FINAL TECHNICAL REPORT

ENERGY TECHNOLOGY DEVELOPMENT AND DEMONSTRATION PROGRAMME (EUDP)

Project title: Biomass and bio-fuel based poly-generation for off-grid and grid-connected operation

EUDP file: 63011-0081

Project partners:
Stirling DK Aps (coordinator)
The Danish Technical University, Dept. of Mechanical Engineering (DTU)
Barritskov Skov- og Landbrug/BlackCarbon
FORCE Technology
I/S Amagerforbrændingen

Summary

The overall objective of this EUDP project was to design and build a combined heat and power plant based on an updraft gasifier and a 35 kW electrical output Stirling engine and further to test the flexibility of the plant with regards to fuel and application.

In the project a containerized combined heat and power plant including a 200 kW updraft gasifier and a 35 kW electrical output Stirling engine was designed, the specified components were procured, the plant was installed in the three containers and the plant was erected at Amagerforbrændingen ready for the COP15 in November 2009. SDK established a visitor's centre next to the containerized plant and the plant has served as a showcase displaying the Stirling technology itself but also an example of green Danish technology for the rest of the World.

The potential of operating the Stirling engine in island-mode (without grid connection) was investigated by mathematical modelling. Using an absorption cooling plant connected to the Stirling CHP plant was also investigated. A technical feasibility study was undertaken and it was concluded that from the two available technologies (water/LiBr and Ammonia/water) the appropriate choice is depending on the required cooling temperature.

Test runs focussed on investigating the fuel flexibility of two different configurations of Stirling engine CHP plants were carried out – respectively the updraft gasifier plant (the containerized plant and the DTU plant) and the pyrolysis plant (the plant situated at Barritskov). In order to perform these test runs a stable operation is required. On both the containerized plant and the pyrolysis plant this proved to be more challenging than expected and therefore the number of fuels tested was limited to willow chips at the containerized plant and dry wood residues, wood pellets and straw pellets on the pyrolysis plant. For all tested fuels it was possible to operate the plants, however different issues mainly related to the quality of the fuels were encountered. And so it can be concluded that the quality of the fuel is critical for the operation of both the updraft gasifier plant and the pyrolysis plant.

A comprehensive desktop evaluation of the feasibility of selected fuels was also carried out. Based on the evaluation an overall remark is that the price and the quality of a fuel are correlated i.e. the higher price the less expected technical problems and vice versa. A fact sheet for each of the selected fuels was prepared and is enclosed in the report.

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1 Introduction

This report marks the conclusion of the project "Biomass and bio-fuel based poly-generation for off-grid and grid-connected operation" funded by The Energy Technology Development and Demonstration Programme (EUDP). The project was initiated with the approval of the project application by EUDP 11th July 2008.

Project coordinator is Stirling DK Aps which is the world leading provider of biomass fuelled Stirling engines. Project partners are:

The Danish Technical University, Dept. of Mechanical Engineering (DTU)
Barritskov Skov- og Landbrug (BlackCarbon A/S)
FORCE Technology
I/S Amagerforbrændingen.

1.1 Background

Stirling DK (SDK) is a spin-off from the Technical University of Denmark, founded in April 2004 with the purpose of commercializing 15 years of research and development within Stirling engine technology conducted by Professor Henrik Carlsen.
In the development of the Stirling engine technology SDK has received grants from Energinet.dk and since the beginning of 2010 also The Business Innovation Fund (Fornyelsesfonden) and of course also EUDP.

SDK has developed a Stirling engine based technology capable of converting low-value biomass into high-value, clean electricity and heat in small-scale applications with an electrical output of 35-140 kWe and a heat output of 140-560 kWth.

The biomass is converted into product gas in an updraft gasifier. The product gas is then combusted in a combustion chamber and the flue gasses are used to heat the Stirling engine. The Stirling engine is simultaneously cooled by cooling water and the temperature difference within the engine drives the Stirling process whereby the mechanic of the engine drives a generator where electricity is generated. The efficiency from biomass to electricity is in the range of 17 % and the total energy utilization (heat and power) around 90 %.

The Stirling engine technology has a large potential for off-grid appliances in remote areas where installation can be difficult and costly. In order to address this, a containerized Stirling engine plant has been suggested. Hereby the plant can be installed where proper tools and lifting equipment is available and as the plant is installed in standard 20 foot containers it is already packed for transportation. The container solution also allows for a modular approach where plants can be sized according the number of engines and thereby the nominal electrical and heat output.

2 Objectives

In the application the objective of the project is described as following:

This EUDP project will demonstrate the applicability of Stirling engine technology in a range of practical applications. Specifically, the aim of the project is:

- To develop and demonstrate a Stirling engine based plant which can operate under off-grid conditions and thus prove the potential of the technology as a substitute product for diesel generators.
- To develop a modular system that enables simple and low-cost transport and erection of the plants
- To demonstrate the fuel flexibility of the technology
- To demonstrate alternative use of the heat generated in situations where heat is not needed

In order to fulfil the above stated objectives the project will contain the following main elements:

A. Building of a demonstration plant based on an updraft gasifier and one (1) 35 kWe Stirling engine. The plant will operate at the facilities of I/S Amagerforbrændingen; one of the project partners.
B. Development of the engine, plant, and control system for off-grid operation.
C. Development of a modular and containerized "plug-and-play" plant system.
D. Demonstration of the potential to use the heat from the system to generate cooling and to desalinate salt water by adding an absorption cooling unit and a desalination unit to the plant.
E. Testing of a range of biological fuel types with the purpose of determining their applicability as fuel for a Stirling CHP plant. For each of these fuel types, operational data and emission data will be measured and reported.

3 The demonstration plant at Amagerforbrændingen

The building of the containerised updraft gasifier plant was one of the core activities in the project and by far the most costly in terms of equipment and man hours. The plant includes one Stirling engine and a combustion chamber that is fuelled with product gas produced in an updraft gasifier. The whole plant is fitted into three containers excluding the fuel container.

3.1 The Stirling engine updraft gasifier plant process

The overall process of the Stirling engine updraft gasifier plant is presented in Figure 1.

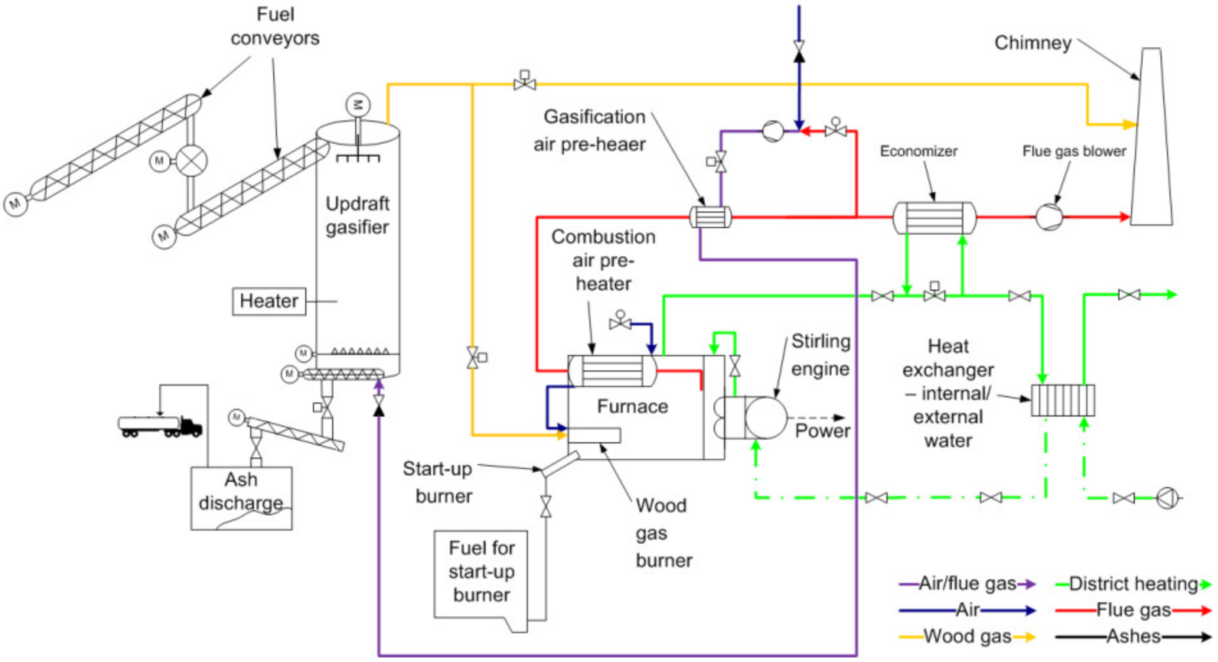


Figure 1: Simplified process diagram of the Stirling engine updraft gasifier plant.

Fuel is fed into the top of the gasifier that converts the fuel into product gas which in turn is led to the combustion chamber. The product gas taken out from the top of the gasifier is between 70° and 80° C and has roughly the following composition:

Component	%-vol
O_2	0
N_2	21
H_2O	42
CO_2	4
CO	18
H_2	12
CH_4	2
Tar	1
Sum	100

Table 1: Composition of product gas from wood chips.
Values are calculated – not measured.

In the combustion chamber the product gas is completely combusted generating temperatures of more than 1,200° C. The hot flue gases transfer heat to the Stirling engine heater by radiation and convection. In order to establish a good heat transfer the hot flue gas is guided through the heater panels of the Stirling engine. The flue gas is then led through a combustion air pre-heater which is built into the combustion chamber. Then the flue gas passes through the gasification agent pre-heater before entering an economizer. The flue gas blower that creates the under pressure in the entire system downstream of the gasifier is positioned between the gasification agent pre-heater and the flue stack.

The Stirling engine is cooled by cooling water of maximum 65° C. The cooling water is the return water from a district heating system. After the Stirling engine the water enters the water jacket of the combustion chamber which is included both to secure an acceptable surface temperature of the combustion chamber in terms of working environment and in order to minimize the heat loss from the process. Prior to being returned to the district heating system the water is lead through the economizer. Downstream of the economizer the water has a temperature of app. 90° C. It is common to have a heat exchanger between the district heating system and the cooling water system for the Stirling engine plant.

In order to enable the gasification process a gasification agent is added to the bottom of the gasifier. The gasification agent is a mixture of air and flue gas which is heated by the gasification agent pre-heater and blown into the gasifier via the gasification agent blower. The only residue from the gasification process is ash from the fuel which is taken out with a screw conveyor in the bottom of the gasifier.

A detailed schematic is included in this report as appendix A.

3.2 Plant layout and specification key components

For this project a one engine plant is chosen in order to keep installation and operation costs down. The plant is fitted into three 20 foot containers excluding the fuel container. As the gasifier is too high to be fitted into one 20 foot container, consequently, the gasifier was split in the middle and put into two containers that are placed on top of each other with a first floor slab in only half of the footprint of the top container. The plant layout is presented in Figure 2.

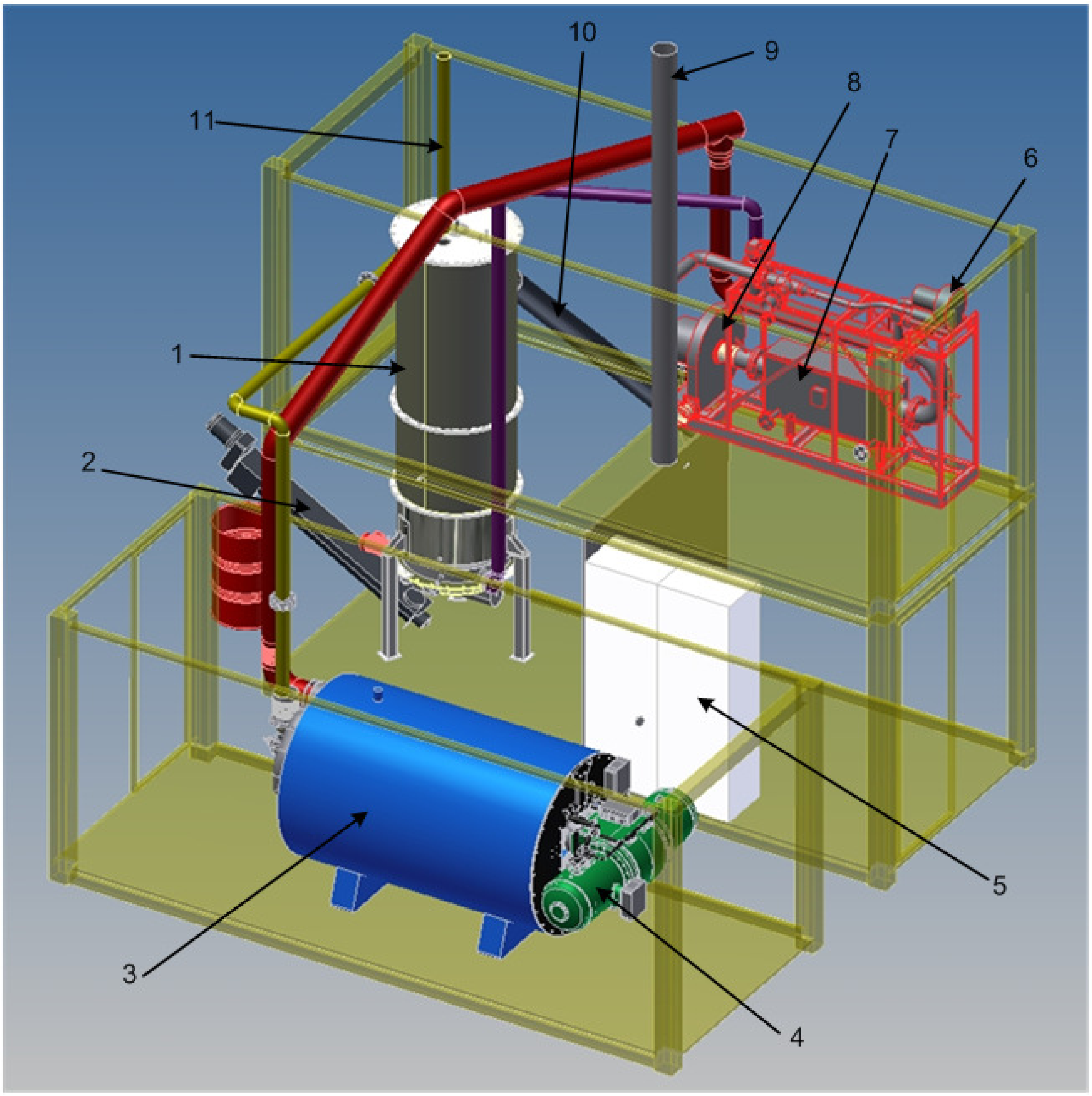


Figure 2: Layout of containerized Stirling engine updraft gasifier plant.
1... Updraft gasifier, 2... Ash conveyor, 3... Combustion chamber, 4... Stirling engine, 5... Control cabinets, 6... Gasification agent blower, 7... Economizer, 8... Flue gas blower, 9... Chimney, 10... Fuel conveyor, 11... Evacuation pipe for product gas.

3.2.1 Updraft gasifier

The gasifier chosen for this plant is a 200 kW updraft gasifier which means that the nominal fuel input to the gasifier is 200 kW corresponding to a mass flow of app. 70-80 kg per hour depending on the moisture content of the fuel. The gasifier has a steel jacket on the outside and is equipped with a refractory lining on the inside to resist the high temperatures of up to 1,200° C in the glowing zone. In the top of the gasifier there is a leveller – a rotating fork-like device that is rotated by a motor with a power relay that detects resistance. In this way the gasifier will ask for fuel when the leveller can rotate freely and stop the fuel feed when the leveller meets resistance which is the wood chips piling up in the gasifier meaning that the gasifier has the intended level of fuel.

With the updraft gasification principle fuel is added in the top of the gasifier whereas the gasification agent (in this case a mixture of air and flue gas) is added in the bottom of the gasifier. This is done through a number of nozzles distributed over the entire area of the bottom in order ensure that the steps of the gasification process is evenly layered in the gasifier. The ash is removed from the bottom of the gasifier by a conveyor and two ash scrapers that are pushing the ash from the sides of to the middle of the bottom of the gasifier where it falls down into the trough of the ash conveyor. The gasifier is designed by SDK and produced by boiler manufacturer Danstoker that is situated in Herning.

3.2.2 Combustion chamber

The combustion chamber is fitted with refractory stones and a customized wood gas burner designed by SDK. The wood gas has only app. 10 % of the calorific value compared to natural gas. Due to this is necessary to employ pilot burners (or start-up burners) in this case oil burners for start-up of the plant. After the start up of the plant and when the combustion chamber has reached the operating temperature the start up burners are turned off. The pre-heated combustion air is produced by four shell and tube air pre-heaters placed along the circumference of the refractory stones. Further, the combustion chamber is cooled by a water jacket in order to lower the outer surface temperature and also to minimize heat loss to the room. The combustion chamber is designed by SDK and manufactured by Danstoker.

3.3 Installation

The installation of the plant was partly done at SDK's premises in Kgs. Lyngby and partly at the location for the demonstration plant i.e. at I/S Amagerforbrændingen. In Kgs. Lyngby the plant was fitted in the containers and all internal piping was installed.

Subsequent to the installation in Kgs. Lyngby the containers were transported to Amagerforbrændingen where the final installation including piping between the containers and connections to district heating system and electricity grid was carried out. Further, a sea water pipe was run from Øresund to the plant for the use of the desalination unit.

Picture 1: The containers are unloaded in Lyngby.

Picture 2: The gasifier is unloaded.

Picture 3: The gasifier is lifted into the container.

Picture 4: The combustion chamber is fitted in the container.

Picture 5: The containers are unloaded at Amagerforbrændingen.

Picture 6: Installation in progress at Amagerforbrændingen.

Picture 7: The Stirling engine plant at Amagerforbrændingen.

Picture 8: The Stirling engine plant in operation with the visitor's centre behind it.

3.4 Public relations and visitor's centre

SDK financed the establishment of a visitor's centre next to the containerized plant at Amagerforbrændingen (this is not incl. in the EUDP budget). The visitor's centre consisted of a pavilion displaying an exhibition that presented the Stirling technology, the history of SDK and the company's current activities. The visitor's centre was employed several times after the grand opening of the plant (see Picture 9 and Picture 10) in particular in relation to the UN Climate Change Conference 2009 (COP15) in Copenhagen, but has also hosted visits from a range of Danish and foreign guests including the Taiwanese Minister of Environmental Protection and delegations from among other Gaza, Serbia, Canada and Norway.

In general the containerized plant at Amagerforbrændingen has served as a showcase displaying the Stirling technology itself but also an example of green Danish technology for the rest of the World.

Picture 9: Grand opening.
From right to left: Minister for Education Bertel Haarder, CEO Lars Jagd (Stirling DK), Managing Director Ulla Røttger (Amagerforbrændingen).

Picture 10: Grand opening.

4 Off-grid operation, load control and simulations

The study of the off-grid operation, load control and simulations is undertaken by DTU and presented in appendix B. Section 4 is a summary of appendix B.

A small CHP plant, that is able to operate without a grid connection, is interesting for remote installations and as power back up in areas with poor security of supply. This is not an important market in Denmark, but worldwide the market potential is vast.

To create a CHP plant that is able to operate without a grid connection, the engine must be modified. The engine must be build with a synchronous generator, instead of an asynchronous generator, or a very advanced electronic power converter must be installed to operate the generator. An electronic power converter must always be installed to cover the fast changes of the load in a small isolated grid. The Stirling engine will not be fast enough to follow the transients in a normal consumption pattern. With an internal helium compressor the engine is able to change the load from 100% to 50% in 20-30 seconds and the demanded size of the battery system can be much smaller compared to a set up where the engine is only operated in on/off mode.

Below the power modulating potential of an engine with a helium compressor is investigated.

4.1 Simulations

In the present design of the four-cylinder Stirling engine type SD4E, the rotor in the asynchronous 6-pole generator is mounted on a shaft directly coupled to the crank inside the hermetic engine. The asynchronous generator is connected to the electricity grid, which in this way is controlling the speed of the engine. However, if the engine is the only power source in an island system, the engine system must control power and frequency itself. The power control has to be fast in order to avoid large changes in grid frequency.

In order to investigate, how the power output of the Stirling engine can be controlled, an analysis of the transient behaviour of the Stirling engine was investigated. A system consisting of compressor piston coupled directly to one of the four pistons in the Stirling engine and connected to a mutual volume was investigated using the Matlab software simulation tool. Figure 3 features the connection between the compressor volume, the mutual volume and the four active cylinder volumes in the Stirling engine. During the normal operation, the pressure in the mutual volume (MV) equals the lowest operative pressure in the cylinders because check valves are mounted in each cylinder pointing from cylinder volume to the mutual volume. In case of a pressure loss in the cylinders, the gas flows from the MV to the cylinders through the automatic (check) valves.

When a power increase is required, only the valve that connects the HPV is opened; the gas will flow from the HPV to the MV and through the automatic valves into the working volumes. A power gain, due to an increased working gas mass, is thus obtained.

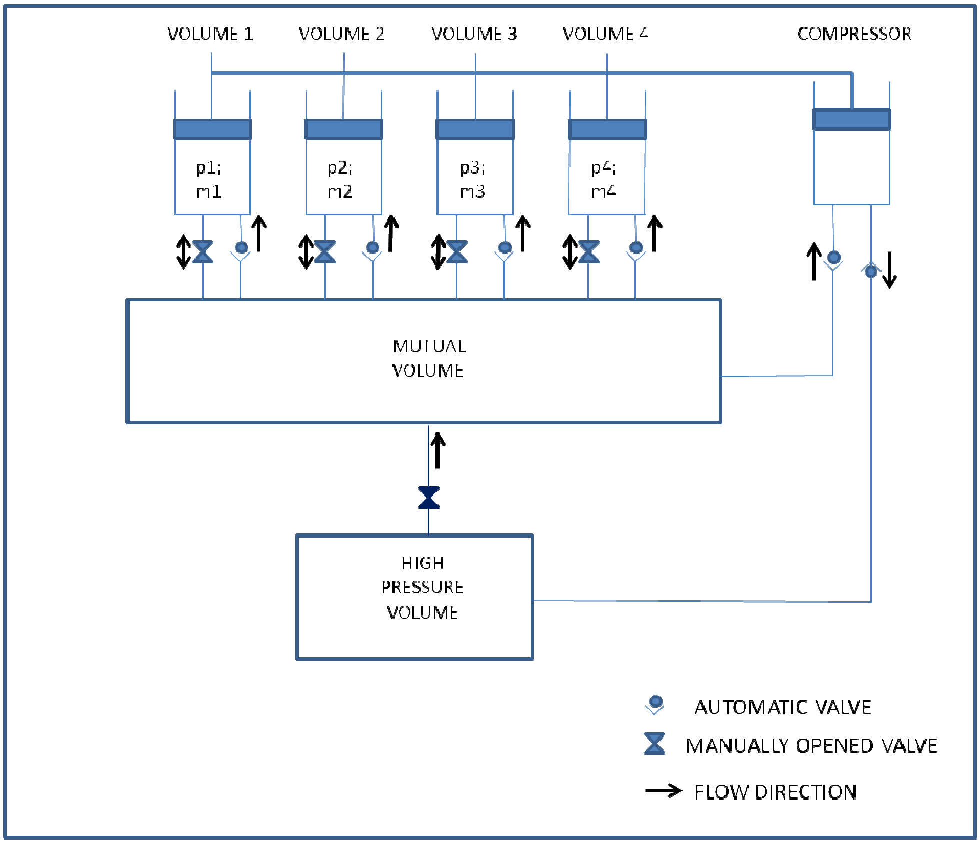


Figure 3: Model of Stirling engine helium circuit for simulation.
When a power decrease is required, the compressor pumps gas from the mutual volume (MV) to the high pressure volume (HPV) reducing the minimum pressure in the cylinder volumes and thereby reducing the power output.

Figure 4 and Figure 5 show examples of decrease and increase of power, calculated by the simulation model. The results show that control of power output of the 35 kW Stirling engine can be made by introduction of a compressor piston with a diameter of 30 mm, and that the time for decrease and increase of power is satisfactory to adapt to the transient behaviour of the biomass combustion system. The model can also be used for the design of the size of valves in the compressor.

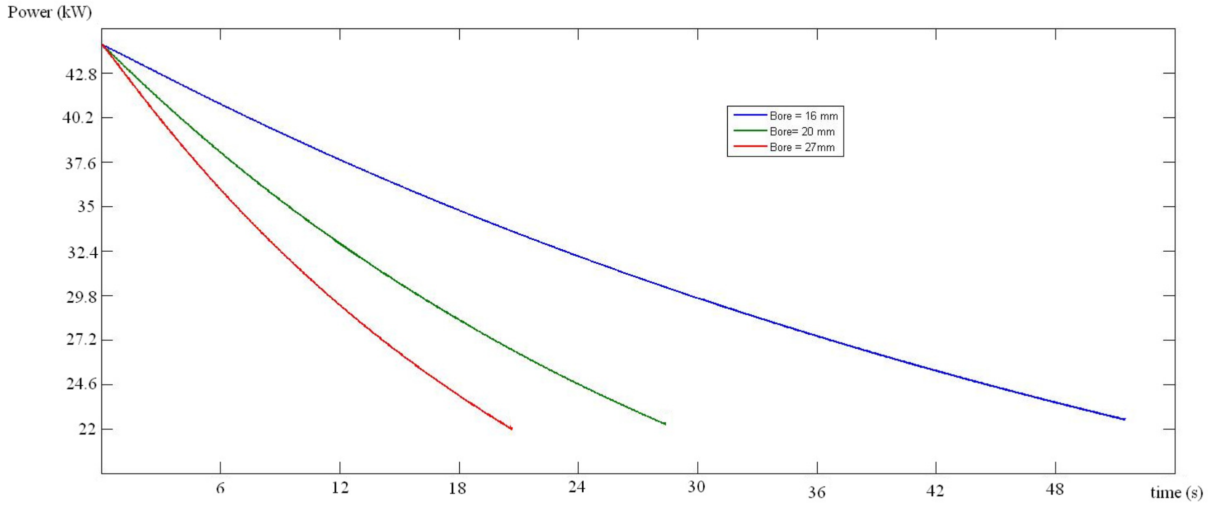


Figure 4: Engine power Vs time.
Increasing the compressor bore entails a faster gas transfer from the working volumes to the HPV. The time requested to get the 50 % of the load is thus reduced.

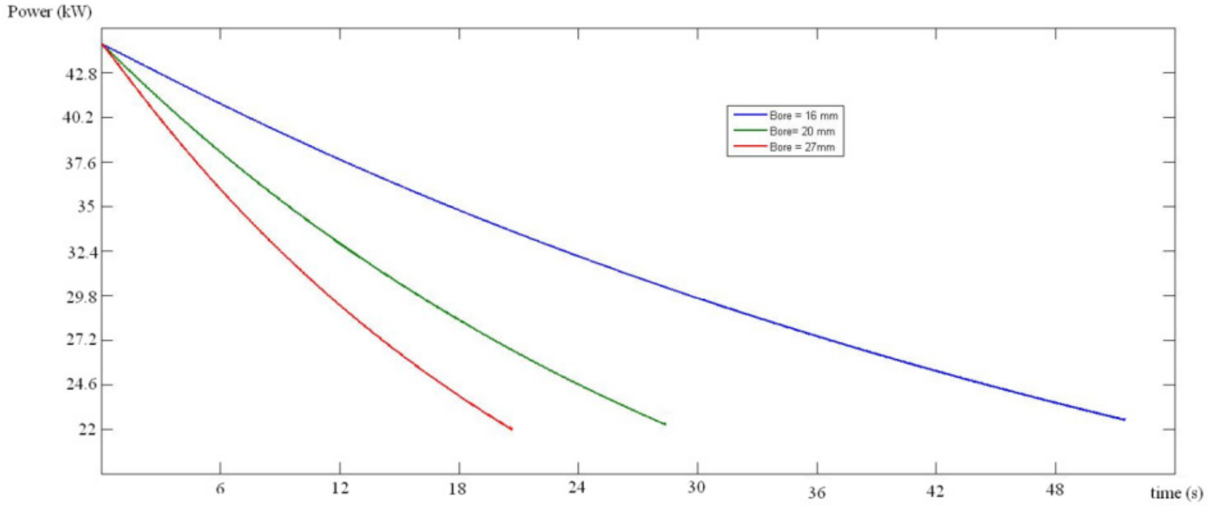


Figure 5: HPV pressure Vs time.
Moving the gas from the MV to the HPV entails a pressure raise in the HPV. The compressor size affects also the temperature increasing in the HPV as well as the compressor pressure ratio and absorbed power.

5 Development of a modular and containerized ”plug-and-play” plant system

The containerized plant installed at Amagerforbrændingen was a first of its type. The idea of a containerized plant has emerged from a wish for a standardized and streamlined installation process. By doing the install in containers the majority can be done in the workshop prior to shipment. This has a number of advantages e.g.:

- minimal repeat engineering incl. documentation from plant to plant
- more efficient installation by having the proper tools and equipment in the workshop
- reduction of onsite installation and thereby travel and transportation costs
- minimization of risk of installation errors and component malfunctions as the replicability is high and mechanical and functionality tests can be done in the workshop
- the pre-fabricated plant represents an added value to the product.

Further, the idea of containerized plant supports the Stirling engine technology’s possibility to form part of modular CHP plants consisting of 1, 2 or 4 Stirling engines.

In other words a containerized plant should be cheaper to build and have a higher sales price.

A sketch of a four engine plant with an 800 kW gasifier in a total of seven standard 20 foot containers can be seen in appendix C. As it can be seen very few pipes are going from one container to another.

5.1 Experiences from building the demonstration plant

Building the demonstration plant for this project revealed some unforeseen issues related to the containerized installation.

5.1.1 Restricted space

The containers supply sufficient but restricted amount of space for the installation of the updraft gasifier Stirling plant. This calls for very accurate planning in terms of 3D installation drawings and sequencing of installation works. Regarding the positioning of the plant components the large components (gasifier, combustion chamber and engine, control panels and economizer) were initially positioned and then the pipe fitting was done according to this and taking service accesses into account. This turned out to be a trial and error process as the reality did not always match up to the drawings which caused a few unnecessary wall penetrations for piping that was subsequently re-positioned. This process revealed some concrete lessons learned, some of these being:

- The space given to the electrical panels in the gasifier container which was half of the floor area of the container was unnecessary large. One third of the floor area would have been sufficient and there is a need for more space in the gasifier end of the container.
- The ash conveyor which is going from the bottom of the gasifier through the door should have penetrated the wall instead of the door as this position is hindering the access through this door.

The final installation is what can be seen in Figure 2. This drawing is a picture of the as-built 3D drawings which can be used for the future containerized one engine plants.

5.1.2 Engine service access

At the current development stage of the Stirling engine scheduled service is to be performed for every 4,000 hours of operation. When this is done the engine is to be demounted and send to the SDK workshop in Lyngby. This means that it has to be possibly to remove the engine from the container and to load on to a lorry as easy as possible. This is complicated by the fact the mass of the engine is app. 2.5 tonnes and that it therefore has to be removed from the container on a customized trolley. This implies that the floor area from where the engine is positioned to the door has to have a smooth surface and be able take the point loads of the wheels of the engine trolley. For the containerized plant a solution with two u-profile steel beams where placed under the wheels of the engine trolley which made it possible to roll out the engine even though the wooden floor in the container could not take the point load of the wheels of the trolley.

Picture 11: Rails for engine service.
The engine is pulled out to access the combustion chamber and the heater section.

The rails showed in Picture 11 worked very well, handling of the engine was quite easy. Minor and medium overhauls like piston ring replacement are usually undertaken on site. This is possible but the working process is somewhat stressed from the missing floor, gravel, steel structures and open sky. A work surface and a shelter can be established. Especially for overhaul of engines on first floor, as suggested for a compact four engine plant, require some preparation, but it can be done.

5.1.3 Stability and vibration issues

In a four cylinder Stirling engine the piston movement is defined by the thermodynamics, it is not an option to balance the engine in the same way as an internal combustion engine. Balancing of a four cylinder Stirling engine is not possible without adding an expensive and complicated mechanism. SDK has tested different solutions, but none was feasible in standard installations. As long as the engine is bolted together with a combustion chamber weighing 5,000 kg, the vibrations are not a problem when the plant is installed on a concrete floor. When the combustion chamber is standing on a container floor there will be a certain level of excitation and unfortunately the eigenfrequency of the 20 foot container is in the same range. A container is like an elastic beam supported in the corners. When the engine was started the first time, the container was vibrating violently and the engine was stopped. A pair of wedges was made to support the middle section of the container and after they where bolted in, the plant was very smooth and quiet in operation. Concerning the suggested layout of a four engine plant in two stories it can be expected to find vibration issues that are difficult to predict, that need a mechanical solution.

Further, there were some concerns with regards to noise issues from the engine specifically and the entire plant in general. In order to minimize the problem the containers were covered on the inside with a noise reducing material. This proved to be sufficient as when the plant was set in operation it was amazingly quiet, even at full load.

6 Absorption cooling and desalination

6.1 Feasibility of absorption cooling plant

Prior to the procurement and installation of an absorption cooling plant an analysis with regards to the technical feasibility was undertaken. Further, two quotations were obtained from suppliers. This was done by DTU in 2009 and the following is a condensate of this study. The full study is presented in a report which is enclosed as appendix D.

Absorption cooling is a technology were low-temperature (70-180°C) heat is utilised for cooling production. The absorption cooling process employs a refrigerant and an absorbent and the pairing of these determines the applicable heat source and cooling temperature.

There are two main absorption cooling technologies available on the market:

- Water/LiBr (water is the refrigerant and LiBr is the absorbent)
- Ammonia/water (ammonia is the refrigerant and water is the absorbent).

6.1.1 Water/LiBr absorption cooling

The water/LiBr technology provides a peak cooling coefficient of performance (COP) of 0.7 and requires heat at 75-120° C which is suitable for the heat available in the water going out of the Stirling plant (cooing water from Stirling engine, combustion chamber and economizer) which is 90° C. However, as water is the refrigerant the chiller cannot produce cooling at temperatures lower than 0° C as this is the freezing point of water, which limits the range of use. Further, the water/LiBr plant requires the use of a cooling tower and thereby availability of fresh water.

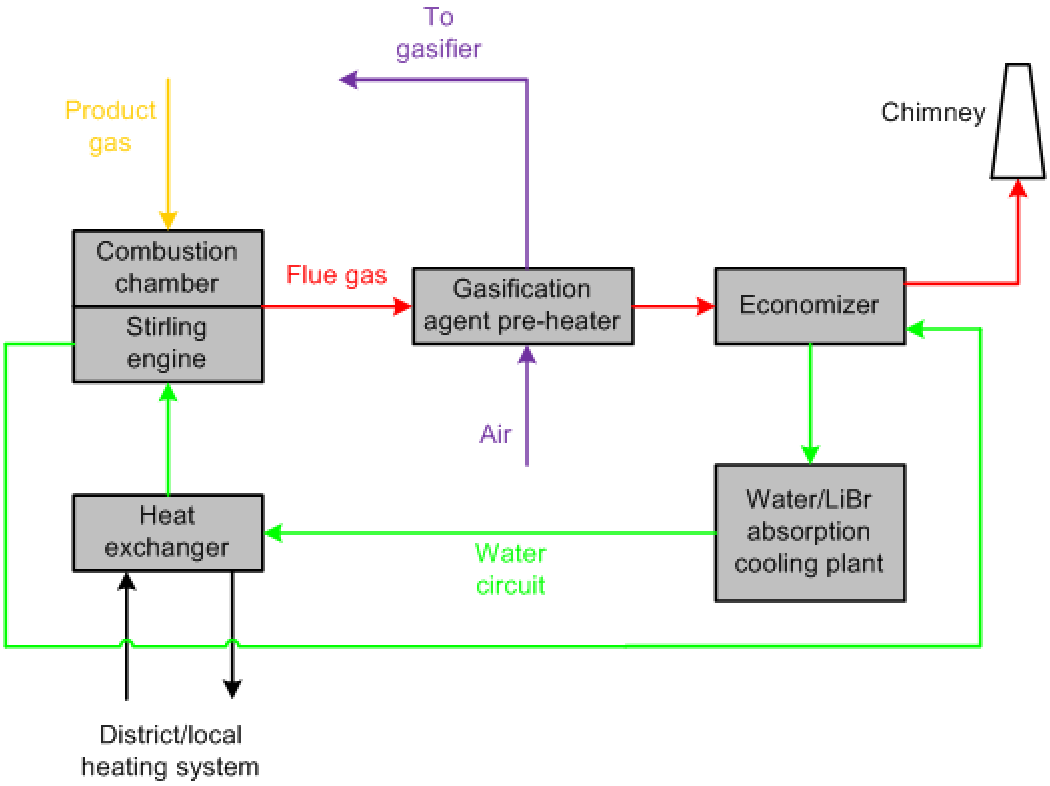


Figure 6: Water/LiBr cooling plant integrated in the Stirling plant.

6.1.2 Ammonia/water absorption cooling

The Ammonia/water absorption cooling technology requires heat at minimum 90° C in order to achieve a satisfactory cooling capacity. This implies that the temperature of the heat available from the Stirling plant's water system is not sufficient. Market research showed that no plants with direct use of flue gas were available in the required size range. Thus, it is necessary to exclude the economizer (which is a part of the standard Stirling plant setup) and introduce an intermediate temperature oil circuit to transfer heat from the flue gas downstream of the gasification air pre-heater to the absorption cooling plant at a sufficient temperature level. The system is shown in Figure 7.

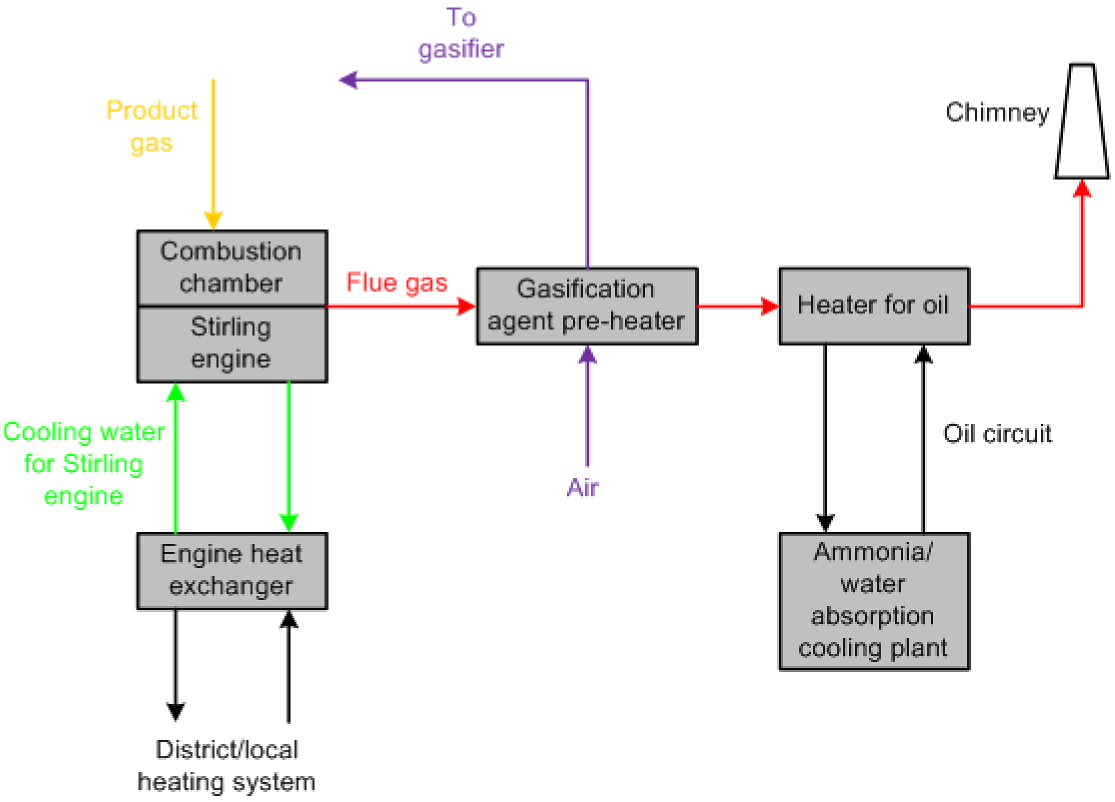


Figure 7: Integration of ammonia/water cooling plant in Stirling plant.

6.1.3 Simulation

Using a computer simulation tool (Engineering Equation Solver - EES), the performances of the two absorption cooling technologies were analyzed; different customized models, integrating the Stirling plant and the chillers, were tested, and a sensitivity analysis was carried out. Optimum solutions were found, taking into account the Stirling plant operational characteristics, the geographic location of the plant and different possible cooling delivery requirements. The presence of cold water availability in case of use of cooling towers was also considered, and the potential water consumption was calculated as well. The most suitable technology and the main design parameters were pointed out for all the analyzed different working conditions.

The analysis suggests that the water/LiBr machine offers better performance in case that the water consumption due to the use of a cooling tower is not an issue, while the ammonia/water unit is necessary if the chiller is air cooled. If cooling has to be delivered at a temperature below 0° C, the ammonia/water unit is the only possible solution. For more details on the simulation work see appendix D.

6.1.4 Investment

Quotations for respectively a 105 kWt and a 200 kWt chillers from the two suppliers "LS Mtron Ltd." and "Finetec Century" were obtained. The two quotations are included in appendix D. Prices and capacities for the two suggested plants can be seen in Table 2. There is not included a quotation for a ammonia / water type cooling plant, as no supplier for an entire plant in the appropriate capacity range was identified.

Supplier	Type	Capacity (heat input / cooling output / COP)	Price	Comments
LS Mtron Ltd.	Absorption chiller, water/LiBr	105 kW / 74.7 kW / 0.714	€43,440	Delivery is including shipment to Danish port, initial start and commissioning, data exchange interface, excluding installation works.
Finetec Century	Absorption chiller, water/LiBr	200 kW / 135 kW / 0.675	€50,500	Delivery is including shipment to Danish port, initial start and commissioning, data exchange interface, excluding installation works.

Table 2: Overview on water/LiBr chiller quotations.

It was decided not to invest in an absorption cooling plant. This was due to economical reasons as the project budget for SDK was not sufficient to contain the investment also due to the fact that the demonstration itself had become more expensive than expected. Further, the absorption chiller technology is known and proven, and so it was assessed that the value to the project was to be overseen.

6.2 Desalination plant

To operate a desalination plant from the heat produced by the Stirling CHP plant could be beneficial to remote areas with limited access to fresh water. At the containerized plant at Amagerforbrændingen a salt water pipe from Øresund was installed for the use of the desalination unit. However, it was decided not to progress with a procurement and installation of a desalination unit. As it is the case for the absorption cooling plant it was assessed that the value of the possible new knowledge gained by a practical test of this also proved technology does not justify the investment of the plant.

7 Plants for test runs

Besides the building and commissioning of the containerized demonstration plant the core activity of the project is to perform test runs on different fuels or feedstocks to investigate into the fuel flexibility of the Stirling engine.

In the project application two test plants are mentioned – the containerized updraft gasifier plant at Amagerforbrændingen and the pyrolysis plant at Barritskov. Due to the fact it was not possible to perform as many test runs as planned it has been decided to include the test results and operational experiences from the updraft gasifier plant located at SDKs premises in Kgs. Lyngby referred to as "the DTU plant".

7.1 Amagerforbrændingen demonstration plant

The demonstration plant located at Amagerforbrændingen is described in section 3 in this report.

7.2 Pyrolysis plant at Barritskov

The BlackCarbon unit (BC300) is a pyrolysis based Combined Heat and Power (CHP) unit with a Stirling engine. It converts biomass feed stock equivalent to 300 kW - of this 35 kW is electricity, 110 kW district heating and 110 kW biochar (se illustration below). The plant is a prototype – the first of its kind combining the pyrolysis technology with a Stirling engine.

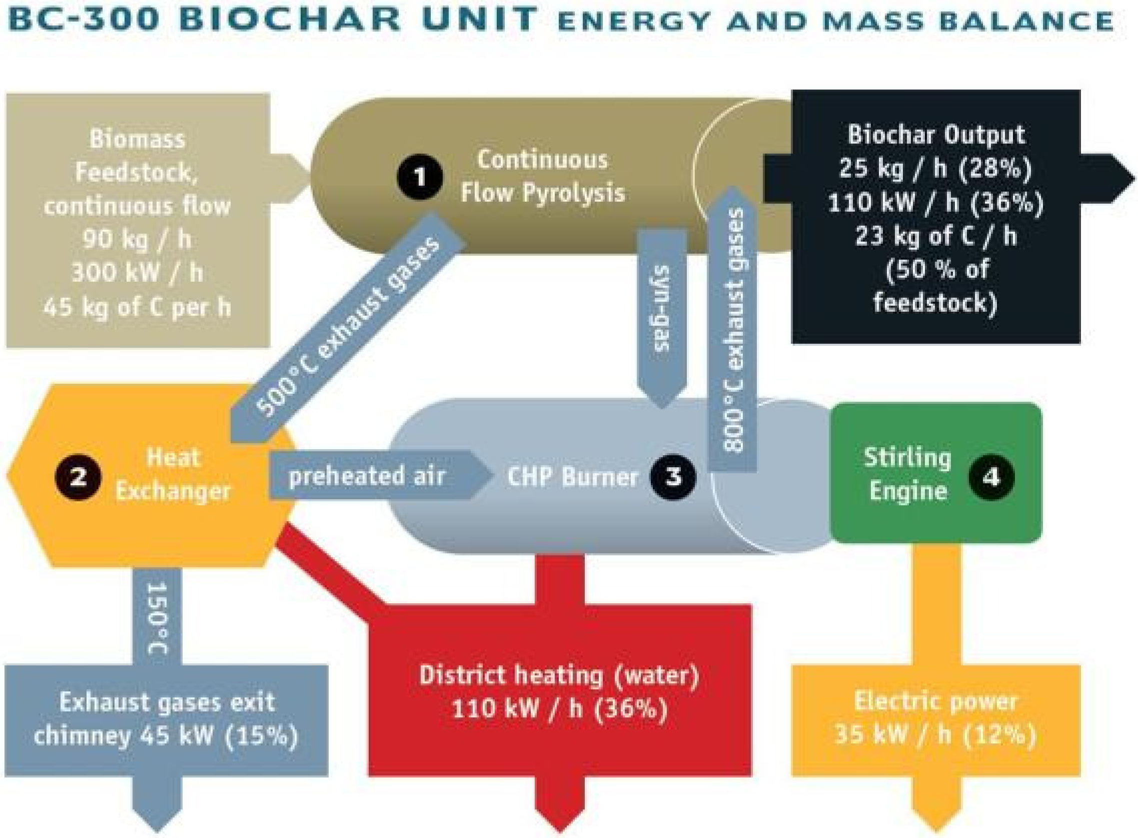


Figure 8: Process schematic of the BC-300 pyrolysis plant process.

7.2.1 Plant description

The pyrolysis unit has a length of approx. 6 meters and consists of two cylindrical chambers. The biomass is fed into the inner chamber and is moved through the pyrolysis unit by a screw conveyor.

Hot flue gases are led into the outer chamber, a process by which the biomass is slowly heated to 600° C. By not allowing any oxygen in the biomass chamber, no combustion takes place. Instead, the volatile part of the biomass leaves the pyrolysis unit in the form of pyrolysis gas. The non-volatile parts of the biomass leave the pyrolysis unit in the form of biochar. The biochar is collected in a container while the pyrolysis gas is led to a combustion chamber at the end of which a Stirling engine is attached.

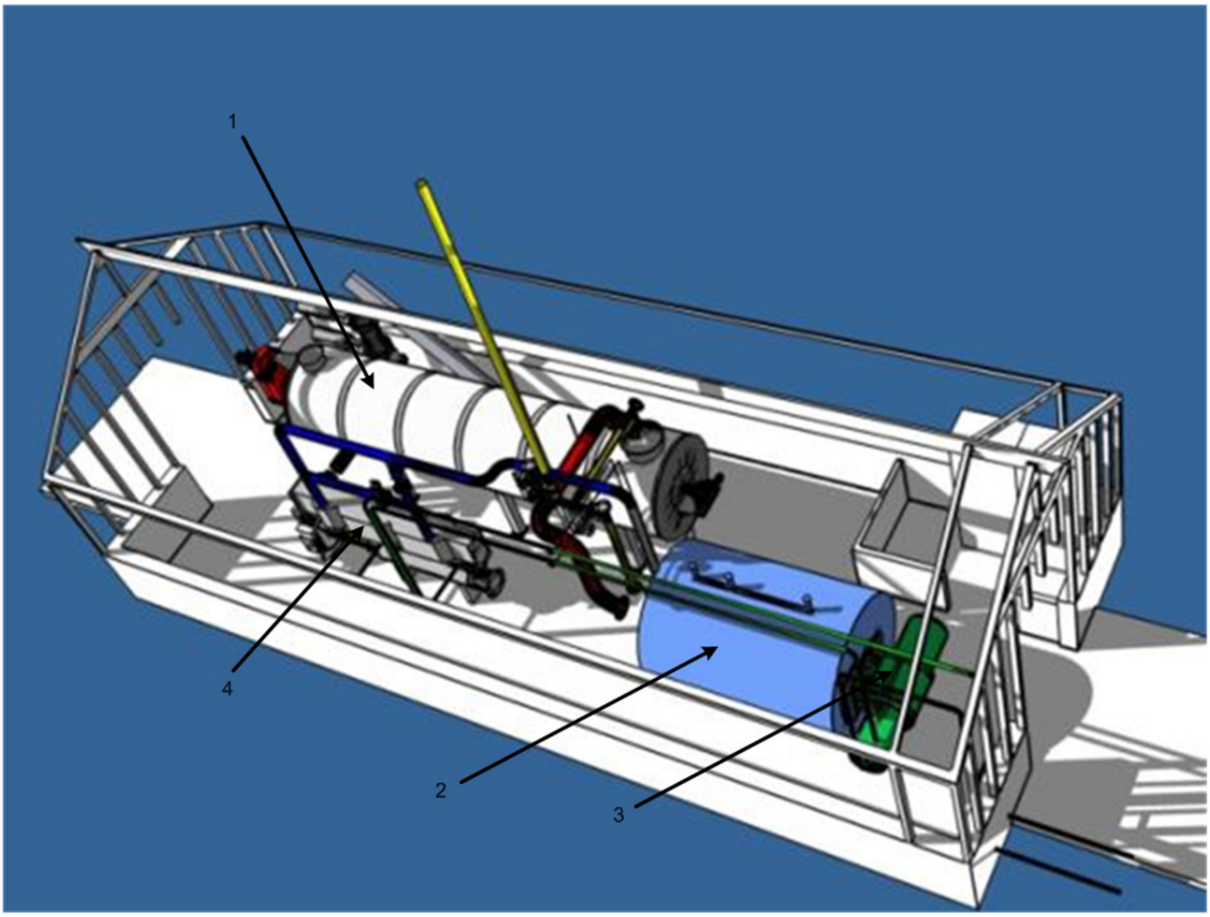


Figure 9: Plant layout of pyrolysis plant.
1… 300 kW pyrolysis unit, 2… Combustion chamber, 3… Stirling engine, 4… Combustion air pre-heater.

In order to obtain high overall electrical efficiency, combustion temperature should be as high as possible. In the combustion chamber, the hot pyrolysis gases are therefore mixed with slightly pre-heated air from the heat exchanger to ensure combustion temperatures of more than 1,200° C. The heater panels of the Stirling engine extract part of the heat of the flue gas. The Stirling engine then transforms the heat energy into electricity. In addition, district heating water is circulating through the Stirling engine thereby producing heat.

The flue gas leaving the combustion chamber is still hot (approximately 750° C). The remaining energy is used to heat the pyrolysis unit and the air pre-heater before it is sent to the chimney at a temperature level of approximately 130° C.

The process and instrumentation diagram (PID) is enclosed in appendix E.

7.3 The DTU plant

The updraft gasifier Stirling plant located at SDKs premises at the Danish Technical University (hereafter "the DTU plant") was build in 2009 and was in its original design similar to the containerized plant. Since then a number of modifications have been done in order to optimize the operation on the plant.

Picture 12: The DTU plant.

8 Operational experiences

To perform fuel test require a stable operation so that the results from the test can be compared to a steady operation scenario and further, so that test also can be performed in a steady operation and without plant shut downs during the test period. The following paragraphs describe the experiences gained from the process of achieving stable operation on each of the three plants included in the test runs.

8.1 Containerized plant

At the containerized plant no stable long-term operation was achieved on the gasifier throughout 2009. In the winter 2009-2010 there were issues with the wood chip container. As there was no anti-freezing measures taken the wood chips froze in the container due to the cold weather and thereby blocked the moving floor that pushes the wood chips into the first of the conveyors that goes to the gasifier. As no feasible solution to the problem was found there was no operation on the plant until the spring of 2010.

The gasifier was upgraded to latest standard in September and October 2010. The plant was restarted in the end of October 2010. Already in the first days of operation it was possible to operate the plant at nominal electrical power output. Figure 10 shows the heat and electrical power output of the plant during the night from the 30th to the 31st of October. The plant operated very stable around 35 kW electrical output and 84 kW thermal output from the Stirling engine. The thermal output of the total plant was around 180 kW.

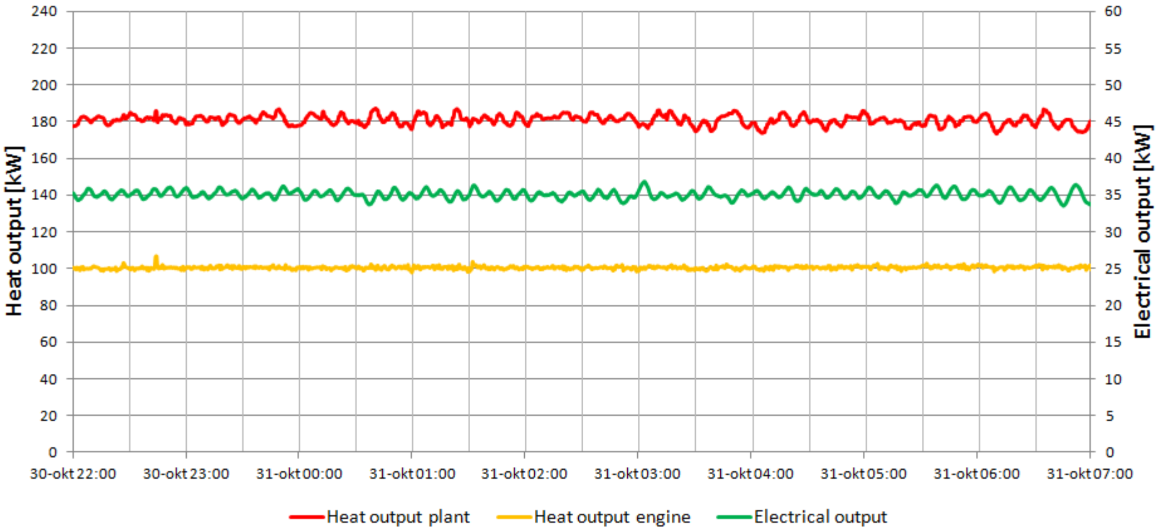


Figure 10: Heat and electrical output from containerized plant.
The heat and electrical output measured over a nine hour period in late October 2010.

In Figure 11 the average temperatures on the heater panels and cylinder heads of the Stirling engine as well as the cooling water temperature also during the night from the 30th to the 31st October 2010 is presented. The averages were calculated from several measurements around the heater and cylinder heads. The heater panel temperature was stable in the range of 700° C as well as the cylinder head temperature in the range of 630° C. The maximal allowed cylinder head temperature was 670° C, which indicates that there is still an optimization potential in the operation of the engine. The cooling water temperatures increased a little during the operation, due to the fact that the water flow through the plant was fixed and no set point was given for the cooling water at the economizer outlet. The temperature at the inlet of the Stirling engine was around 53° C and around 68° C at the outlet of the engine. The cooling water temperature at the outlet of the economizer was around 79° C.

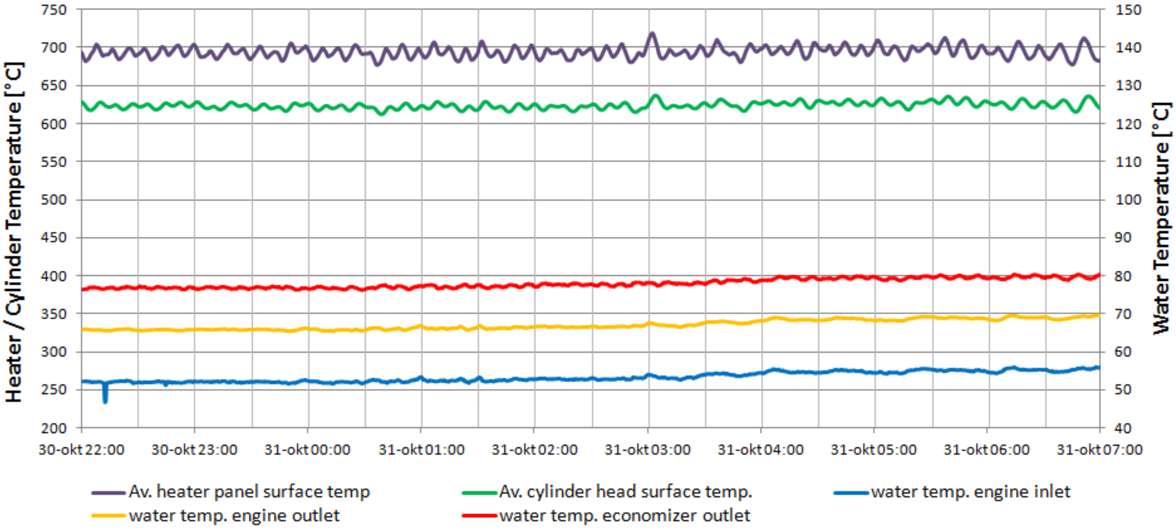


Figure 11: Cooling water, average heater and average cylinder temperatures on the containerized plant.
The average temperatures on the heater panels and the cylinder heads of the engine as well as the cooling water temperatures.

For the period shown in Figure 10 and Figure 11 an energy balance was performed. The results are shown in Table 3. The energy balance shows an overall efficiency of the plant of around 85 %. The reason for this was the high flue gas temperature of around 200° C at the economizer outlet. The electrical efficiency of the Stirling engine was calculated to about 29 %, which was higher than the nominal electrical efficiency of 28 %. This was the consequence of the low cooling water temperature at the inlet of the Stirling engine. However, due to the fact that the average heater heat temperatures were below the allowed 670° C there is still a potential to further increase the electrical Stirling engine efficiency. The overall electrical efficiency of the plant is 16 %, which is 1.5 % points lower than the nominal overall electrical efficiency of 17.5%. The reason for this is a problem with a bypass at the Stirling engine heater as well as minor efficiency problem of the combustion air pre-heater. Both issues were investigated and addressed. A new combustion chamber design has been developed and is currently being tested at the DTU plant. So far the results are promising.

input		
biomass	kW	218,5
output		
Stirling		
electric power output Stirling	kW	34,9
thermal power output Stirling	kW	83,4
plant		
thermal power output economiser	kW	68,4
total thermal power output	kW	151,8
efficiencies		
overall thermal efficiency	%	69,4
overal efficiency	%	85,4
electric efficiency	%	16,0
electric efficieny stirling	%	29,2

Table 3: Energy balance at nominal load for containerized plant.

8.2 The DTU plant

The gasifier was reengineered and updated in the beginning of 2010 and restarted in the end of April. A total amount of about 2.700 hours of successful operation were achieved. After a period without heat demand, the plant was restarted on the 23rd of September and is since this in continuous fully automated operation. In the first period of the operation several parameter investigations at reduced load were performed in order to verify the thermodynamic model of the gasifier and the overall plant. This was done without any focus in the achievement of a high electrical efficiency of the plant. Operation at increased load was started after the first 3 weeks and showed capacity problems at the installed economizer that finally prevented a full load operation of the plant. Finally the maximum possible load at this plant was 30 kW. An upgrade that will enable full load operation has been planned.

Figure 7 and 8 show the operating data from the 23rd of September until the 23rd of October. In this period 677 hours of continuous operation were achieved (720h are possible). Within the whole period a few stops of the plant occurred, due to some blockages in the feeding system. Beside this faults at the feeding system and the filling of the biomass storage as well as the emptying of the ash container no manual work was done at the plant. Consequently, the operation of the plant can be regarded as fully automated unmanned operation. In addition the plant can be operated remotely. The average electrical power output was 24 kW and the thermal power output was 135 kW. In total more than 16.3 MWh of electricity was fed to the grid. During this period the availability of the plant was more than 94%.

Figure 7 shows the thermal and electrical power output of the plant for the before mentioned period. The thermal power output changes with the overall load of the plant and is the sum of the thermal power output of the Stirling engine and the economizer. The electrical power output of the engine, which is the main set point for the power control of the plant, was varied during the operation between 15 kW and 30 kW. This was done as mentioned due to parameter investigations at the engine and gasifier. Figure 7 illustrates that the thermal power output of the engine is not connected to the electrical power output. The thermal power output of the Stirling engine is direct proportional to the helium pressure in the Stirling engine. The helium pressure was modified between 22 and 32 bar, which is corresponding to a thermal power output from the Stirling engine in the range from 75-95 kW. In the period from the 3rd to the 4th of October the plant was not able to follow the set point of 27 kW on the engine, due to a parameter investigation in the mixture between flue gas and air for the gasification agent that is supplied to the gasifier. These investigations reduced the product gas production of the gasifier and consequently reduced the electrical power output of the plant.

Figure 8 shows the average temperatures on the heater panels and the cylinder heads of the engine as well as the cooling water temperatures in 3 different places. The averages were calculated from the measurements on the 4 heater panels and 4 cylinder heads. During continuous operation the maximal allowed cylinder head temperature was 670° C. The set point for the temperature of the cooling water at the economizer outlet was 82° C. The control system has been improved during the operation, which resulted in quite stable cooling water feed temperature at the end of the period. In the beginning the cooling water temperature at the inlet of the engine was in the range of 65° C, which is the highest acceptable temperature for continuous operation. In the end of the period the cooling water temperature changed during the day between 50° and 65° C. Important in this respect is that a lower cooling water temperature results in a higher electrical efficiency at the engine as well as in higher overall electrical plant efficiency.

input		
biomass	kW	180,0
output		kW
Stirling		
electric power output Stirling	kW	24,0
thermal power output Stirling	kW	77,1
plant		
thermal power output economiser	kW	58,4
total thermal power output	kW	135,5
efficiencies		
overall thermal efficiency	%	75,0
overal efficiency	%	89,0
electric efficiency	%	13,3
electric efficieny stirling	%	23,5

Figure 9: Energy balance for the average operation of the plant DTU (23rd September – 23rd October)

The overall electrical plant efficiency for the whole period was calculated to around 13%, as shown in the energy balance in figure 9. Due to the fact that this was achieved in part load operation it is an acceptable result. Moreover there was no focus to operate the engine at the highest efficiency. Due to this the helium pressure was not optimized for the present load. This finally resulted in lower average heater and cylinder temperatures. Consequently the average engine efficiency was at about 23.5% which is quite low compared to the nominal electrical efficiency of 28%.

During the operation of the plant ash samples were taken in regular intervals. Some ash samples were analyzed. The ash was a fine powder without agglomerations, during the whole period. The carbon content in the ash was determined to below 5 wt% of the total ash on dry base.

Additionally flue gas emission measurements were performed by FORCE Technology. The measurements showed 190 mg/Nm^3 CO, 150 mg/Nm^3 NOx, 5.2 mg/Nm^3 TOC (total organic carbon) and <5 mg/Nm^3 for particle emissions (all measurements are related to dry base and 10% O2). Consequently, the emissions are within typical emission limits. After the measurements it has been determined that the CO emissions in the flue gas could be further reduced with some small adaptations to the burner (further tests will follow). Very interesting are the extremely low dust emissions, of less than 5 mg/Nm^3, which were achieved without any flue gas cleaning system. The reason for this is manly the updraft gasification process. The biomass in the gasifier acts like a filter for the product gas and most of the dust and aerosol formatting elements remain in the gasifier and can be taken out with the gasifier ash. This was verified with chemical analysis of the gasifier ash that was compared with a typical chemical composition of grate ash from direct combustion plants.

8.3 Pyrolysis plant

The BC300 is the first of its kind – a prototype combining the Stirling engine with pyrolysis technology. The operational experiences of the plant have been a typical prototype process with many challenges in achieving the optimal operation of the plant. The main challenges have been as follows:

8.3.1 Feed in system

The plant runs mainly on waste wood (from wooden boxes and disposable pallets) and wood chips. There have been problems with jams in the feed in screw, which has been solved by using a stoker screw, feeding the pyrolysis screw from the top instead of pushing it in from the side of the pyrolysis screw.

8.3.2 Product gas pipe

Tar depositions have jammed the product gas pipe. The pipe is too narrow and too long and runs vertical with no inclination at all. This all contributes to the deposition of tar, which otherwise would have been transferred to the combustion chamber and burned.

8.3.3 Biochar screw

At the end of the pyrolysis-screw the carbonized biomass drops into at small box with a horizontal screw and from there into a screw transporting the biochar to a container. Problems due to jams in the screw are now solved.

8.3.4 Leakage of helium

There has been a leakage on the helium circuit on the Stirling engine. In order to repair this the heater panels on the Stirling engine have been replaced.

8.3.5 Combustion chamber

In the BC300 you want a feed-back loop of the hot flue gases from the combustion chamber back to the pyrolysis screw. As is for now, the combustion chamber draws in "false" air in the return of flue gases to the screw, reducing the temperature of the flue gas. This is currently being dealt with, that further results in problems to supply the needed temperature gradient between the flue gas and the pyrolysis screw system.

8.3.6 Electrical output

It has been a challenge to reach a satisfying electrical output. This was supposedly due to higher water content in the feedstock and the low density in the waste wood. Test runs with dried wood chips, however did not solve the problem, probably because the lower water content increased the tar deposition in the product gas pipe. If it would be possible to increase the fuel flow into the screw the effect would presumably rise.

The problems have been solved along the way, and a re-design of the plant would take these experiences into consideration. Due to the many challenges the number of operational hours is less than expected, and only three preliminary feedstock tests have been carried out. The plant has run 3,000 hours in total (over a three year period) and not the expected 6,500 hours per year. For elaborated description of operational experiences see appendix F.

9 Selection of fuels for test runs

FORCE Technology was responsible for the analysis and selection of fuels for the test runs. In the initial project plan the following preliminary list of candidate fuels for the test runs were stated:

- Wood chips
- Waste wood fraction e.g. scrap (demolition) wood from buildings
- Energy crops
- Straw
- Lignin
- Bio-oil / pyrolysis oil
- Glycerine
- Coconut shells
- Rice shells
- Olive residues such as pruning, pits and other
- Wine residues such as pruning and other
- Palm tree residues
- Algae

In co-operation with SDK and the rest of the project partners, criteria, options, advantages and disadvantages with different fuels, both from the preliminary list and others were discussed and assessed in detail. A methodology were developed, where fuel options were assessed according to a range of criteria, and following the positive identification of candidate fuels, a technical and market report on each fuel was developed.

9.1 Criteria for selection of fuels

A series of criteria was set up for the screening of fuels for the test runs. The purpose was to make sure that the relevant properties were evaluated in order to support successful test runs and as far as possible the opportunity for a successful market introduction.

The criteria were divided into three groups:

- Market relevance criteria
- Economic criteria
- Technical criteria.

The market relevance criteria aim at identifying fuels, which are available in markets, where the Stirling technology has a good chance of success because favourable framework conditions exist such as support schemes, feed-in tariff etc. Example: olive residues may seem like a good choice, but if the residue is only available in countries with unfavourable economic conditions for small scale CHP units, then the choice is not so obvious. A simple 5 star rating system was introduced, where 5 identifies a highly relevant market, and 1 means the fuel is not available in necessary volumes at a compatible price. 0 (zero) means the fuel is not available at all. Further, a general assessment of the availability of the resource ("volume" in the table) was made on an overall/global level and in comparison to the other fuel options.

Economic criteria simply rank the fuels according to the anticipated price in the most obvious markets. Again, a simple 1 to 5 star rating was introduced, where 5 means a fuel with an in comparison low cost, and 1 is a fuel which in comparison is expensive.

The technical criteria evaluate the fuels according to their technical properties, using a rating system where 5 is best and 1 may mean serious technical obstacles. The following technical issues were evaluated:

- Foreign materials - for transport systems, the gasifier, ash transport systems etc. it is essential to avoid materials such as stones, nails etc. from a purely technical point of view. Also various plastic pieces, painted pieces and otherwise contaminated fuels may comprise as well technical as legal problems
- Trace elements in the fuels should be avoided as this leads to emissions and to contamination of ashes from the plant. Trace elements may originate from the biomass material uptake of e.g. cadmium during the growth in forestry, agriculture or plantation, or it may result from contamination such as paint or impregnation in demolition wood.
- Ash melting temperature should generally be high in order to avoid slagging and deposition of sticky ash materials on surfaces in the gasifier, furnace or heater. Fuels with a low ash-melting point and large content of ashes might not be suitable for updraft gasification because the ashes will deposit and form slag inside the gasifier. These types of fuel could possibly be pyrolyzed instead. In this process the fuel is heated to approx. 650° C in an oxygen-depleted atmosphere. This creates a combustible pyrolysis gas with low ash content which is burnt in front of the Stirling engine.
- The amount of ash should be low, as this reduces problems with depositions first of all in the heater section, where it would lead to reduced heat transfer and thus lower electric efficiency.

Table 4 and Table 5 show the result of the evaluation of fuels versus selection criteria in a matrix format. The two tables serve as a support tool in the selection of fuels, thus focus has been on identification of specific advantageous or disadvantageous fields and no attempt has been made to evaluate all criteria for all fuels. A few fuels, which were recommended in the early stages of project development but never assessed in detail, are kept in the table for future reference.

Fuel	**Low price**	**Technical feasibility**			
		Few foreign elements	**Low trace elements**	**High ash melting temperature**	**Low amount of ash**
Forest wood chips (reference)	3	5	4	4	4
Energy crops – willow	2	5	3	4	3
Energy crops – miscantus	2	5		3	2
Straw (wheat)	4	5	5	1	1
Lignin		5			
Palm kernel shells	2	4			4
Rice husks	3	4		3	1
Coconut shells		4			
Olive residues (kernels)	3	4			
Wineyard prunings		4			
Sugar cane residues					
Demolition wood	4	1	1	4	4
Cocoa nut shells					
Coffee shells					
Algae	1				
Bio-oil - rape seed oil	1	5			5
Bio-oil - fish oil		5			
Bio-oil - animal fat (seals)		5			
Bio-oil – glycerine	2	5			2
Bio-oil - used frying oil					
Pyrolysis oil	1	5			
Waste oil	5				

Table 4: Assessment of fuel options versus cost and technical selection criteria.

Fuel	**Market relevance**							
	DK	**EU**	**Canada**	**SE Asia**	**IT**	**DE**	**UK & IE**	**Volume**
Forest wood chips (reference)	5	4	3	3	3	5	2	4
Energy crops – willow	2	2					4	2
Energy crops – miscantus	1	1					4	
Straw (wheat)	4	4				4		5
Lignin								
Palm kernel shells			0	5		0		5
Rice husks and straw			0	5	3	0		4
Coconut shells			0	3		0		4
Olive residues (kernels)			0		4	0		3
Wineyard prunings	0	3	0	0	5	2	1	4
Sugar cane residues			0	3	0	0	0	4
Demolition wood	4	4			4		5	5
Cocoa nut shells								2
Coffee shells								2
Algae	1	1	1	2	1	1	1	1
Bio-oil - rape seed oil	3	3				4		4
Bio-oil - fish oil								2
Bio-oil - animal fat (seals)								1
Bio-oil – glycerine		4						3
Bio-oil - used frying oil								2
Pyrolysis oil								1
Waste oil								3

Table 5: Assessment of fuel options versus market relevance criteria.

Based on the above analysis 8 fuels were selected for further studies and possibly test runs: wood chips, willow, wheat straw, rice straw, olive residue, pyrolysis oil, rape seed oil and glycerine.

9.2 Specification of fuels

9.2.1 Fuel factsheets

In order to support the final selection process for fuels for the test runs, a series of fuel factsheets were prepared. The purpose of the fuel factsheets is to be able to assess the selected fuels based on combustion related parameters as well as market price and estimations of availability and potential. The assessment of the selected fuels is part of demonstrating the fuel flexibility of the Stirling technology in off-grid applications with various nationally available fuels.

9.2.2 Content and extent of factsheets

Combustion performance is related to the physical and chemical characteristics of the fuels. The physical characteristics account for the exterior quality of the fuel, such as the particle size, impurities, manufacturing influence, transportation and storage and etc. The chemical characteristics of the fuels account for the interior quality of the fuel, such as species, composition and concentration, heating value, water content, ash content, viscosity etc. Applied quality standards are specified in the factsheets for the relevant fuels, if the standards are referenced in terms of trading. Price and availability estimations are carried out on a national level and focuses primarily on the Danish, Italian, German, Austrian and British market based on the above assessments of market opportunities.

The factsheets are prepared as reference sheets, which can be used to assess the selected fuels based on common fuel properties, and to compare the fuels with each other both in terms of expected combustion performance and cost and availability in different national markets. Specific properties of the fuels are included in the factsheets where they are considered to influence the technical possibilities and obstacles, including the gasification/combustion performance of the Stirling engine.

9.2.3 Data search methodology

The content of the factsheets is primarily based on reviewed literature, published reports from Danish and European organisations, conference presentations and practical experience from the project participants. The level of detail is selected in accordance with the purpose of the factsheets, namely to be able to do an assessment of the fuels based on common fuel properties and market estimations.

9.2.4 Basis of the factsheets

Headings and content of the factsheets are selected with the intention to specifically assist the assessment of the fuel flexibility of the Stirling engine technology. The factsheets may therefore not be sufficiently comprehensive to assess the fuels in regards to other combustion or similar processes than the Stirling technology.

9.2.5 Summary of fuel factsheets

The individual fact sheets prepared by FORCE Technology are enclosed as appendices to the report.

Appendix G: Wood chips
Appendix H: Willow
Appendix I: Wheat straw
Appendix J: Rice straw
Appendix K: Olive residue
Appendix L: Pyrolysis oil
Appendix M: Rape seed oil
Appendix N: Glycerine

The factsheets are summarised in Table 6 (solid fuels) and Table 7 (liquid fuels) which shows selected combustion parameters etc. The tables also include market price and availability assessments.

Solid fuels					
	Woodchips	**Willow**	**Straw**	**Rice straw**	**Olive residue**
Physical					
• Homogeneity	Hom.	Hom.	Inhom.	Hom.	Hom.
• Transportation and storage	Partly stable (composting)	Partly stable (composting)	Stable if dry	Partly stable (composting if wet)	Partly stable (composting)
• Applied quality standards (trading)	Factsheet 160 (Centre for Biomass Technology) EN 14961	None	Factsheets (Centre for Biomass Technology), EN 14961	None	None
• Possible impurities	Soil, sand, rocks	Bark, soil, sand, rocks	Soil, stones	Soil	Nickel from manufacturing
Chemical					
• Heating value MJ/kg, dry basis	18.4 - 19.8	17.7 - 19.0	15.8 - 19.1	15.3	18.1 - 20.7
• Water content, %	35 – 60	30 - 55	10 - 25	Dried: < 17	6 - 24
• Ash content %, dry basis	1	2	2 - 10	12 - 20	10
• Composition %, dry basis ▶ Carbon, C ▶ Hydrogen, H ▶ Oxygen, O ▶ Other	 50 6.3 43 -	 48 6.1 43 S: 0.05; Cl:0.03	 47 6 41 Cl: 0.4	 41.8 4.6 36.6 S: 0.08; Cl: 0.34	 50 6.9 30 S: 0.2; Cl: 0.2
Market					
• Price, €/GJ					
▶ Highest	UK: 9.4 - 10.5	IT: 6.7	DK: 7.0	No market in Europe	No info
▶ Lowest	DK/DE : 6.5	DE: 3.8 - 5	DK: 5.0		
• Availability	DK/IT/DE/AU	As grown (projects)	EU	IT	IT

Table 6: Summary of properties for selected solid fuels

Liquid fuels			
	Pyrolysis oil	**Rapeseed oil**	**Glycerine**
Physical			
• Homogeneity	Inhomogeneous	Homogeneous	Homogeneous
• Transportation and storage	Unstable (phase sep.)	Stable (prevent heat)	Stable (prevent cold)
• Applied quality standards (trading)	None	RK – Qualitäts-standard	USP, EP
• Possible impurities		Phosphorus, plant residues	Sodium from catalyst
Chemical			
• Heating value MJ/kg, dry basis	16	37	16- 20
• Water content %	15 – 30	< 0.075	0.5 - 15
• Ash content %, dry basis	0 - 0.3	0.01	2 - 3
• Composition %, dry basis			
▶ Carbon, C	56	-	39.1
▶ Hydrogen, H	6	-	8.7
▶ Oxygen, O	38	-	52.2
▶ Other	-	Triglyceride	Na: 1 (crude)
Market			
• Price, €/GJ			
▶ Highest	No market	25.5	9.4 - 11.4
▶ Lowest		-	-
• Availability	Pilot plants	Widely in EU	Widely in EU

Table 7: Summary of properties for selected liquid fuels.

9.2.6 Conclusive remarks on fuel assessments

Based on the research for the fuel fact sheets, the above summary tables and discussions in the project group, the following remarks regarding the suitability of the individual fuels can be concluded:

Wood chips are the reference biomass fuel, available in most places, and with relatively modest technical problems. Comparatively, the price of wood chips may be higher than other solid fuel options.

Willow chips may offer lower prices, if support schemes apply or under favourable growing conditions. Technical problems to be expected with a fuel lower density in the gasifier, and with a - depending on the chipping machine used - higher tendency for creation of "bird nests" in the fuel transport lines.

Wheat straw is less costly than wood fuels, but offers new challenges with fuel transport, low density in the gasifier and with the high amount of ash to be handled in the gasifier and in the heater section as transported with the gas.

Rice straw seems to be prohibitively difficult to handle because of the extremely high content of ash. Further there is risk of corrosion and mechanical wear.

Pyrolysis oil may look attractive, but it is not homogeneous, and it will be available at a low price only in certain specific conditions.

Rapeseed oil will offer less technical problems than other liquid fuels and is widely available. The main problem is that it will be too expensive in most cases.

Glycerine is widely available and likely to offer small technical problems. The price may be around twice that of solid fuels, but the plant design will be significantly simpler.

9.3 Fuel procurement

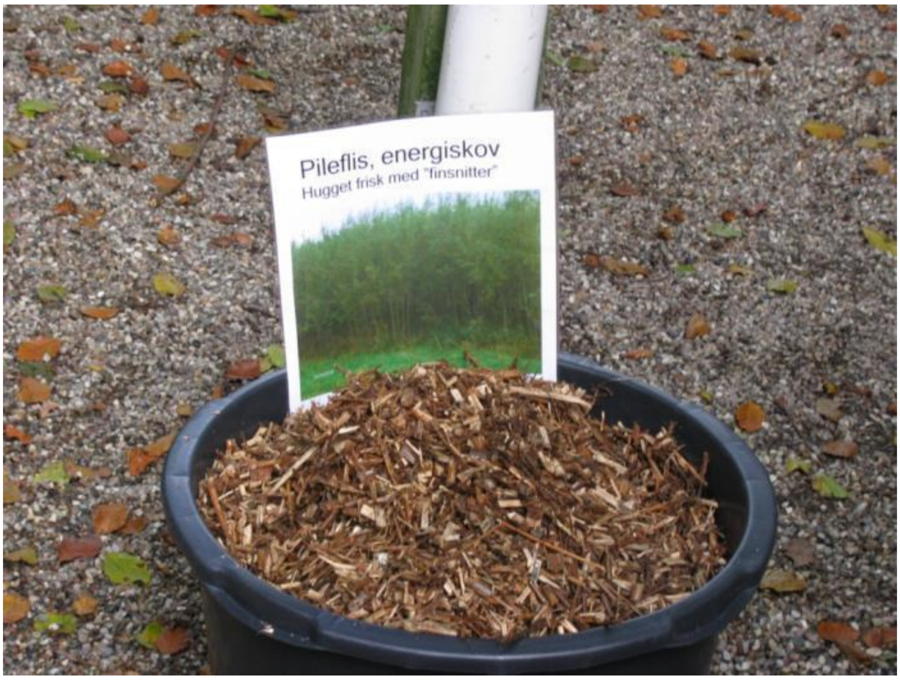
FORCE Technology was responsible for procurement of fuels for the test runs. Calculations of necessary fuel amount for each fuel are shown in Appendix O. In practice SDK took charge of fuel purchase in most cases, while FORCE especially for the willow test runs spent time on fuel specification and purchase.

For wood chips made from willow, special consideration is needed to ensure that moisture content is not too high, that long flexible pieces are few so that blocking in transport augers etc. are avoided, and that the amount of small size particles are low in order to ensure free flow of air and gas in the gasifier.

SDK has specified requirements for wood chips used in the gasifier according to Ö-norm M7 133 from Austria as follows:

Size: G50 (max. 20% less than 6 mm, max length 12 cm and other size restrictions)
Moisture content: W40 or W50 (between 35 % and 50 % moisture)
Material density: S250 (min. 250 kg pr. loose m^3)
Ash content: A1 (max. 1 % ash on fuel weight basis)

Two suppliers of willow fuel were identified, pictures and samples were acquired and analysis data and other observations from other energy plant using the same supply were collected through interview. HedeDanmark were chosen as the preferred supplier.



Picture 13: Willow chips supply from HedeDanmark.
The willow chips were made from freshly harvested material using in fine chopper equipment.

10 Test runs

10.1 Wood chips reference test (Amager)

A reference test run was performed at the containerized plant with wood chips as fuel. The test programme can be seen in appendix O.

Flue gas emission measurements were performed by FORCE Technology (accredited by DANAK in measurement of air pollution within air emissions, outdoor air quality and occupational environment). The measurements showed 120 mg/Nm³ CO, 110 mg/Nm³ NOx and 6.0 mg/Nm³ for particle emissions (all measurements are related to dry base and 10% O2). Consequently, the emissions are within typical emission limits. The test report is enclosed as appendix P.

In the test report is also included an analysis of the wood chips used at the test. Based on the results from the fuel analysis and the data from the plant PLC an energy balance is set up for the period of the flue gas measurements (13th April 2011, 10am to 4pm). The data from the plant PLC includes:

- Data from the weighing cells on the fuel container
- Process temperatures
- Water flow on the cooling water system.

The results of the energy balance are shown in Table 8.

The energy balance is not a closed balance as the mass flow of the flue gas out of the chimney and the mass flow of the ash out of the bottom of the gasifier are all unknown. These are the main unknown mass flows however; also the mass flow of ash and unburned fuel in the flue gas is not included in the energy balance. Even so the when comparing the calculated fuel consumption with the one measured by the weighing cells the difference is relatively small (6.5 %) which shows that the energy balance, even though the mass balance is not closed, is reliable.

The energy balance shows an electrical efficiency of 12.5 % which is a lot lower than the expected which is 18 %. This is mainly due to the fact that the heat transfer from the hot flue gas to the Stirling engine's heater panels is not optimal. Therefore, a higher amount of energy is left in the flue gas downstream of the engine. This so-called blow-by issue has been addressed by SDK in the new design of the combustion chambers which is used for Stirling plants since the fall of 2011. The thermal power output is a little less than the expected 140 kW and so the excess heat in the flue gas is not utilized for extra heat production, but is lost as a part of the 28.8 kW of heat loss from the plant.

Overall energy balance and efficiencies		
Input		
Biomass	kW	192.3
Air burner	kW	0.1
Air gasifier	kW	0.0
Total input	kW	192.4
Output		
Power output		
Helium pressure Stirling	bar	21.0
Electrical output, Stirling engine	kW	24.0
Thermal power output, Stirling engine	kW	81.9
Thermal power output, economizer	kW	56.5
Thermal power output, total	kW	138.5
Total output, thermal and electrical	kW	162.5
Heat losses		
Heat loss, Stirling engine	kW	1.0
Gasifier	kW	0.8
Combustion chamber	kW	3.8
Air pre-heater	kW	0.5
Gas pre-heater	kW	0.3
Economiser	kW	1.3
Flue gas (chimney)	kW	21.1
Total heat losses	kW	28.8
Total power output	kW	192.4
Efficiencies		
Overall thermal efficiency	%	72.0
Overall efficiency	%	84.4
Electric efficiency	%	12.5
Electric efficiency, Stirling engine	%	22.4
Verification of energy balance		
Total thermal power output (calc)	kW	138.5
Total thermal power output (plant)	kW	142.3
Difference	kW	3.8
Difference	%	2.0

Fact sheet		
Input		
Biomass	kW	192.3
Biomass	kg/h w.b.	89.5
Output		
Helium pressure Stirling	bar	21.0
Water inlet	℃	51.0
Water outlet	℃	72.0
Cylinder heat temp	℃	656.0
Delta max/min	℃	50.0
Flue gas Stirling outlet	℃	680.8
Electric power output Stirling engine	kW	24.0
Thermal power output Stirling	kW	81.9
Plant		
Thermal power output economiser	kW	56.5
Total thermal power output	kW	138.5
Efficiencies		
Overall thermal efficiency	-	72.0%
Overall efficiency, heat and power	-	84.4%
Electrical efficiency, plant	-	12.5%
Electrical efficiency, Stirling engine	-	22.4%
Biomass weighing		
Start time	h	10:00
End time	h	16:00
Runtime	h	6.0
Start weight	kg	11190
End weight	kg	10686
Used biomass	kg	504
Verification of calculation		
Biomass calculated	kg/h	89.5
Total biomass calculated	kg	537
Result from weighing cells	kg	504
Difference	kg	33
Difference	-	6.5%

Table 8: Overall energy balance and efficiencies.
Reference test with wood chips 13/04/2011 at the containerized plant.

10.2 Willow (containerized plant)

10.2.1 Observations during test run

20 m^3 equal to app. 7.0 tonnes of willow chips was delivered to the containerized plant at Amagerforbrændingen on 10th May 2011 and the plant was started up at app. 2pm. A sample of the willow chips can be seen in Picture 14.

The following observations were recorded during the two-day test:

1. No alarms from the plant PLC (e.g. no operational problems were registered by the plant control system)
2. No problems with feed in of fuel to the gasifier except from a fault on the fuel leveller in the top of the gasifier towards the end of the end of the test run
3. Difficulties in achieving set point for electrical output of 26 kW
    - a High vacuum in combustion chamber
    - b Low temperature in combustion chamber
    - c High level of O2 in flue gas
4. From app. 0am 12th May in the morning electrical output dropped to <10 kW
5. 5pm 12th April the plant shut down.

Picture 14: Sample of willow chips from test run.

10.2.2 Analysis of observations

The observations described under point 3 indicate a blockage in the product gas pipe that goes from the gasifier to the combustion chamber. This would cause that the flue gas blower that draws the product gas from the top of the gasifier through the product gas pipe, into the combustion chamber, through the combustion air pre-heater, gasification air pre-heater and the economizer cannot suck a sufficient amount of product gas to the combustion chamber. Hereby, the set point for the temperature in the combustion chamber cannot be reached and the amount of heat transferred to the heater panels of the Stirling engine is not sufficient for the engine to reach the set point for the electrical output – in this case 26 kW.

10.2.3 Inspections after test run

When the containerized plant was demounted prior to removal from Amagerforbrændingen the gasifier and product gas pipes were inspected. In Picture 15 and Picture 16 it can be seen that the assumption regarding the blocked product gas pipes was correct. The two pictures are taken into the product gas pipe which has been connected to the product gas outlet on the gasifier. The pipe is filled with an almost solid mixture of tar and particles from the willow chips with almost no area for the product gas to pass through.

Picture 15: Blocked product gas pipe after willow chips test run

Picture 16: Blocked product gas pipe after willow chips test run

When taking of the top plate of the gasifier another issue with the quality of the willow chips was revealed. Long tweaks of willow had coiled up around the fuel leveler in the top of the gasifier. The leveler is designed as a form of rake-like rotating device that detects the height of the fuel in the top of the gasifier. The electrical motor that drives the leveler has a power relay so that the leveler stops rotating if it feels resistance e.g. when the height of the fuel inside the gasifier is satisfactory. When the leveler stops a signal goes to the control system that fuel feed system shall stop. Some of the tweaks that were removed from the top of the gasifier can be seen in Picture 17.

Picture 17: Willow tweaks that had coiled up in the gasifier during test run.

10.2.4 Conclusive remarks

As SDK has never tried to use willow chips as a fuel on an updraft gasifier plant the focus on the test run was to investigate whether willow is a suitable fuel for this kind of plant from a practical point of view. Therefore investigations into the performance of the plant (electrical and thermal output and efficiencies) were not carried out.

From the test run with willow as a fuel it can be concluded that willow can be converted to product gas in the gasifier and that the product gas can burned in the combustion chamber. However, the quality including the size distribution of the willow chips is critical. In the batch of willow chips for the test run both a high amount of fine particles (dust) and a number of long flexible tweaks were present. This is not tolerable for a fuel for a Stirling plant with an updraft gasifier.

10.3 Test runs at pyrolysis plant

Three preliminary test runs on feed stocks have been carried out at the BC300: waste wood, wood pellets and straw pellets. The test runs were preliminary in the sense that they gave a rough indication of the feed stock quality, but the tests were run over a short period (7-16 hours), with a fairly small amount of feed stock and unknown water content in the feed stock. The variables logged in the tests were power production, biochar production, temperatures in and out of the pyrolysis screw and gas temperature. Also logged is Delta T as the difference between flue gas temperature at the inlet and flue gas temperature at the outlet, and signifies how much energy is delivered to the biomass. This is positively correlated to the power production. The biochar produced from wood waste and from straw pellets was analyzed for carbon and nutrient content. The plant needs to start up on fuel oil to reach at temperature sufficient to produce the syngas and start the feed back loop. Therefore approximately the first two hours of the test runs are fuelled by fuel oil.

The two pelletized feedstocks showed the best performance concerning electrical output and biochar production, probably due to the lower water content and the higher density compared to the waste wood. There were no problems of jamming in neither of the test runs, but generally the pelletized feedstocks cause less trouble than the chipped feedstocks.

Below a summary of the findings from the three test runs is presented. For further details see appendix P.

10.3.1 Dry wood residues

The waste wood feed stock is based on chipped wooden boxes and disposable pallets from Aarstidernes production. The feed stock is characterised by a water content of 20-25 % (estimated), and low density (146 kg/m^3). During the test the electrical output was 10-15 kW, and the syngas temperature between 400 and 500° C. The low electrical output is not satisfying, and is probably caused by a higher water content compared to other feed stocks and the low density, which makes it difficult to feed in sufficient feed stock to the pyrolysis screw. The relatively high density of the biochar produced indicates that the biomass has not been completely pyrolyzed. The carbon content was high, 92 %, and the nutrient content low (phosphorous (P) 0.21 kg/ton, potassium (K) 2.3 kg/ton).

10.3.2 Wood pellets

The wood pellet feedstock is dried and pelletized sawdust with a water content of 6-8 % and a density of 690 kg/m^3. During the test the electrical output was 15-20 kW, and the gas temperature is steady rising reaching almost 600° C. The density of the produced biochar indicates a more porous structure of the biochar, which is desirable.

10.3.3 Straw pellets

The straw pellets has a density of 682 kg/m^3, water content unknown but estimated to be around 10 %. During the test run the electrical output was steadily rising from 15-20 kW and the gas temperature rising from 450 towards 550° C. The biochar produced has the lowest density of the three test runs indicating a porous structure. Carbon content was lower than the wood pellets (75 %), but the nutrient content higher (P: 1.2 kg/ton; K: 35 kg/ton).

11 Conclusion

In the project a containerized combined heat and power plant including a 200 kW updraft gasifier and a 35 kW electrical output Stirling engine was designed, the specified components were procured, the plant was installed in the three containers and the plant was erected at Amagerforbrændingen ready for the COP15 in November 2009. SDK established a visitor's centre next to the containerized plant and the plant has served as a showcase displaying the Stirling technology itself but also an example of green Danish technology for the rest of the World.

The potential of operating the Stirling engine in island-mode (without grid connection) was investigated by mathematical modelling. With an internal helium compressor the engine is able to change the load from 100% to 50% in 20-30 seconds and the demanded size of the battery system can be much smaller compared to a set up where the engine is only operated in on/off mode. The modelling shows that control of power output of the 35 kW Stirling engine can be made by introduction of a compressor piston, and that the time for decrease and increase of power is satisfactory to adapt to the transient behaviour of the biomass combustion system. Island mode operation was not tested in practice.

Using an absorption cooling plant connected to the Stirling CHP plant was also investigated. A technical feasibility study was undertaken and it was concluded that from the two available technologies (water/LiBr and Ammonia/water) the appropriate choice is depending on the required cooling temperature. The water/LiBr technology offers better performance in case that the water consumption due to the use of a cooling tower is not an issue, while the ammonia/water technology is necessary if the chiller is air cooled. If cooling has to be delivered at a temperature below 0° C, the ammonia/water unit is the only possible solution.

A practical test of an absorption cooling plant driven by the heat produced by the Stirling CHP plant was not undertaken as the investment of a cooling plant was found too high compared to the value of testing a proven technology such as absorption cooling.

The test of a desalination plant was also included in the objective of the project. As it is the case for the absorption cooling plant it was assessed that the value of the possible new knowledge gained by a practical test of this also proved technology does not justify the investment of the plant.

Test runs focussed on investigating the fuel flexibility of two different configurations of Stirling engine CHP plants were carried out – respectively the updraft gasifier plant (the containerized plant and the DTU plant) and the pyrolysis plant (the plant situated at Barritskov). In order to perform these test runs a stable operation is required. On both the containerized plant and the pyrolysis plant this proved to be more challenging than expected and therefore the number of fuels tested was limited to willow chips at the containerized plant and dry wood residues, wood pellets and straw pellets on the pyrolysis plant. In general all the fuels it proved to be possible to operate the plants, however different issues mainly related to the quality of the fuels were encountered. And so it can be concluded that the fuel specification and the quality of the fuel is critical for the operation of both the updraft gasifier plant and the pyrolysis plant.

A comprehensive desktop evaluation of the feasibility of selected fuels was also carried out. Based on the evaluation an overall remark is that the price and the quality of a fuel are correlated i.e. the higher price the less expected technical problems and vice versa. A fact sheet for each of the selected fuels was prepared and is enclosed in the report.

12 Outlook / Prospects of the project

To conclude this final report a brief outlook for the Stirling engine CHP technology within the technical development and market strategy of SDK is presented.

Currently SDK is commissioning two 4 Stirling engine updraft gasifier CHP plant in the UK. These two plants are the result of SDK's efforts with regards to both technical development of the Stirling CHP technology based on updraft gasification and sales strategy employed by SDK. The two plants are both sold to a British ESCO (Energy Service Company) contractor and installed at a supermarket in order to cover the energy consumption of the supermarket.

These two projects also represent the market strategy of SDK which is to liaise with partners that have an established client network in the countries that have the most advantageous financial framework for small scale CHP and which are located within a reasonable distance from Denmark.

The Stirling engine CHP technology holds a unique market position as no other renewable CHP technology in the range up to 200 kW electrical output is available. Currently, the main challenge for SDK is to achieve stable operation in the range of a diesel genset (~6,000 hours of annual operation). However, no irresolvable technical issues with regards to the overall design and performance of nor the Stirling engine itself or the latest Stirling CHP plants have been met.