next project entitled ZeroWastePilot, where a 100 kW pilot plant will be build and tested together with a number of partners.

DK: ZeroWastePreStudy er forløberen til at realisere et 100 kW forgasningssystem. Den eksisterende laboratoriemodel er blevet udstyret med regenerering af energi for at reducere forbruget af elektrisk strøm til pyrolysesektionen. Som forberedelse til pilotanlægget er der udviklet en systemkontroller som er testet i en simulator for at verificere systemets drift. Forgasserens 3 moduler – pyrolyse, koks reduktion og hot-section – er simuleret og kontrolleren kan udføre start, drift og nedlukning.

Fra forgasseren får man en energi-rig gas og biokoks. Forgassergassen og hot-section er undersøgt i tidligere projekter, så det er koks-reduktions zonen som er undersøgt i dette projekt. Plantetilgængeligheden af fosforen i biokoksen er målt og værdifulde input til driftsparametre i koksreduktionszonen er dokumenteret. Kulstoffet og det plantetilgængelige fosfor i biokoksen afhænger begge af luftmængden tilført koks reduktionszonen. Dette giver et kompromis imellem plantetilgængeligheden af fosforen og mængden af kulstof i biokoksen. Højere temperaturer fjerner kulstof og reducerer plantetilgængeligheden af fosforen.

Biokoksen er undersøgt for tungmetaller, og tungmetallerne forbliver fortrinsvis i biokoksen afhængig af grundstoffets kogepunkt. Noget tungmetal forlader biokoksen som støv og sendes igennem hot-section for derefter at fanges i gasrensesystemet. Baseret på litteratur, mikroplast og medicinrester vil fordampe under pyrolysen, hvilket reducerer miljøbelastningen ved at anvende biokoks på landbrugsjord sammenlignet med udbringning af afvandet spildevandsslam.

Kommercielt vil resultaterne fra dette projekt blive udnyttet af Biowaste2Gas i næste projekt – ZeroWastePilot hvor der bygges og testes en 100 kW forgasser sammen med en række partnere.

3. Project objectives

The ZeroWastePreStudy project (ZWPS) pursued the following objectives:

1. Reduce of the energy usage of the gasifier during operation and start-up
2. Developing an industrial control system for gasifier control
3. Develop better understanding of pyrolysis, char reduction and hot section parameter optimization
4. Characterize the biochar and optimize the operating point of the gasifier process
5. Gain better understanding of the market situation within sludge from national WWTP – technically and commercially
6. Gain better understanding of the state-of-the-art of gasifier technology global and application within sludge gasification
7. Investigate possibilities for establishing a pilot plant at a national WWTP

4. Project implementation

Project evolution: Compared to the project plan and the expected outcome, the 2 largest impacts were the COVID-19 related lock-down of the society and the abandoning of integration of the industrial controller with the laboratory model.

The project kick-off was delayed by 1 month as the administrative conversion of the grant-receiving company (GGC technology) to a limited liability company turned out to be more time-consuming than expected. Therefore, the project was not initiated before the company conversion was completed and the administrative setup ready for project execution.

The current project has a technical focus on the process verification, energy optimization and development of the system controller. The commercial focus is the state-of-the-art analysis and the investigation of the problems and rules related to the current handling and disposal of sludge from wastewater treatment plants (WWTP).

Risks: The technical risks of the project were limited as the core-functionality of the gasifier has already been verified in terms of the generation of tar-free gas for either upgrading to bio-fuel or usage in internal combustion engine to generate heat and electricity. The possibility of optimizing the quality of the biochar was examined and improved operating points have been investigated. The fate of heavy-metal through the process has been clarified and is documented in encl. AU.

The problem with balancing the pressure inside the gasifier had not been foreseen, as this problem evolved when a detailed list of operating parameters and electrical interface for the system controller was developed. It became clear that the pressure balance was maintained by a set of manually operated valves based on a very small differential pressure. The main problem is the pressure difference generated by the gasifier recirculation pump, which can generate a slight difference pressure. It is vital for the stable and safe operation, that the generated gas is not brought into contact with ambient air as the temperatures when the hot gasifier gas meets oxygen in ambient air causes ignition.

For the next generation of the gasifier, the input and output ports for infeed and biochar will be tight and automatically operated. This step will generate an oxygen free atmosphere inside the gasifier and enable automatic control of the gasifier.

Unpredictable problems: The biggest problem for the project has been the impact from COVID-19 and especially the related society lock-down that impacted the project execution and the entire flow of the project. Most of the project’s meetings have been held as video-meeting, limiting the hands-on experience that we were hoping to have together with the entire team. As mentioned previously, the pressure balance problem also came up during project execution, lowering the ambition of the system controller’s development stage for the laboratory-system. However, the developed I/O simulator has performed sufficiently for verifying the controller’s behaviour.

COVID-19: The COVID-19 lock-down had several unexpected impacts on the project. The general lock-down of the society had a large impact on the time schedule for the activities at Aarhus University, where a large part of the laboratory analysis were delayed. Thanks to a large degree of flexibility from the project participants and creative reorganization of planned work, the only result has been delaying of work-packages.

The laboratories were shut down and closed for operation. According to project plan and to keep the cost down, the analysis work was supposed to be carried out by students and temporary hires. However, the society lock-down also closed the laboratories of the university and the work of reaching a stable analysis method was at first delayed, and afterwards the work had to be handed over from person to person. At the beginning of the project, it was planned to investigate sludge from several WWTPs, but as it became clear that the COVID-19 virus is measurable and present in wastewater sludge, only sludge from Aalborg Øst has been analysed and used for the process optimization and analysis. The process of drying and preparing sludge from other sources was deemed too risky for the people performing the operations. Instead, we found a database of sample results from wastewater analysis and simulated results of the pyrolysis process.

The planned dissemination activities have to a large part, been cancelled, conferences have been cancelled and many companies have been reluctant to arranging non-essential meetings. Most companies refuse to set up non-vital physical meetings, and many employees have been scattered around in homes, summerhouses etc. This has significantly reduced the project teams' possibilities to meet with possible new customers and establish new relations. We have had a couple of meetings per phone or video. But unfortunately, this part of the planned activities suffered from the COVID-19 situation. Despite these challenges, we have found a WWTP that is willing to participate in the continuation project 'ZeroWastePilot' to analyse the consequences of installing a gasifier plant at WWTP 'Fredericia Spildevand og Energi'.

Integration of controller with laboratory model: Despite B2Gs wish to integrate the in-project-developed system-controller with the laboratory model, the integration work had to be redirected. The main technical issue is the internal pressure balance in the gasifier. This balance is maintained manually by the operator in the laboratory model. For the system to operate autonomously, this parameter needs automated measurement and control. The solution is to introduce sliding gates at the input and output ports of the gasifier, which would eliminate the need for pressure control within the operating range of the gasifier. However, this modification would be a major rebuild of the laboratory model. The project team decided that the integration of the system controller will be undertaken in conjunction with the construction of the pilot-system. In the scope of the current project, a few input-output simulators have been developed, enabling programming and system level testing of the system controller. System verification has been undertaken by simulating the expected system response on the I/O simulators. This is not an optimal solution, but basic controller behaviour has been verified.

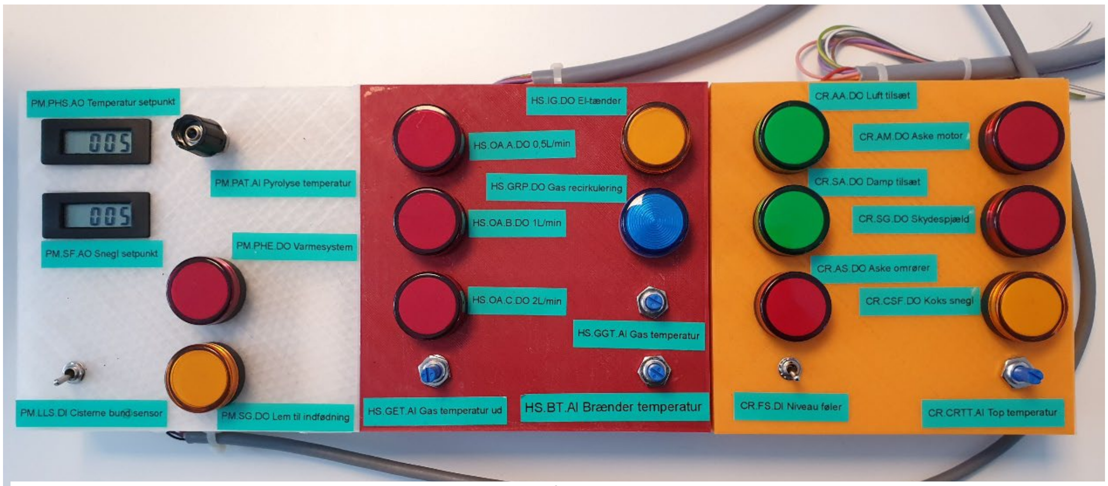

Figure 1: Input/output simulator

For each of the 3 modules in the gasifier – pyrolysis (white module), char-reduction (orange module) and hot-section (red module), a corresponding I/O simulator has been developed. This has enabled the possibility to simulate the operation of the gasifier, and enabled simulated start-up, heating up, operation and shut-down of the gasifier. The expected behaviour of the program has been verified; however, a significant portion of work is still needed as the physical interface stills needs to be developed and adapted to the gasifier's actual sensors and actuators.

In term of **milestones**, the gasifier system was upgraded with energy regeneration from the gasifier gas to the pyrolysis section, reducing the usage of electricity to heat up and operate the pyrolysis process (WP B2G1 and Milestone M1 in application App 3). This milestone was met as expected, so the gasifier system was ready for process validation. However, the process control was still manual. The update of the thermal recuperation system is documented in enclosure B2G-1.

The process validation was performed using manual control, where the system was left operating for an hour at a stable operation point, the samples were extracted, and the operation point was changed to a new setting and the system again operated for an hour at the new setting.

This procedure was repeated until enough operation points was reached. Then the material (biochar) was sent to AU for analysis.

These samples were analysed, and the results from the analysis leads to M2, where AU together with Bio-waste2Gas evaluated the results and investigated specifically the char-reduction-zone operation parameters (WP B2G3 and WP AU2).

WP AU1 was carried out independently from the technically work undertaken in the remainder of the project, and the WP was executed as expected.

WP B2G2 was focused on the choice of system controller, and the development and testing of the system controller. This WP was originally planned to have been carried out by updating the control of the laboratory model, but instead the pilot plant was modelled, and the system controller developed to control it. That resulted in new and unexpected tasks, as the pilot plant needed to be described and a control scheme needed to be developed. Also, a set of input/output simulators needed to be built to simulate the pilot plant. Therefore, the WP B2G2 was extended to run the entire time of the project. As the development could be made independent of the laboratory model, the extension of the WP had no significant impact on the project execution and schedule.

5. Project results

As described in section 3, the project had 7 focus points. The results from each focus point are described in the sections below.

5.1 Energy usage reduction

The recuperation of the thermal energy of the gas when leaving the hot section has successfully been optimized by heat-exchanging the exit gas with the circulating air around the pyrolysis tube. This has significantly reduced the electrical energy to warm up the circulating air for the pyrolysis tube. See report in encl. B2G-1. The energy usage for starting the system has been reduced, as the preheated air for starting the pyrolysis section is circulated through the hot section. The heat injected during the preheating phase is recuperated by the heat exchanger before it leaves the system. During operation, the transferred heat from the hot process gas from the hot section to the pyrolysis section almost eliminates the need for electrical heating of the pyrolysis section. Calculations in encl. B2G-1 has showed that external energy may not be needed, depending on the amount of gasifier gas generated by the pyrolysis of the in-feed. Another advantage is the possibility to control the gas exit temperature – in the event of infeed with high energy content and low thermal mass, the recirculation gas flow can be adjusted to match the need for thermal energy to heat up the pyrolysis section.

5.2 Industrial control system

The controller has been implemented on the Kunbus system Revolution Pi (www.kunbus.de):

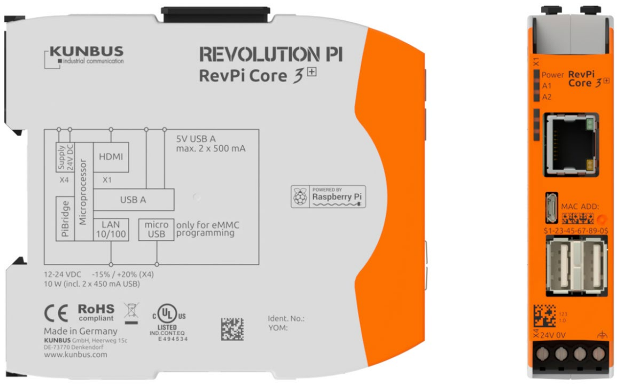

Figure 2: Used controller in system

The Revolution Pi system is based on the Raspberry Pi computer, a well-known embedded computer system for various automation systems tasks. However, Kunbus has taken the development of the Raspberry Pi further by adding input and output ports in a modular system and protecting these ports to meet the electrical and mechanical demands seen in an industrial application.

The entire software base known from the Raspberry Pi is available for development. For the user interface, the Node RED has been chosen for fast development of a graphical front-end. An advantage of the user interface is that it can be accessed using a web-browser on various devices:

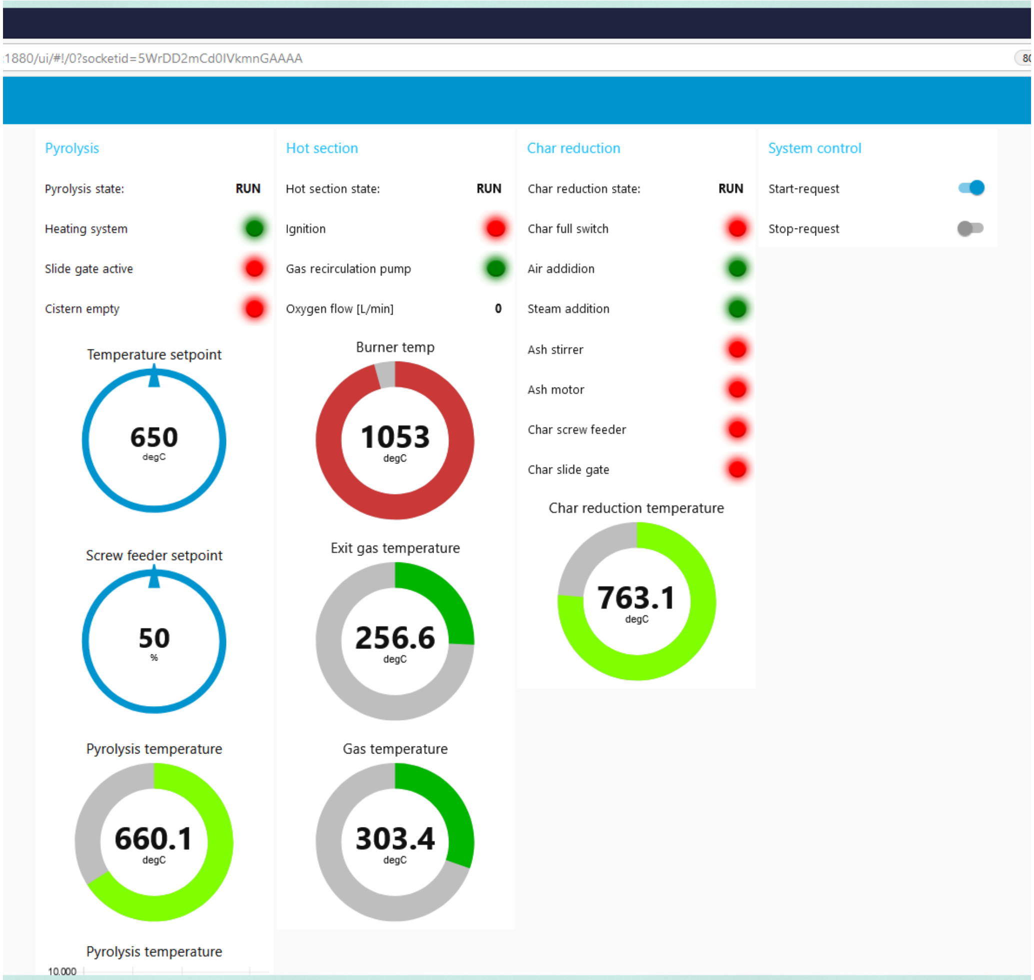

Figure 3: User interface

Please note that the numbers seen on Figure 3: User interface does not reflect relevant operation parameters, but only reflect the state of the simulator. The 3 left-most columns reflect the status of the 3 IO simulators seen in Figure 1: Input/output simulator. First column relates to the pyrolysis module (white module), the second column to the hot section (red module) and finally the third column reflects the char reduction module.

The fourth column is the ‘System control’ interface, where the system can be requested to start up or shut down. Internet safety will be added, so access to the system will be restricted by username/password authentication and encrypted communication.

The operation parameters – eg. temperature setpoint (left-most column) is currently coded into the ST program, future work will allow to change the parameters remotely. Depending on the feedstock at a specific site, the parameters are expected to be adjusted locally, depending on local energy content in the feed-stock and the desired result of the gasification process, energy or fertilizer.

The IO simulator measures the analogue control signals generated to the pre-heating system and the speed of the pyrolysis screw feeder. These 2 indicators can be seen in Figure 1: Input/output simulator in the upper left corner as PM.PHS.AO and PM.SF.AO. The signals are named using WBS[1] convention, eg. PM = Pyrolysis Module. PHS = Pre-Heating Setpoint. SF = Screw Feeder. AO = Analog Output.

[1] Work Breakdown Structure

The integration work between controller and gasifier has been postponed to the next project 'ZeroWastePilot' and will be conducted in parallel with the mechanical work that results in the pilot plant. The controller has already been prepared to the actual number of sensors and actuators in the pilot-plant. If the controller, on the other hand, was designed for the laboratory scale model, significant work would be needed before the controller was adapted to the pilot plant. The number and placement of sensors and actuators has been significantly changed as several optimizations were needed for the update from lab-model to pilot plant.

For the integration of the system controller tasks into an embedded system, the Revolution Pi controller system were chosen. The system is based on the well-known Raspberry Pi controller. The system has an acknowledged performance as it is based on the open Linux system. The system is extremely price competitive, while still having a high quality of the electronics used. The system controller has been programmed using the ST language (in LogiCAD3), the Linux operating system and the NodeRED front-end for user interface. The industrial controller has been programmed to control the gasifier and using simulated input and output modules, the controller operation has been verified. Compared to the ambition in the project application, the process of sketching the system control took longer than expected and the building and testing of the simulated input/output modules were new tasks. Time was also spent on the selection of a controller system to use for the project, but it quickly became clear that the Revolution Pi had the lowest entry-cost compared to other systems, which had a significant start-up cost for purchasing the development system. The down-side of the Revolution Pi system has been limited support (but free) and also the development required knowledge and skills regarding Raspberry Pi and Linux. Other systems exist, where you can start to program with little or no skills on programming, but often the possibilities are limited and there is no upgrade path in case there is a need for further input/output modules. The current solution is quite flexible as more modules for analogue or digital input/output pins can be added as required.

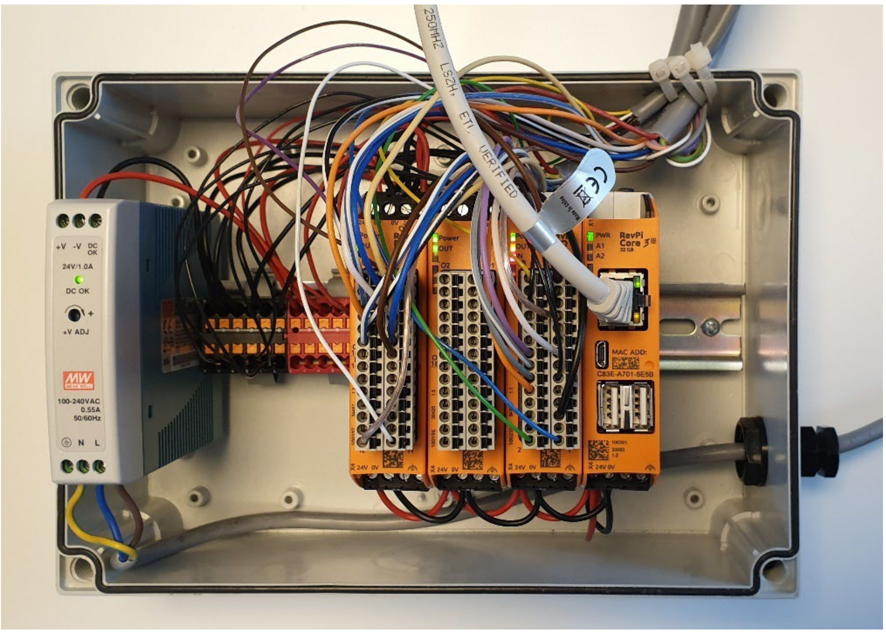

Figure 4: Controller system with PSU and I/O modules

On the above picture Figure 4: Controller system with PSU and I/O modules, the controller system can be seen. Left in the box is the power supply, generating +24V and power distribution block (black+red). Next module is the digital input and output module, which offers 14 digital input and 14 digital output pins for controlling eg. Relays, lamps, buttons and enabling heating system, sliding gates etc.

Next module is the digital output module, with 16 output pins, the module is currently not used and the pins are available.

Analog input/output module is the next module. This module offers upto 6 analogue input channels and 2 analogue output channels. The module can be configured in different ways, allowing for both voltage and current control of connected electronics.

The rightmost module is the CPU, which connects the controller to the internet and the to computer used for application development. The CPU offers 2 USB ports, ethernet port and HDMI interface. The CPU (like all modules attached to the CPU) is equipped with a so-called PiBridge interface, which enables communication between the installed modules.

For us, a less relevant down-side of the Revolution Pi is the communication speed on the PiBridge, which introduces a latency of a few milli-seconds from an input has changed to the state-change is reflected in the CPU/controller. For industrial control within eg. Robotics, this delay may pose a problem.

Specifically, for the pyrolysis module, the controller specification and implementation will be explained. The pyrolysis section has been chosen for this, as the pyrolysis section has no confidential information, and the construction and control are standard industrial procedure.

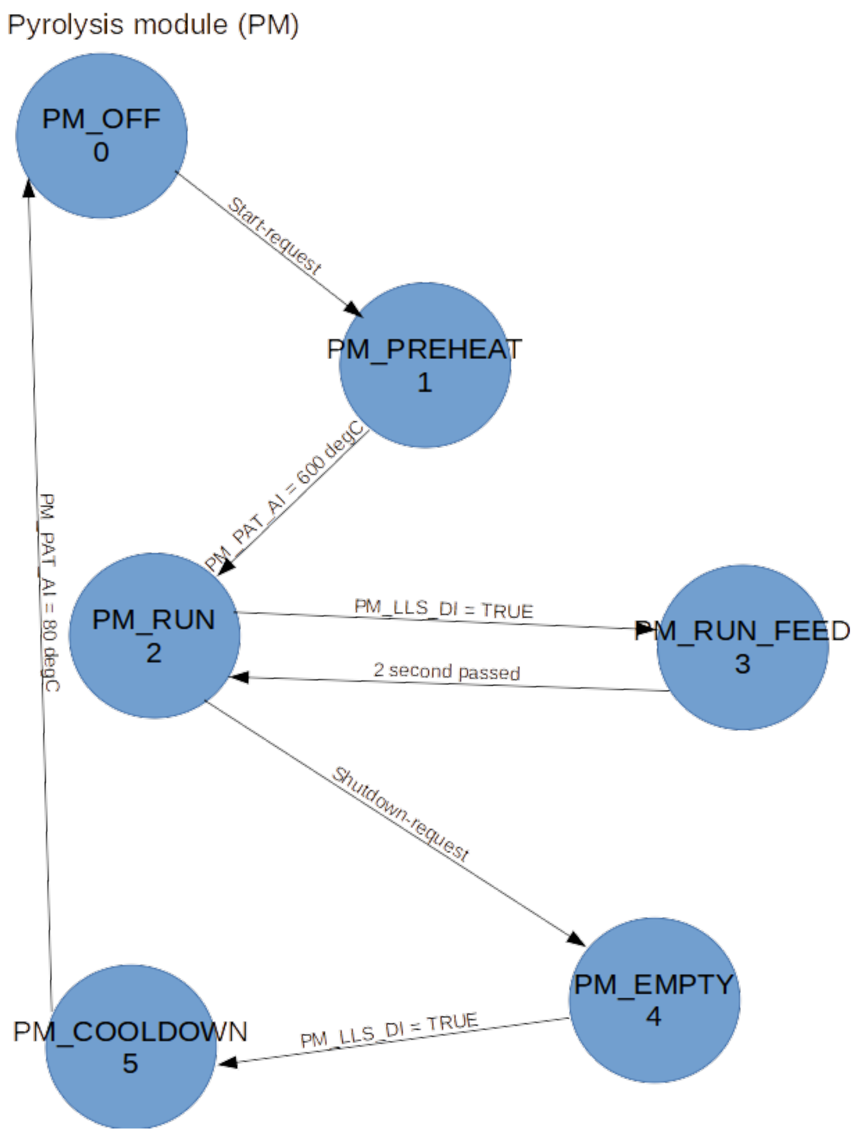

Figure 5: State machine pyrolysis module

The state machine controlling the pyrolysis module is shown in Figure 5: State machine pyrolysis module. Per default, the module is in 'OFF' state until a start request is given from the user interface. When requested, the heating system is activated and the entire pyrolysis tube is heated to 600 degC, at that temperature, the state is shifted from 'PREHEAT' to 'RUN'. During 'RUN' the screw feeder inside the pyrolysis tube is started and will initiate the processing of the in-feed into the pyrolysis tube. The screw feed speed is a setpoint, allowing to either reduce or increase the process time inside the pyrolysis section. The process time will be dependent on the energy content of the infeed, where high energy infeed may experience longer process time, not to extract the energy, but to allow the hot section to sufficiently remove the generated tar from the pyrolysis gas. The optimization of the operation points between the different modules must be optimized on a case-by-case level until further knowledge can be gained from the different operation sites and infeed material.

A difference from the laboratory scale model is the detection of the level in the infeed cistern, when this buffer tank is empty (indicated by sensor PM.LLS.DI), the pyrolysis section shifts from 'RUN' to 'RUN_FEED' where the buffer tank is filled by opening and closing of the infeed buffer tank sliding gates (Actuator PM.SG.DO). This process is done manually in the laboratory gasifier but will be automated in the pilot plant. When requested from the user interface, the pyrolysis module will shut down by running the pyrolysis process until the buffer tank is empty. At this stage, the screw feed will stop, the heating system will shut down and the gas production will decline and eventually stop.

The control signals for the pyrolysis module can be seen in this figure:

Name	**Where**	**Type**
PM.LLS.DI - Low level sensor	Bottom of infeed buffer tank	Digital input
PM.SG.DO – Sliding gate	After the infeed silo, before infeed buffer tank	Digital output – timer controlled
PM.SF.AO – Screw feeder	Screw feeder inside pyrolysis tube	0-10 V analogue output
PM.PHE.DO – Pyrolysis heating enable	Circulation fan and electrical heating element	Digital output
PM.PHS.AO – Pyrolysis heating set point	Setpoint for heating system for pyrolysis air	0-10 V analogue output
PM.PAT.AI – Pyrolysis air temperature	Temperature measurement of heating air from heating system	0-10 V analogue input

Figure 6: Input and output signals related to pyrolysis section

Again, note the WBS naming convention applied to the signals:

<Module Name>.<Signal Name>.<Signal Type>

This increases the readability of the signals descriptions and allows for easier reference across the systems both hardware and software signals.

For each state in the pyrolysis state machine, output signals have a determined value or state:

Signal / State	**PM.SG.DO Slide gate**	**PM.PHE.DO Heating system**	**PM.PHS.AO Setpoint for heating system**	**PM.SF.AO Screw feeder speed**
OFF	OFF	OFF	0 degc	0%
PREHEAT	OFF	ON	650 degC	0%
RUN	OFF	ON	650 degC	50%
RUN_FEED	ON	ON	650 degC	50%
EMPTY	OFF	ON	650 degC	50%
COOLDOWN	OFF	ON	0 degC	0%

Figure 7: Output signal state

Noteworthy here is analogue output signals (Signal type AO), which are setpoints for the system operation and it is expected that these setpoints will require further work on the pilot plant, when the plant has been build.

The signals in the software must be linked to the physical signal, which is done the following figure, where also the electrical specification is stated:

Name	**Type**	**Electrical specification**	**IO module and pin**
PM.LLS.DI Low level sensor	Digital input	+24V → high	DIO.I1 (pin I1)
PM.SG.DO Slide gate	Digital output - timer	+/-100 mA (push-pull mode)	DIO.O1 (pin O1)
PM.SF.AO Screw feeder	Analogue output	>1 kOhm load (0-10V)	AIO.OUT1 V+ (pin 1)
PM.PHE.DO Pyrolysis Heating System Enable	Digital output	+/-100 mA (push-pull mode)	DIO.O2 (pin O2)
PM.PHS.AO Pyrolysis Heating Setpoint	0-10 V analogue output	>1 kOhm electrical load	AIO.OUT2 V+ (pin 2)
PM.PAT.AI	0-10 V analogue input	>900 kOhm input resistance	AIO.IN1 V (pin 28)

Temperature from heating system			

Figure 8: Hardware signal and electrical specification

This process of developing and specifying the state machine, state conditions and HW signals has also been done for the hot section and the char reduction module. However, some of the control and detailed process information is confidential and some of the control system may also be patentable. Therefore, no detailed information is shared on these parts of the control system.

In general, the task of learning the new system took longer than expected, where especially the integration between the GUI and the LogiCAD turned out to be complicated to get running. But at the current state of system performance, it is ready for integration to the pilot plant.

5.3 Parameter optimization of char reduction

A main process variable studied in the project has been the flow of air to the char reduction zone. Spanning the range of feasible operation – i.e. from minimally to maximally acceptable gas production – it has been found, that the increasing production of gas does not adversely affect the phosphorus plant availability. However, the analysis of the experimental samples suffers from significant measurement uncertainties. Although the chemical analysis of phosphorus (total and plant available) has an associated inherent experimental variation, it is believed, that the main measurement variation originates from sampling of heterogeneous biochar. The selection of a given representative sample for analysis will reflect on the stability and control of processing parameters during operation. And in the current laboratory scale gasification unit, there are several operational challenges that is believed to be manifested in sample heterogeneity.

It is a clear expectation, that scaling up with improved process control will markedly reduce the internal sample variation, and thus bring down the measurement uncertainty. Future work should thus focus on reproducing experimental samples, where judiciously chosen processing parameters have been systematically varied, and then performing phosphorus analysis on these samples.

In addition to the flow of air to the char reduction zone, it would provide valuable information to also modify the amount of steam supplied, as well as the temperature in the hot section. These processing variables present a trade-off between the amount of gas produced to that of the produced biochar. To this end, an experimental design could be beneficial, in order to optimize the number of samples produced, and to decouple individual variables.

5.4 Biochar characterization

The biochar analysed in the project originated only from the Aalborg Øst drying system. More WWTP sources for samples were planned, but as the COVID-19 virus is present in most wastewater sludge, the pre-processing of the sludge for the gasifier was rejected. The safety of the person handling the sludge is critical, as the process of especially drying the sludge will release fumes and dust into the near environment of the process. Therefore, the result presented here are based on a single source of dried sludge.

The dried sludge and the biochar have been analysed for total phosphorus content and the plant-available phosphorus, Figure 9. For more information on plant availability of phosphorus, see encl. AU for ways to analyse for this property.

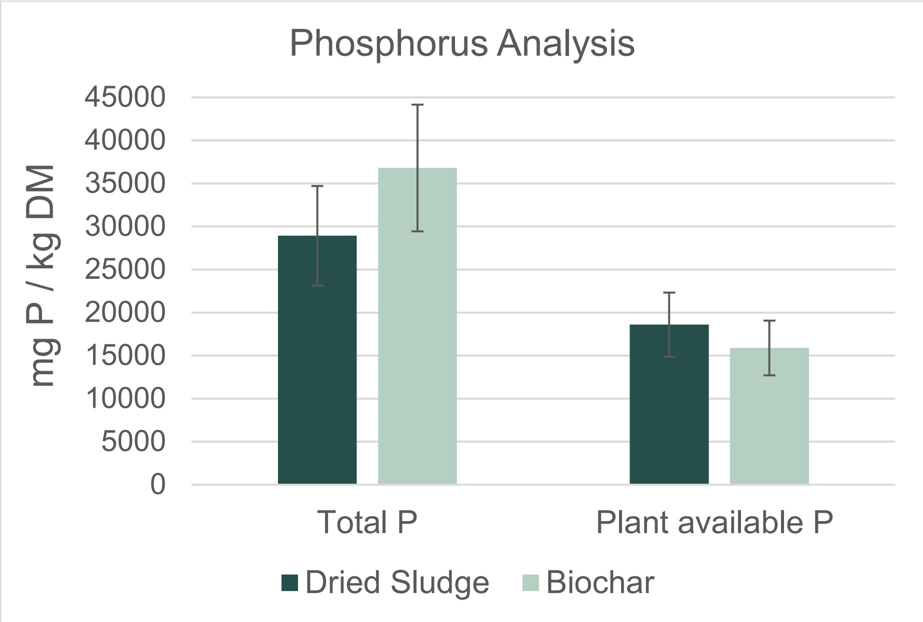

Figure 9: Phosphorus availability in dried sludge and biochar. Values are reported as mg P per. kg of dry matter (mg P/ kg DM). The left-side bars represent the total amount of P, whereas the right-side bars reflect the phosphorus available for plants.

Unfortunately, the analytical methodology surrounding analysis of phosphorus plant availability is difficult to perform, and to generate stable and reproducible results requires a certain degree of skill and experience. Also, the method is still being discussed within the scientific community, with regards to whether alternative and better indicators exist for plant availability of phosphorus in a substance. Finally, inherent sample variation due to inhomogeneities, are certainly a major contributing factor to the overall measurement uncertainties reported herein.

Still, the concentration of phosphorus in dried sludge is lower than biochar produced via gasification, as the volatile components leave the sludge during the pyrolysis step. This concentrates the relative content of phosphorus per dried matter. Based on the analysis, it is also clear that the plant availability of the phosphorus is relatively lower in the biochar. This is most likely due to the high temperature that the biochar is exposed to during the water-gas shift inside the char reduction zone. This will create dense products wherein the phosphorus is more tightly bound, thus lowering the amount of plant available P.

To shed some light on how the phosphorus content and availability varies with processing parameters, the amount of air introduced to the char reduction zone has been varied (from minimally to maximally acceptable gas production). The initial data in Figure 10 indicate, that whereas the increasing airflow does result in greater gas production, it does not adversely affect the fraction of phosphorus that in available for plants.

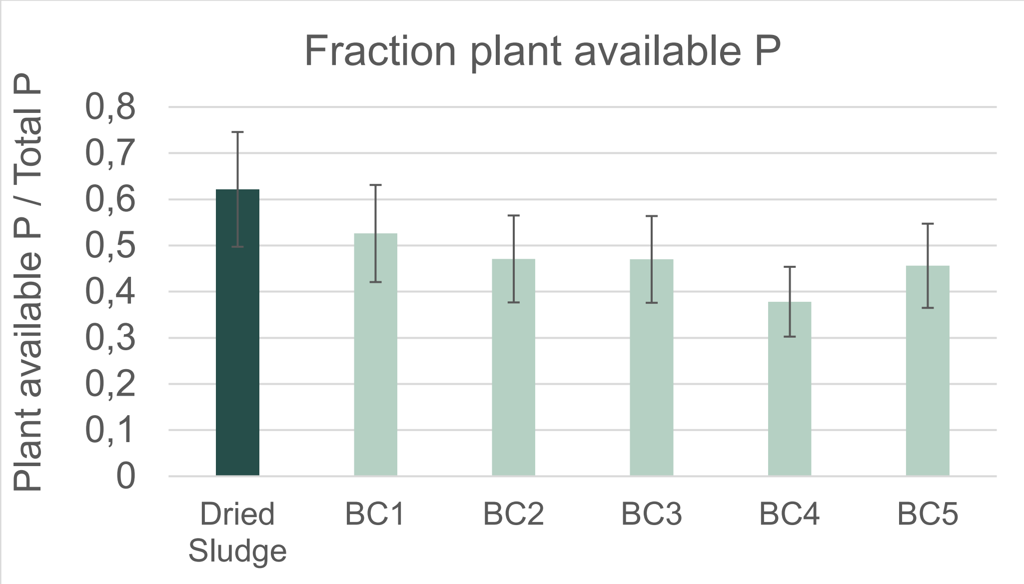

Figure 10: Plant availability of phosphorus in biochar at different air supply settings in the char reduction zone

Representative sample of dried sludge and biochar have also been analysed for content of various metals – see encl. AU for details. In short, almost all mercury has vaporised during the pyrolysis process, and is thus only present in very small amounts in the biochar. Other somewhat volatile elements – in particular arsenic and cadmium – do not show the same extent of decrease, and further experiments should explore this is more detail, as these elements are also expected to be partially vaporised. Otherwise, the elemental analysis principally reflects the fact, that as organic matter in converted into gaseous products, there is a concomitant concentration of metals in the biochar.

Due to very limited access to the experimental facilities required for performing the elemental analysis (imposed to covid-19 restrictions), the abovementioned conclusions are based on scarce amount of data. Future experiments should focus on acquiring more data to substantiate these initial trends.

5.5 Market situation within sludge from national WWTP

AU has been doing a literature study of the quality of Danish municipal wastewater sludge with respect to phosphorus, heavy metals and organic micropollutants regulated by the Danish legislation for agricultural application of sludge (Statutory Order no. 1001/2018). There is no national overview of the quality of Danish wastewater sludge, but in this study 100 sets of sludge sample analysis have been randomly picked from a range of Danish wastewater treatment plants (WWTP), and the quality of the sludge is compared to the current requirements for agricultural application. Furthermore, it has been evaluated to which extent the estimated change of sludge composition due to treatment by the gasification process has to the compliance with the limit values for agricultural application of the sludge.

The results (enclosure AU, section 4.1 – 4.4 and appendix A) show that although the absolute criteria for maximum allowable concentration of one or more heavy metals is exceeded in 45 % of the sludge samples, the phosphorus-related criteria is only exceeded in 3 samples. And, since compliance with just one of the criteria is required, only 3 % of the sampled sludge cannot be used for agricultural purposes due to the content of heavy metals. 45 of the samples had been analysed for organic micropollutants. None of the samples exceeded the criteria for organic micropollutants.

Most organic micropollutants and microplastics are expected to be broken down in the pyrolysis process. Literature studies point to that some heavy metals can be removed from the biochar product and transferred to the residue from the gas treatment, and hence reducing the concentration of these metals in the biochar. For most heavy metals, the concentration in the biochar will increase due to the gasification of organic matter and subsequent reduction in dry matter (DM) in the biochar. However, the analysis of the 100 sludge samples indicates that the gasification process will change the non-compliance percentage from 3 % to 7 % based on heavy metal content. On the other hand, it is likely that the percentage of sludge not complying with standards for organic micropollutants is reduced. So, it seems from this theoretical assessment, that the vast majority of sludge from Danish WWTP will comply with the current legislative requirements for agricultural application after a gasification process. Measurements of heavy metals in sludge and biochar from the process show that mercury is removed. For other metals, the expected slight increase in metal concentration in biochar seem to appear although the measurements are not conclusive (enclosure AU table 3).

Agricultural application of sludge is also subject to requirements to the content of pathogenic microorganisms. Gasification will sterilize the sludge and remove all living microorganisms from the biochar, and such hygienic restrictions will not apply to the resulting biochar.

There are huge differences in how WWTP sludge is managed in in the various European countries. Germany and Austria have already passed legislation prohibiting agricultural application of sewage sludge. In many countries concerns to the potential harmful effect of pharmaceuticals and microplastics in sludge is of great concern. Gasification could prove to be a tool that eliminate these organic micropollutants in sludge and hence open a way for recycling of the phosphorus in the sludge embedded in the biochar. EU proposed marked standards for fertilizer products based on pyrolysis biochar does, however, not include sewage sludge, as a possible raw material, but handling of the biochar according to the national legislation for sludge application is an option.

Current costs in Denmark for application of sludge to agriculture is approx. 1300 DKK/ton DM (enclosure AU figure 3). In addition to this the municipal water-companies has considerable costs for storage of sludge (9 months storage capacity is required). The sludge is typically stored with a dry matter content of 20-25% in large tanks or storage facilities. As gasification will require dried sludge for infeed and the dry-matter content is reduced in the order of 50 % (enclosure AU figure 8) this alone will provide a considerable cut in costs associated with storage, transport and final disposal of the sludge.

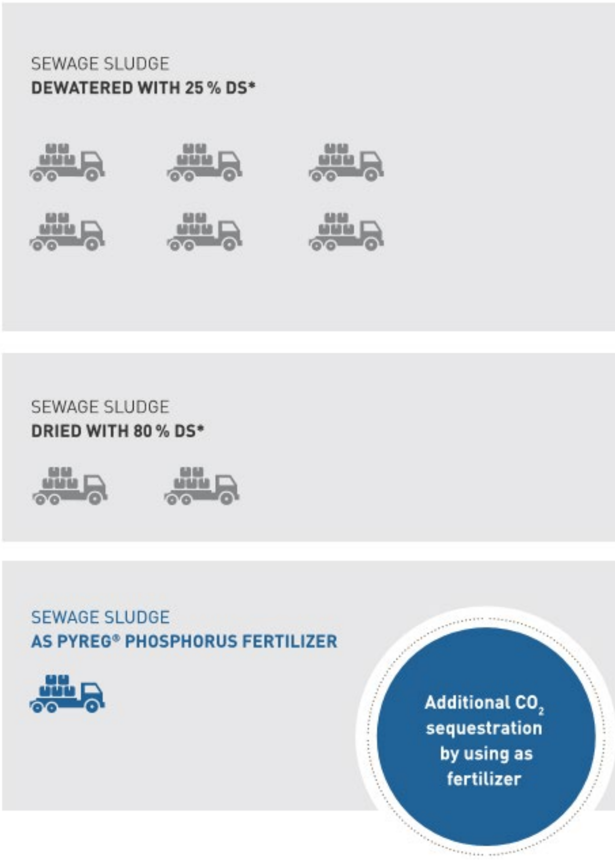

Figure 11: Sludge weight and volume reduction - from www.pyreg.de brochure

Production of wastewater sludge in Europe is in the order of 20 kg DM/person/year. The average calorific value is 12 MJ/kg DM. The potential power and heat generation from the gasification process is an important element to include when assessing the economy of the technology.

5.6 State-of-the-art of gasifier

Thermal gasification of biomass has been developed for many decades with the objective of generating heat and electricity or potentially feedstock for fuel production maintaining a high efficiency and providing a more greenhouse gas friendly alternative than fossil fuels. While many fuel types and residues are typically mentioned in the initial phase of the development paths of biomass gasification concepts, most successful gasifiers have been operated on woody fuels as these represent the least problematic feedstock in terms of being homogenous and having attractive ash properties. Switching focus to making thermal gasification able to solve an environmental challenge or a disposal issue by treating a feedstock containing harmful substances and making this work properly is younger, more challenging and less developed - especially when an aim or even a legislative requirement to separate unwanted components while recycling valuable components to society is introduced.

The work has aimed at studying the development level and the international experiences in laboratories and in commercial applications of thermal gasification of sewage sludge to provide input for further gasifier optimization and operation.

In practice, the work has involved a search of databases using the Deep Dyve search engine for peer-reviewed scientific papers to find scientific papers containing keywords evolving around sludge and gasification. Furthermore, the study has looked at articles and reports from applied research projects and development and demonstration projects in Denmark and internationally, including the publication gallery of IEA Bioenergy Task 33 Gasification of Biomass and Waste and personal contacts to networks of gasification experts and interviews with key persons.

As focus of this project is development of a gasifier concept that enables recycling of nutrients while separating or destroying unwanted substances while maintaining a clean producer gas, it is surprising to see that the main focus in most of the identified papers is to demonstrate the ability to generate a clean gas and maintaining the process in operation. Apart from recent Danish research, focus in the remaining 11 papers is hardly on nutrient recycling and separation of trace metals nor are they occupied with gasifier topology and design optimisation. Most of the research papers rely on rather short campaigns of gasifier operation with sludge. In this way it is possible to generate a gas that can be analysed, and primary tasks of the gasification can be analysed and assessed. But as it is not the objective for the systems to reach a stable stage of continuous operation, no focus is needed on optimising design.

The identified research takes place in a range of countries and involves all generic gasifier types: fixed-bed gasifiers, circulating fluidised bed and entrained flow types in different setups and combinations. One concept seems to relate somewhat more to the Combi Gasifier than other concepts: a Korean three stage gasifier that consists of an auger gasifier, a fluidised bed reactor and a tar cracking reactor containing active carbon gasifier. The aim of the cracking reactor is to enable generation of a tar free producer gas without utilising secondary gas cleaning vessels such as a scrubber or filters that typically entail very high operational costs. The purpose of the reactor is the same as the hot section of the Combi Gasifier. However, the concept is only in laboratory scale and (as far as can be understood from the paper) not much thought has yet been given towards continuous operation in larger scale.

Handling and disposal of the ever-increasing amounts of sewage sludge can be done in numerous types of plants, the traditional being biogas and combustion. In some countries - seemingly mainly Sweden, Germany and Denmark, increasing requirements to recycle nutrients along with restrictions on spreading untreated sludge on farming land, more advanced thermal processes like pyrolysis, hydrothermal liquefaction and thermal gasification come into play.

Suppliers of these technologies can all be competitors to B2G. The study has resulted in a list of existing plants and a list of plant suppliers. The most important suppliers identified cover:

- German Pyreg that markets pyrolysis systems that generates biochar from various feedstock. The generated gas is used for maintaining the pyrolysis process, and surplus heat is up for utilization in a district heating network.
- Aquagreen that also markets a pyrolysis concept where the generated gas is used for maintaining the pyrolysis process and feedstock drying.
- Sülzle-Kopf that has for many years marketed and operated a fluidized bed gasifier solution for sewage sludge. They have more plants on their reference list and have the option of utilizing the gas for small scale electricity generation. The ash from the process can be used in many ways, examples being as a mineral rich additive in asphalt production or as a basis for fertilizer production.

Please refer also to paragraph 6.

While some concepts including the Combi Gasifier focus on a low temperature approach to preserve the availability of phosphorus to be recycled, some concepts go for high temperature co-processing with coal aiming at evaporating the phosphorus and subsequently extracting it from the ash.

Finally, several market actors and researchers focus on the importance of drying and effort is going into developing more efficient drying concepts that can improve the energy efficiency of the whole sludge gasification process.

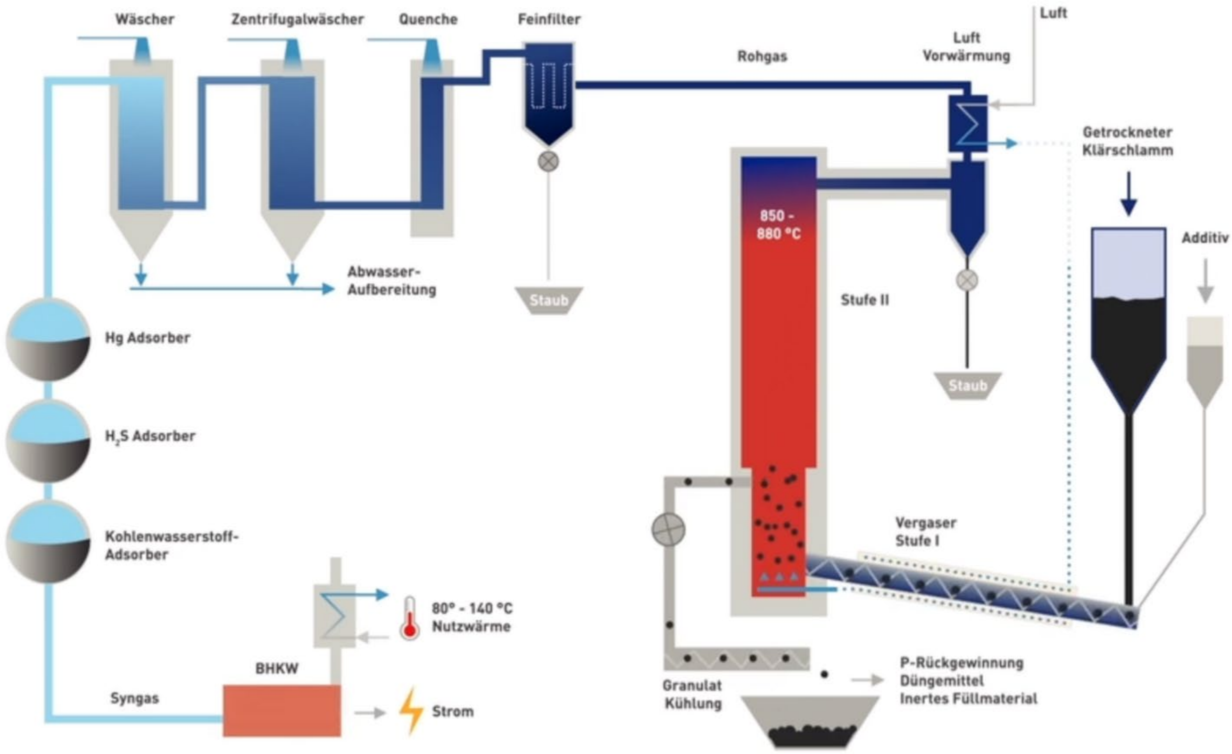

Figure 12: Sewage sludge gasification concept from Sülzle-Kopf

Based on the findings of the study it is fair to state, that the Combi Gasifier is an advanced approach that seems to be unmatched in terms of combining and optimising three objectives - to produce a clean and tar free gas while recycling nutrients and neutralise unwanted substances. While much of the research identified here as well as research on gasification of other feedstock and other information available regarding existing sludge gasification plants and concepts will be relevant as inspiration for the development and operation of the Combi Gasifier, the development of the 100kW upscale can most likely not be based on existing research already carried out by other teams or for other concepts.

A condensed report on the study of experiences with gasifier design and application within dried sludge from WWTP is an appendix to this report (enclosure EA) along with a note about the survey of scientific papers and reports.

5.7 Pilot plant at a national WWTP

Together with Denmark's 2nd largest WWTP – Fredericia Spildevand og Energi, we will investigate the feasibility of installing a pilot or full-scale gasifier plant. After discussions with FRSE it was clear that the task of detailing the technical and economic boundary conditions was too large for current project. Therefore, this task is undertaken in ZeroWastePilot together with experts from FRSE and AU.

Technical feasibility: The goal in the work package is to detail the physical flows surrounding the gasifier and to evaluate the feasibility of the pre-processing and final disposal of the biochar. The resulting gas also needs to be used local, we will assume for the feasibility study that the gas can either be used in a combined heat and power plant or be used in a burner to district heating.

Economical feasibility: The economical boundary conditions of the gasifier plant operation will be detailed; however, this is a quite complex problem. The work will be divided into the investment cost and the operation cost. Based on the technological system required, the site will be selected, and the preparation cost and the machine investments will be detailed. In terms of operation cost, biochar is still a new product (in Denmark at least), the economic surrounding this specific substance may be difficult to clarify. The energy flows that interface the pre-processing and gasifier plant will be detailed and the associated cost/benefit will be detailed.

Political feasibility: The WWTP is an industry subjected to a large set of special government rules and restrictions. Still, they must maintain a high level of cleaning but still at a low cost. Their development is subjected to a mixture of political focus and climatic changes. However, in the latest Danish political environmental agreement, WWTPs are mentioned and they are encouraged to investigate the possibility to utilizes gasification to reach a lower environmental footprint due to their processes. Also, the WWTPs are encouraged to investigate the possibility to reuse phosphorus and to avoid burning the wastewater sludge.

6. Utilisation of project results

Biowaste2Gas ApS is formed as a result of the successful creation of the laboratory scale gasifier. Therefore, the natural company to develop the gasifier further is this company. Current projects results will be utilized in the EUDP supported project 'ZeroWastePilot'. During this project, a 100 kW pilot plant of the gasifier will be build, tested and life-time tested.

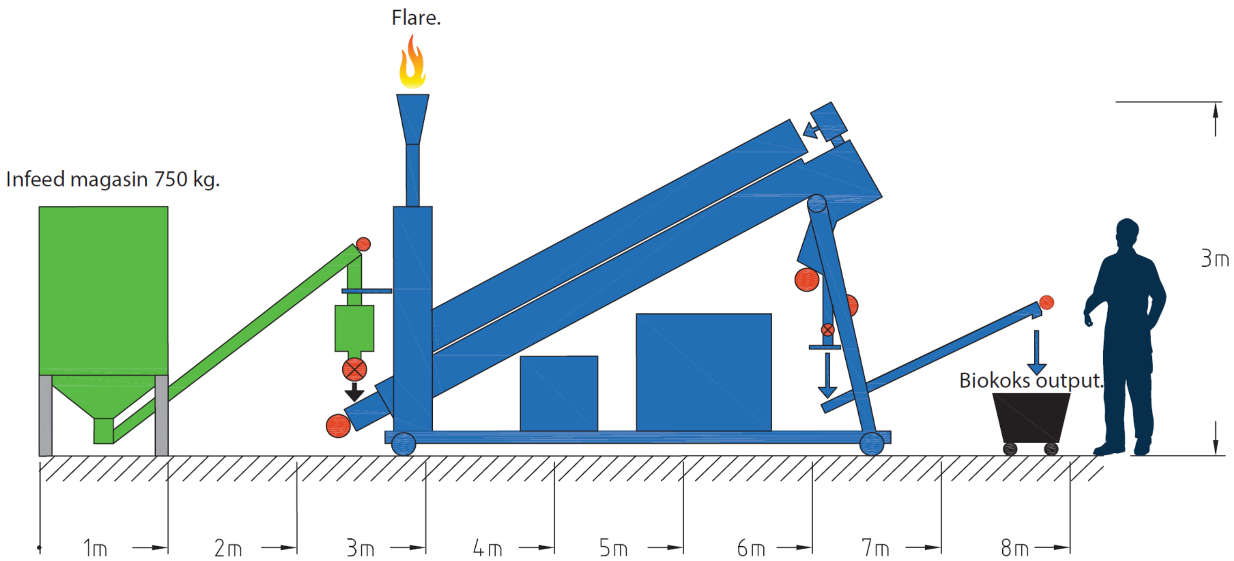

Figure 13: Pilot plant sketch

'Dansk Biofiber og Gødning' (DBG) will work as a demonstration host for the pilot scale plant, which offers ideal possibilities to test different in-feeds into the gasifier. DBG has the possibility to produce in-feeds with different mechanical pre-treatments and different dry matter content. Testing of different in-feeds will be done in parallel with lifetime testing of the pilot plant. DBG is also highly relevant as a potential customer, as their core business is pre-treatment of different biowaste.

We expect the pilot-scale demonstration of the gasifier will be enough to attract private investments and either allow Biowaste2Gas to build a full-scale system as a demonstration project with public funding or sell our first gasifier system on commercial terms. There has already been some interest about the technology, and a demonstration plant in a relevant scale with automated control allows for better documentation and testing of the systems capabilities.

The first potential customers will be found either within waste-water treatments plants or biogas system owners. Depending on AU results on bacteriological upgrade of gasifier gas to bio-methane the market focus can be changed. The results from analysing the technical and economic feasibility of incorporating a gasifier at the 'Fredericia Spildevand og Energi' will impact the market focus of Biowaste2Gas.

However, the potential market includes any type of industry which produces waste products with an energy or/and fertilizer value. Applying the gasifier with these industries will potential reduce their waste and harmful emission by converting their waste to energy and a biochar, potentially converting their waste to value.

The business model canvas for 3 potential business models is enclosed in B2G-2. The revenue stream is divided in 2 business segments – projecting and installing gasifiers systems followed by service contracts for system maintenance. The service contract is an integrated part of the system, and for all potential customers, it should be obvious that the service contract is paid by savings from operating the gasifier system. In other words, the economical savings should be big enough to pay for the service contract. Apart from that, since the in-feed can be very different on different sites, it is vital for system performance that the system is followed closely during the first critical weeks and months while operation parameters are tuned and optimized.

For now, the requirement of dried infeed (DM>90%) poses an entry barrier, as the availability of different infeed is limited, although still available. The future market of the circular bioeconomy will be characterized by the availability of many different types of dried biowaste, used for different purposes like energy and fertilizer. In that future market, biochar will be a natural product offered, making it easier and economical attractive to sell biochar as an owner of a gasifier.

In terms of competition, the possibilities for buying a gasifier are limited. Investigating the possible producers has discovered a few possible solutions:

Pyreg (https://www.pyreg.de/): This German company produces and sell pyrolysis systems that can generate a biochar from various sources. The generated gas is used for maintaining the pyrolysis process, and surplus heat can be recuperated by cooling the exhaust gas in a heat exchanger. They offer exhaust gas cleaning as an option. They have been selling system on commercial terms for almost a decade now. They offer systems in 500 kW-1.500 kW range and claim they can run on sludge infeed >80%DM .

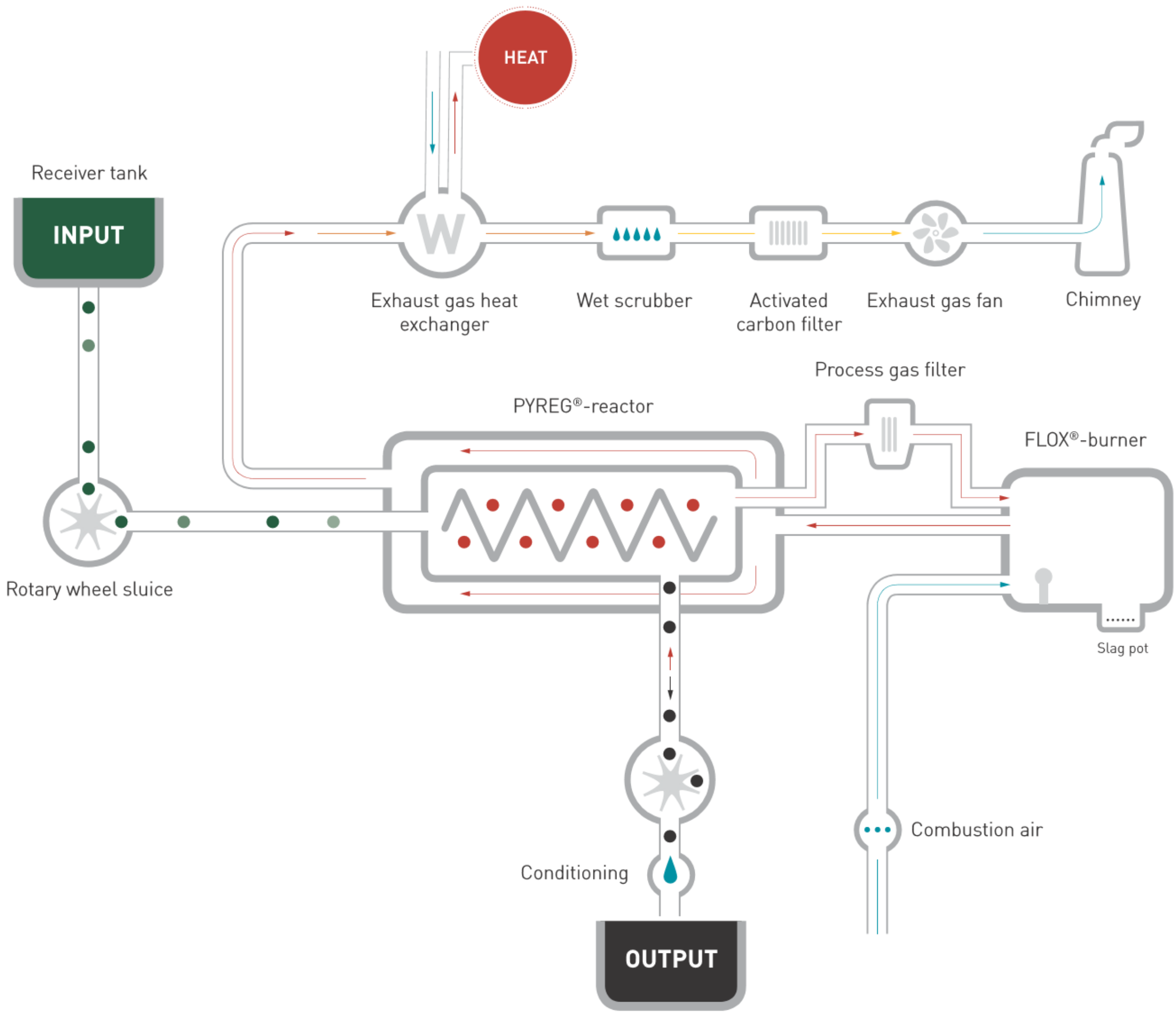

Figure 14: Pyreg (www.pyreg.de) process diagram on wastewater sludge

Looking into their process, they utilize the pyrolysis process to generate combustible gas to maintain the pyrolysis process. Some surplus heat energy can be recuperated from the exhaust gas from the burner, before the exhaust gas is scrubbed and cleaned by active carbon.

Pyreg has 6 wastewater gasification systems in operation.

Aquagreen (http://www.aquagreen.dk/): AquaGreen is a relatively new player on the Danish market, originating from DTU. From a technical perspective, their solution is comparable to Pyreg's solution. However, Aquagreen has more capacity in their drying facility, allowing them to accept infeed at 15-25% dry matter. Like Pyreg, they undertake a pyrolysis process at 650 degC and use the generated gas for fuelling the pyrolysis and drying unit.

AquaGreen has several systems under preparation, but no systems are in operation (January 2021).

Sülzle-Kopf (https://suelzle-gruppe.de/en/): They have a gasifier in operation feed with sewage sludge for 20 years. Their oldest plant (Balingens) has a capacity of 2.000 ton/year DM. The gasifier plant was upgraded in 2011, enabling a combined heat and power plant to operate on the gasifier gas, delivering net 60 kW electricity to the grid. The gasifier also delivers heat for the drying process. The pyrolysis is undertaken at 850 degC, Sülzle-Kopf suggests that the ash can be used for either fertiliser production or for industrial purposes as the technology produces an ash that is carbon free. Therefore, it cannot be called biochar as there is no char/carbon content.

For Denmark, the market outlook is promising as there is a significant political focus on the environmental load from the national WWTPs. The 'Klimaloven' from June 2020 states that WWTP in Denmark should be motivated to reuse phosphorus from the wastewater sludge and the energy balance of the entire WWTP should be evaluated to optimize the energy flow. The gasification process is mentioned directly in the agreement:

> Endelig skal der ske følgende for at understøtte målet om en energi- og klimaneutral vandsektor:
>
> - Undersøges om den økonomiske regulering kan indrettes, så drikke- og spildevandsselskaber får stærkere incitamenter til at udnytte egne ressourcer effektivt til gavn for forbrugerne, herunder blandt andet i forhold til forgasning. Understøttelse af ressourceeffektivitet skal have fokus på teknologineutralitet.

Figure 15: Gasification process mentioned in agreement about 'Klimaloven 2020'

The outlook for penetrating the WWTP sludge processing market with a gasifier system seems promising.

7. Project conclusion and perspective

The conclusions from the project can be seen from the technical, commercial and environmental perspective.

Technical: The laboratory model performs as expected, and the results from analysis of the biochar is as expected. As mentioned by the scientists from AU, the number of samples analysed is a little too low – due to the COVID-19 situation. But the results establish a possible trade-off in the char-reduction zone, where more air supply results in less biochar. Unfortunately, we have not optimized the water addition in the char-reduction zone. However, based on the results and the market interest in biochar, it is relevant to consider the optimal operation point of the char-reduction zone. Our previous optimization parameter has always been the gas production, but the char-production can also be optimized by adjusting air and water supply in the char reduction zone.

The energy reduction part has been a success, and the lessons learned will be brought into the pilot plant. The methodology of designing the heat exchanger has been verified.

From a controller perspective, the selected controller system performs as required, it offers remote access and due to the modular I/O system, the controller can be scaled as required. The developed SW is verified on the simulator but needs further work on the physical interface on the pilot plant and more work on internet security and remote control of process parameters.

The phosphorus plant availability has also been analysed, and the amount of plant availability is linked to the temperature in the char reduction zone. Therefore, the optimization of the operation parameters in the char reduction zone but requires the pilot plant is built and a new mapping of the operation parameters for the char reduction zone is needed. On top of that, the economical possibilities may alter the optimal operation point. Still, the initial findings indicate, that the production of biochar – irrespective of operating conditions – does not have detrimental effects on the plant availability of phosphorus.

Commercial: The state-of-the-art investigation has emphasised the duality of the technology of Biowaste2Gas' gasifier. Looking into the products of the existing market, the gasifiers available either produce biochar for fertilizers or gas for energy, but only Biowaste2Gas possesses a technology capable of both. That being said, the companies in Germany both have an interesting track-record and they both have market access, so they are significantly ahead in terms of commercial development compared to the 2 Danish companies, AquaGreen and Biowaste2Gas. The 'Klimaloven' in Denmark directly encourages the WWTP to investigate and invest in technology to optimise their use of resources, making gasification a relevant technology to explore in reaching this goal.

The biggest impact from COVID-19 is in the commercial part of the project, as it has been difficult to build network of potential customers and present our current results. Hopefully, this can be improved when the society lock-down is released. Biowaste2Gas has managed to get the right project team for the next project.

Environmental: During next project, it will be explored, together with AU, if it is possible to establish and maintain a bacteriological upgrade of the gasifier gas to bio-methane in a very small scale. In theory, the carbon-monoxide and hydrogen will be easily converted into bio-methane, enabling the upgrade of gasifier gas to renewable natural gas[2]. This business possibility can be offered to the existing owner of biogas plants, assuming economics bacteriological upgrade of gasifier gas to RNG is more efficient than keeping the digestive in the biogas tank. The plant needs to be of a size, where they already export to the natural gas grid in Denmark and hence operate the gas-cleaning equipment. Assumed that every RNG producing plant in Denmark will be expanded with a gasifier system the potential is to increase the 26% content of RNG in the Danish natural gas grid to a promising 35%. This can be achieved only by extracting the energy of the degassed sludge from the biogas plant, an energy content otherwise lost when the sludge is used on the agricultural land.

Looking into the wastewater business model, the political winds are helping as the WWTP are required to minimize their environmental load and reuse phosphorus. By adding Biowaste2Gas' gasifier technology, both the energy content and the fertilizer value of the sludge can be used. The new product – biochar – can be produced carbon-rich and increase the environmental benefit from use of biochar on agricultural land. The pyrolysis and char-reduction process reduces the heavy-metal content in the biochar. The pyrolysis process eliminates the micro-plastic present and most likely also removes any pharmaceutical products otherwise present in the in-feed. Current research (outside the scope of this project) indicates that the carbon used on the agricultural land will be stored in the soil for centuries and enhances the mechanical properties of the soil to eg. absorb water and release it when needed.

As a prominent result of ZeroWastePreStudy, Biowaste2Gas can build a pilot plant in 2021 and test it in 2022.

8. Appendices

- Enclosure B2G-1
- Enclosure B2G-2
- Enclosure AU
- Enclosure EA
- Www.biowaste2gas.dk

[2] Renewable Natural Gas = RNG