



Bioliquids-CHP
Power generation from Biomass

**Main Project
Results**
2011

Summary

This brochure presents an overview of the main project achievements and highlights some conclusions and perspectives towards future development. The full title of this collaborative project was : Engine and turbine combustion for combined heat and power production. More information, publications and reports are available at the project website: www.bioliqids-chp.eu

PROJECT OBJECTIVES AND APPROACH

The Bioliqids-CHP project was set up to reduce the technical barriers preventing the use of advanced bioliqids in prime movers to generate combined heat and power (CHP) in the range of 50-1000 kW_e. The objective was to adapt or develop engines and turbines to enable operation on a variety of bioliqids, including fast pyrolysis liquids, and to find a technical and economic optimum between fuel upgrading and engine and turbine modification.

PROJECT ACTIVITIES

There were four main activities:

- Bio-liqids production, analysis, characterisation, upgrading and blending: improving the combustion properties of bioliqids by chemical and/or physical upgrading and blending or emulsification in order to enable their use in prime movers
- Prime mover development and modification: modification and development of different engines and a micro gas turbine so that these can run efficiently on bioliqids including biodiesel, vegetable oil, and fast pyrolysis oil; and their blends
- Exhaust emissions reduction: the project developed methods and techniques to control exhaust emissions particularly including NO_x, CO, and particulates, to improve the environmental sustainability of the CHP combinations
- Assessments: the project evaluated the complete chain in terms of sustainability, economics, technology, environment, and market opportunities for application in EU Member States and Russia.

IMPACT

- New opportunities to provide reliable and cost effective electricity and heat from biomass at a small scale
- Development of existing technologies, including bioliqids, prime movers and cogeneration units so that they can be used together in an integrated system
- Contributions to improving the environment, quality of life, health and safety and the security of energy supplies.

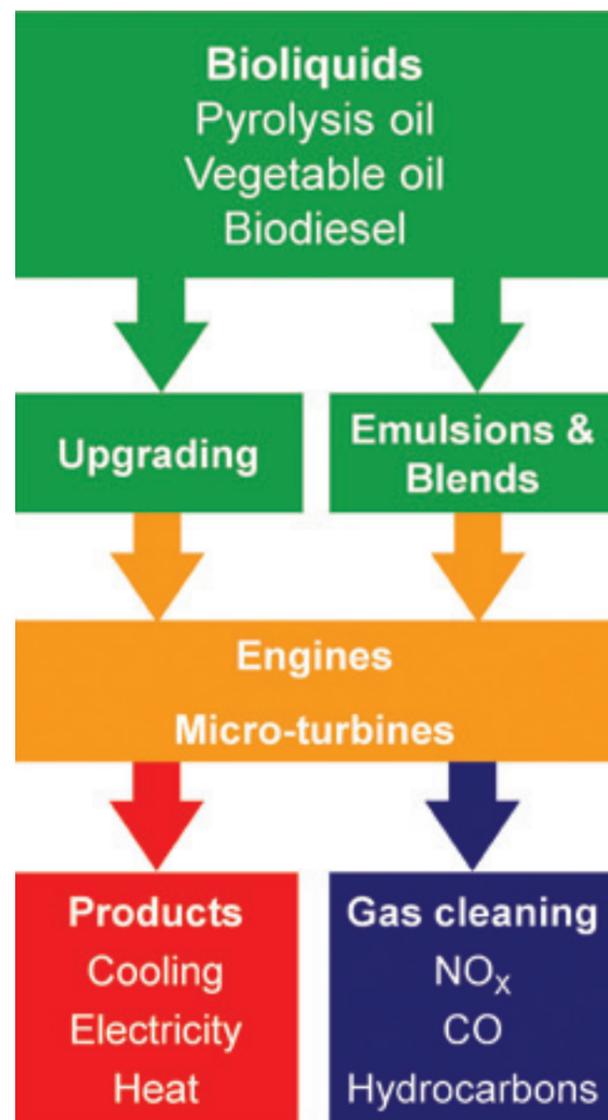


Figure 1: Structure of project

Bioliqids selection, production and characterisation

SELECTION AND PRODUCTION OF BIOLIQUIDS

In the Bioliqids-CHP project, several different bioliqids were evaluated for use in prime movers. The 'primary' bioliqids were biodiesel, pure vegetable oil and fast pyrolysis oil. The biodiesel (FAME) was produced from rapeseed and purchased in Germany. The vegetable oil used was sunflower oil that was purchased in Italy. The fast pyrolysis oil was produced in BTG's pilot plant from pinewood. Two batches of fast pyrolysis oil were produced and used for the experiments. 'Secondary' bioliqids used were bio-ethanol and bio-butanol, which were used in several cases to improve fast pyrolysis oil properties. Additionally, bio-ethanol was added as a rinsing fuel in BTG's diesel engine when switching fuels from diesel to fast pyrolysis oil and vice versa.

PROPERTIES OF BIOLIQUIDS

For all bioliqids a range of properties were determined and these are summarized in Table 1 (overleaf). Fast pyrolysis oil differs significantly from (rapeseed-derived) biodiesel and sunflower oil with respect to acidity (pH), tendency to carbon formation (MCRT), water content and density. For use in prime movers relevant properties are for example the heating value, Cetane number and viscosity. The viscosity of liquids can be lowered by preheating the fuel as illustrated in Figure 2.

Another important property of any bioliqid - but in particular for fast pyrolysis oil - is its ageing behaviour. A suitable method to study this aspect is the change in the kinematic viscosity over time. This change in viscosity was monitored for the different bioliqids over several months. The bioliqids were stored at 40°C and the viscosity was measured on a regular basis. The observed change in viscosity for biodiesel and sunflower oil was negligible. The ageing behaviour of fast pyrolysis oil is a strong function of the storage temperature. Ageing can be kept within acceptable limits as long as the temperature is kept below 40-50°C as illustrated in Figure 3.

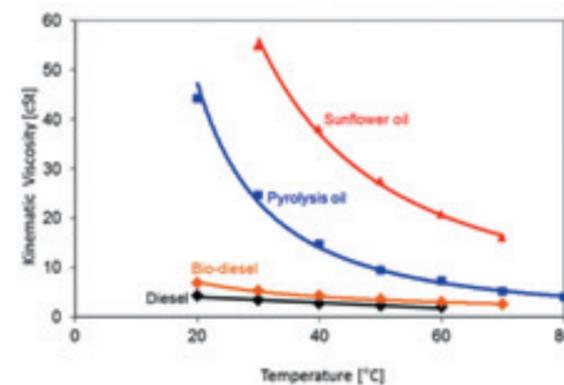


Figure 2: Kinematic viscosity as a function of temperature for the different bioliqids

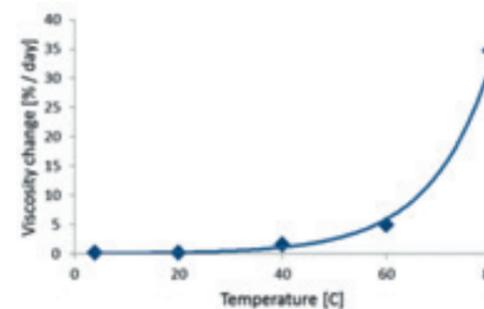


Figure 3: Change in viscosity of fast pyrolysis oil as a function of the storage temperature

OBJECTIVES

The main objective was to evaluate different bioliqids and to produce fast pyrolysis oil from different sources in sufficient quantities as required in the project. All bioliqids used in the project needed to be properly characterized.

OUTCOMES

For the testing of prime movers biodiesel, sunflower oil and fast pyrolysis oil were selected as fuel. Fast pyrolysis oil was produced in BTG's pilot plant from pine and straw. Additionally, bioethanol and butanol have been characterized as these alcohols can be relevant for the preparations of different fuel blends with fast pyrolysis oil.

Bioliquids upgrading and blending

Table 1: Properties of the primary liquids

| Property | unit | Biodiesel | Sunflower Oil | Fast Pyrolysis Oil | | | Bio-ethanol ^A | Bio-butanol |
|-----------------------------|-------------------|-----------|---------------|--------------------|---------|-------|--------------------------|-------------|
| | | | | Pine I | Pine II | Straw | | |
| C | wt% | 77.3 | 77.5 | 42.8 | 45.5 | 48.6 | 50.9 | 64.9 |
| H | wt% | 12.1 | 11.9 | 7.6 | 5.8 | 7.9 | 12.7 | 13.5 |
| N | wt% | <0.01 | <0.01 | <0.01 | <0.01 | 0.4 | <0.01 | <0.01 |
| O (Balance) | wt% | 10.6 | 10.6 | 49.6 | 48.8 | 43.0 | 36.4 | 21.6 |
| Water content | wt% | - | - | 21.7 | 25.4 | 21.2 | - | - |
| Ash content | wt% | - | - | 0.047 | 0.016 | 0.053 | - | - |
| Solids content | wt% | - | - | 0.27 | 0.04 | 1.28 | - | - |
| Density | kg/m ³ | 871 | 910 | 1,207 | 1,170 | 1,184 | 780 | 810 |
| LHV | MJ/kg | 27.1 | 37.4 | 17.1 | 16.1 | 20.1 | 27.1 | 34.4 |
| HHV | MJ/kg | 40.2 | 40.0 | 18.7 | 18.8 | 21.9 | 30 | 37.4 |
| LHV | MJ/L | 32.7 | 34.0 | 20.6 | 18.8 | 23.8 | 21.4 | 27.9 |
| pH | - | - | - | 2.85 | 2.85 | 3.3 | - | - |
| MCRT | wt% | - | 0,06 | - | 15.1 | - | - | - |
| Kinematic viscosity at 20°C | cSt | 6.9 | 80.7 | 65.1 | - | 80.4 | 1.5 | 3.6 |
| at 40 °C | cSt | 4.2 | 40.6 | 20.0 | 13.0 | 21.2 | 1.1 | 2.8 |
| Cetane Number | - | ~60 | ~40 | ~10-25 | - | - | ~8-15 | 17 |
| Contaminants | ppm | | | | | | | |
| Cl | | <10 | <10 | <10 | n.d. | 240 | n.d | n.d. |
| Fe | | 1.3 | 2.2 | 11 | | 11 | | |
| Mg | | 3.7 | 4.4 | 6 | | 37 | | |
| Mn | | <1 | <1 | 1.2 | | 12 | | |
| Ca | | 1.3 | 5.2 | 15 | | 135 | | |
| Sr | | <1 | <1 | <1 | | 1.3 | | |
| Sn | | <1 | >1 | <1 | | 2.6 | | |
| Si | | 2.0 | 42.9 | 6.6 | | 83 | | |
| P | | <1 | 2.3 | <1 | | 15 | | |
| Al | | 5.3 | 6.6 | 35 | | 48 | | |
| K | | 14.4 | 13.4 | 21 | | 254 | | |
| Na | | 18.4 | 17.8 | 20 | | 22 | | |

Note A 4wt% of Beraid (Cetane improver) is added to the fuel;

Fast pyrolysis oil is considered the most difficult fuel of the bioliquids tested. The quality of fast pyrolysis oil was improved using various approaches:

REMOVING WATER FROM FAST PYROLYSIS OIL

Fast pyrolysis oil from biomass typically contains about 25 wt% of water. This high water content reduces the calorific value and has a negative impact on ignition properties. Therefore, partial removal of water may be advantageous. However, removing water leads to an increase in oil viscosity and oil ageing becomes more severe. Adding ethanol to the dewatered fast pyrolysis oil can offset these detrimental impacts.

REDUCING SOLIDS CONTENT IN FAST PYROLYSIS OIL

Untreated fast pyrolysis oil can have a high solids content. When applied in prime movers this can lead to plugging and wear of fuel pumps and injectors. Devices tested for their suitability for solids removal include a self-cleaning scraper filter, a batch centrifuge, a self-cleaning centrifuge, and a centrifugal filter separator. The best results of high solids removal, easy operation and limited oil loss were obtained with the self-cleaning centrifuge.

MILD HYDROTREATMENT OF FAST PYROLYSIS OIL

Mild hydrotreatment implies catalytic treatment of fast pyrolysis oil in the presence of hydrogen at elevated pressure but without complete oxygen removal. The resulting product has reduced acidity, increased energy content and improved ignition and thermal stability properties. The hydrotreatment was performed in BTG's hydrogenation unit using a patented catalyst developed jointly with the Boreskov Institute of Catalysis (BIC) and Rijksuniversiteit Groningen (RUG). The operating pressure is typically around 200 bar, with reactor temperatures up to 350°C. The hydrogen consumption is about 10-20 gram/kg oil. The fuel produced is referred to as "Mild-HDO" (see Table 2).

Table 2: Properties of modified oils

| Property | unit | Emulsion | PO-Ester | Mild HDO | Blend (30/30/40) |
|-----------------------------|-------------------|----------|----------|----------|------------------|
| C | wt% | 44.4 | 58.4 | 67.6 | 65.8 |
| H | wt% | 6.4 | 7.4 | 8.1 | 10.8 |
| N | wt% | <0.1 | <0.1 | <0.1 | <0.1 |
| O (balance) | wt% | 49.2 | 34.2 | 24.2 | 23.3 |
| Water content | wt% | 22.8 | 6.6 | 6.7 | 6.8 |
| Ash content | wt% | 0.298 | 0.018 | 0.017 | |
| Solids content | wt% | - | - | - | |
| Density | kg/m ³ | 1198 | 1158 | 1106 | 9331 |
| LHV, calculated | MJ/kg | 16.3 | 24.0 | 27.0 | 28.4 |
| LHV | MJ/ltr | 19.5 | 28.0 | 29.9 | |
| pH | - | 2.1 | 3.0 | 3.1 | 3.8 |
| MCRT | wt% | 18 | 20 | 11 | |
| Kinematic viscosity (40 °C) | cSt | 36 | 115 | 149 | |
| Acid number | mg KOH/g | - | 22 | - | |
| Carbonyl number | mg BuO/g | 133 | 112 | 10 | |

ESTERIFICATION OF FAST PYROLYSIS OIL

Fast pyrolysis oil was treated with an alcohol in a reactive distillation process in the presence of a catalyst. The resulting product has a lower acidity and water content, and higher energy content. The operating pressure is typically 300 mbar. The best results were obtained at a reactor temperature of 85°C, with butanol as the reactant and using a solid acid catalyst (Nafion SEC13). During the process the butanol reacts with the acids in the fast pyrolysis oil to form esters. Water is removed by evaporation. On a weight basis the pyrolysis oil:butanol ratio is around 10. This fuel is referred to as "PO-Ester" (see Table 2).

continued on next page.

EMULSIFICATION

Emulsification of fast pyrolysis oil and biodiesel has been investigated as an upgrading method to mitigate some of the adverse characteristics of fast pyrolysis oil. A specific surfactant was dissolved in biodiesel, then the biodiesel/surfactant solution was cooled to room temperature and emulsified with fast pyrolysis oil by vortex mixing. The process led to the formation of a stable emulsion as the main phase and a very small amount of a mixed phase that floated on top. The main phase was a stable dispersion of biodiesel in fast pyrolysis oil, whereas the mixed floating phase was composed of bio-oil dispersed in biodiesel. The mixed phase can be mechanically separated and processed back into the original components by centrifugation.

BLENDING

A new development was achieved through blends of fast pyrolysis liquid with biodiesel and bio-alcohols. Fast pyrolysis oil is immiscible with biodiesel, however, the presence of a bio-alcohol acts as a co-solvent and allows the blend to stabilize and form a single homogeneous phase. The most important feature of this achievement is the ability to tailor the blend to the end user requirements, e.g. heating value, viscosity or flash point. Three-phase charts were prepared for each of the alcohols used. A number of homogeneous one-phase blends were tested for long term stability, viscosity, pH and density. The concept is being patented and was nominated as one of the best 10 ideas in the Cleantech Open UK 2011 competition.

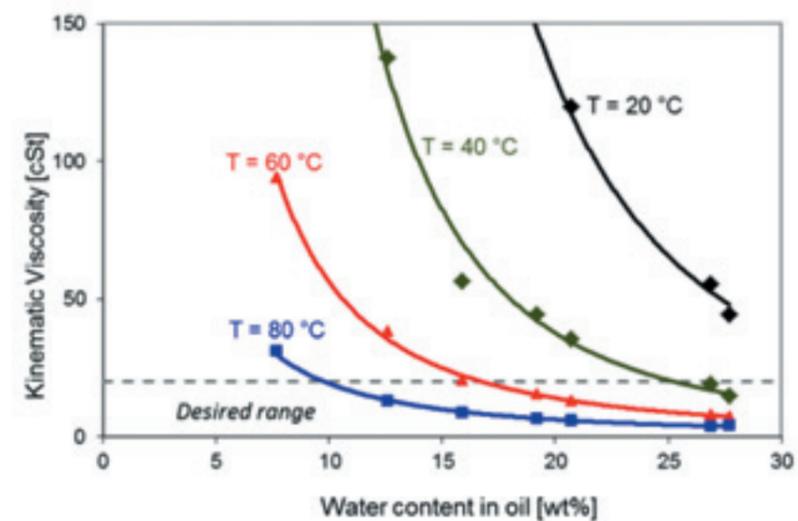


Figure 4: Viscosity as a function of the water content of fast pyrolysis oil for different temperatures

PROPERTIES OF UPGRADED BIOLIQUIDS

Table 2 summarizes the properties of the upgraded fast pyrolysis oils. Clear differences can be observed such as e.g. heating value, water content, viscosity and carbon residue. In all cases the fuel remained acidic.



Figure 5: Water removal from pyrolysis oil



Figure 6: Fast pyrolysis oil hydrotreating



Figure 7: Screening for selection of surfactant for emulsions

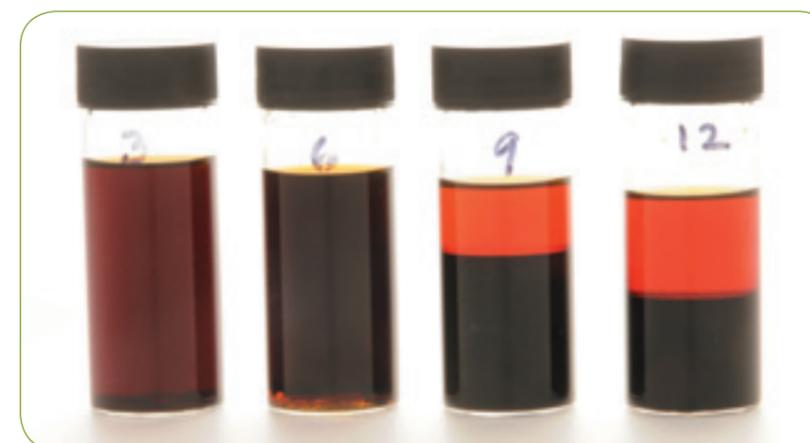


Figure 8: Miscible and non-miscible blends of fast pyrolysis liquid, biodiesel and butanol

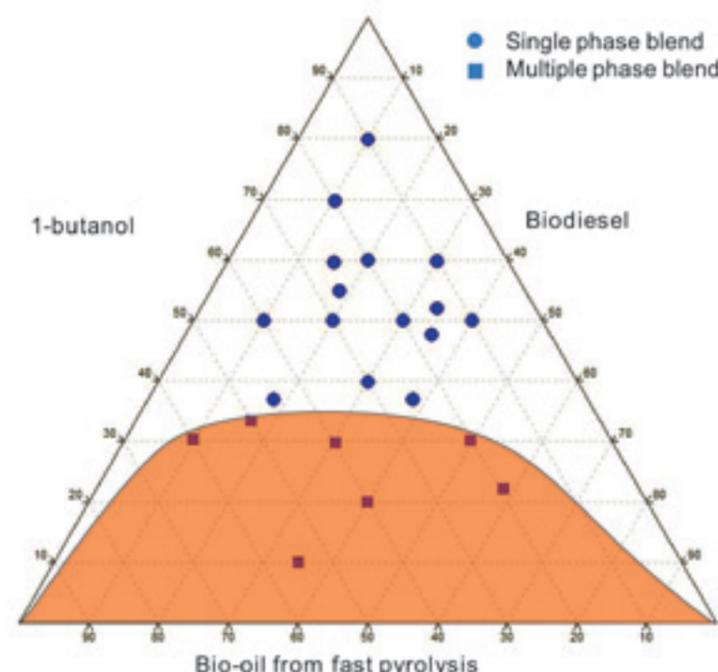


Figure 9: Three phase chart for butanol blends with fast pyrolysis oil and biodiesel

OBJECTIVES

The main objective was the production of biofuels with improved fuel characteristics by physical treatment, chemical treatment, and preparation of blends and emulsions.

OUTCOMES

- Solid particles in fast pyrolysis oil can be most effectively removed by centrifugation.
- Catalytic upgrading of fast pyrolysis oil produced two improved fuels: hydrotreated oil and esterified oil. Both have reduced acidity, lower water and higher energy content
- A stable emulsion of 5 wt.% biodiesel in fast pyrolysis oil was successfully produced
- Homogenous tertiary blends of fast pyrolysis oil with biodiesel and a bio-alcohol were successfully produced, such as 30 wt.% fast pyrolysis oil, 30 wt.% biodiesel and 40 wt.% butanol.



Micro Gas Turbine

Micro gas turbines (MGTs) offer several advantages compared to compression ignition engines when fed with biofuels, because of the stationary combustion, the lower fuel injection pressure, and the carefully controlled flame development through accurate modelling of the combustor geometry. While natural gas, kerosene, diesel oil or even clean biogas can be directly used in micro gas turbines, biofuels from thermo-chemical conversion of biomass or raw liquid biofuels such as vegetable oils are still challenging to standard components and technologies.

SELECTION OF SUITABLE MATERIALS AND MODIFICATION OF THE MICRO GAS TURBINE

The issue of material compatibility was carefully investigated, and new components such as auxiliary heaters, pumps, filters, as well as piping and sealing were selected and fitted. The micro gas turbine (Figure 10) was modified to make it more versatile and tolerant toward critical characteristics such as aggressiveness, viscosity and acidity of biodiesel, vegetable oil, ethanol, pyrolysis oil, fast pyrolysis oil/diesel emulsions, and blends. Materials such as PEEK, HDPE, Teflon and stainless steel (AISI 316 and 304) were used for the new fuel lines. A test rig was set-up and equipped with appropriate instruments to characterize MGT performance at different loads.

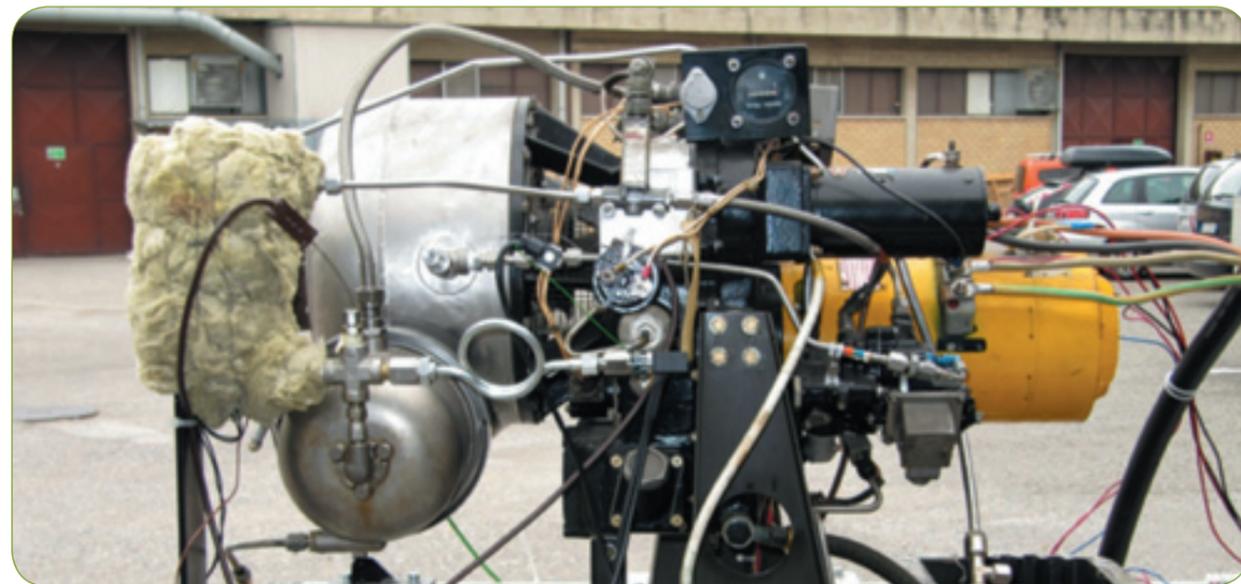


Figure 10: The micro gas turbine

RE-DESIGN OF THE COMBUSTION CHAMBER

Use of fast pyrolysis oil required a radical adaptation of the micro gas turbine combustion chamber, the component in which the chemical energy of the fuel is converted into heat by burning the fuel along with the compressed air coming from the compressor. Fast pyrolysis oil features a very specific behaviour during combustion in which the oil droplets experience a final combustion phase in which a solid carbonaceous particle is formed. This extends the time that is required to complete combustion. In addition, two contradictory effects had to be satisfied: on the one hand, fast pyrolysis oil is a highly oxygenated fuel that requires a reduced amount of air for combustion compared to conventional fossil fuels such as diesel; on the other hand, the calorific value of the fast pyrolysis oil is roughly half of that of diesel, and an increased fuel flow is therefore required to provide the same thermal output.

TESTING OF THE MODIFIED MICRO GAS TURBINE

The modified micro gas turbine was successfully tested with ethanol, biodiesel, vegetable oil and mixtures of vegetable oil and biodiesel. The effect of fuel preheating on CO concentration in the exhaust was investigated between 80°C and 120°C. Biodiesel preheating largely effects CO concentration: at 80°C a reduction of approx. 37% in CO concentration compared to diesel at 20°C was observed, as well as 51% compared to biodiesel at 20°C. When running biodiesel, a slight decrease of the calculated heat rate was observed, when compared to diesel fuel. To avoid engine shut-down, vegetable oil and vegetable oil/biodiesel mixtures had to be preheated at 120-130°C. Operation with vegetable oil was only possible by preheating to 120°C and with a minimum load of 5 kW_e and preheated vegetable oil generated CO emissions very similar to diesel at 20°C. Measurements of CO emissions for mixtures were in-between vegetable oil and biodiesel at the same preheating temperature. NO_x emissions were only a few ppm for all fuels. Some results of testing are reported in Figure 11.

OBJECTIVES

The main objectives were to investigate the modification of a micro gas turbine to accommodate first and second generation biofuels and to test biofuels in the modified micro gas turbine.

OUTCOMES

The micro gas turbine fuel line was successfully modified to handle biofuels

- The engine was characterized with diesel fuel to provide a reference baseline for performance comparison
- The engine was operated on vegetable oil, biodiesel, ethanol, mixtures of vegetable oil and biodiesel, and tested with fast pyrolysis oil
- A new combustor, featuring a modified geometry and a modified air distribution system was designed, built and tested. This resulted in a six-fold reduction in CO concentrations in the exhaust for diesel fuel under the same load conditions.

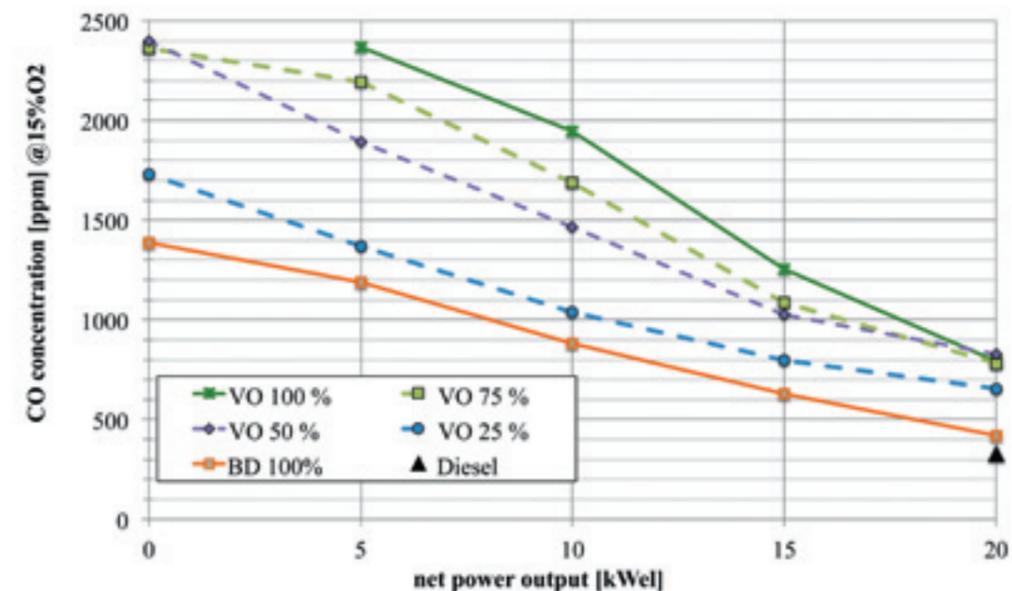


Figure 11: CO concentration in the exhaust (referred to 15 vol.% oxygen) for pure vegetable oil and several mixtures with biodiesel.



External combustion engines

WORK CARRIED OUT

Engines which convert heat into mechanical energy with recovery of byproduct heat are the key equipment of CHP systems. Engines with external combustion such as steam engines and Stirling engines are preferable for operation on bio-liquid fuels. A continuous combustion process allows major improvements in combustion efficiency and reduces pollutant emissions compared to internal combustion engines where combustion is transient. However, the efficiency of steam engines is too low in both micro and small power range. Stirling engines have a high theoretical efficiency, but their inherent disadvantages of low specific power, high cost, frictional losses, leakage of working fluid, dead volumes, and problems with balancing of pistons make their application difficult.

To overcome typical problems of engine design and performance, Encontech B.V. has focussed on the development of novel external combustion engines for CHP systems. This included new engine concepts, thermodynamic analysis of engine cycles, evaluation and selection of the best concepts, design of engines, detailed modelling, optimisation of the design parameters, construction of the engines, and finally engine tests and further modifications.



Figure 12: Steam engine

RESULTS OBTAINED

Three types of external combustion engines have been developed: a Rankine cycle engine, Manson based cycle engine and a radically new engine. The engines can be fuelled with bio-liquids and seem to be effective alternatives to the established methods of energy conversion. The main advantage of the engines developed is their simplicity.

The first engine developed was a modified steam or Rankine cycle engine. This has several distinctive features, including:

- There are no piston rings and no oil lubrication
- A crank gear with a straight line mechanism and gas lubrication instead of oil lubrication
- The piston is self-aligning by maintaining a gas flow in the narrow gap between the piston and the cylinder
- There are no conventional valves, with the piston playing the role of a slide valve
- New materials of construction
- A prototype of the novel engine combined with an alternator was demonstrated and tested in a power range of several hundred watts.

Secondly a Manson cycle based engine was developed as an alternative to Stirling engines. The main advantage is its simplicity resulting in higher efficiency, increased lifetime and decreased cost. In contrast to any type of Stirling engine, the novel engine has only one moving part. A power piston is integral with a displacer and a heat regenerator. It solves the problem of high-temperature sealing of the piston and the displacer. Both strokes of the piston are working ones. The engine can be considered maintenance-free as it has no piston rings or any other rubbing components requiring oil lubrication. The only seal is contactless and located in the cold part of the cylinder. As a result the leakage rate during operation can be one to two orders of magnitude less than in Stirling engines. Balancing the engine is much easier compared to Stirling engines with two masses reciprocating with a phase lag. In addition the displacer volume is combined with a regenerator permitting the elimination of heat losses from the external gas circuit. A prototype of the engine was built and the technical feasibility of the engine concept was demonstrated.

Thirdly a radically new and very promising engine was developed which combines all the advantages of the first two engines. In addition, the engine can easily be scaled up and down in the range of 1W – 1MW per cylinder and can use any heat source with a temperature from 50 to 1000°C. The engine has been constructed and tested.

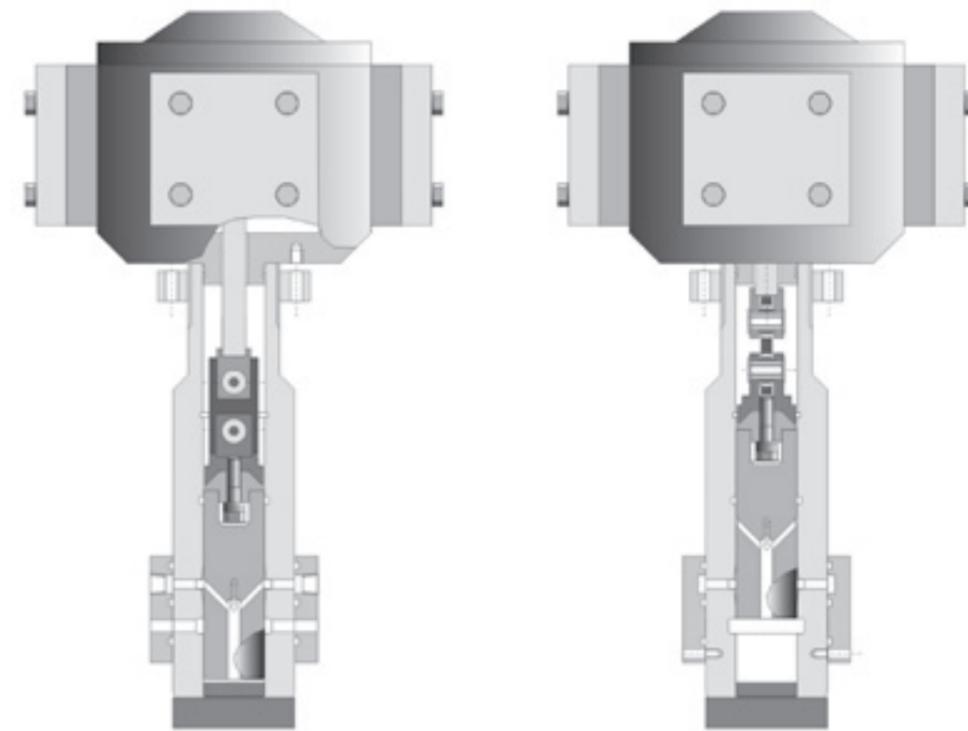


Figure 13: Steam engine drawing

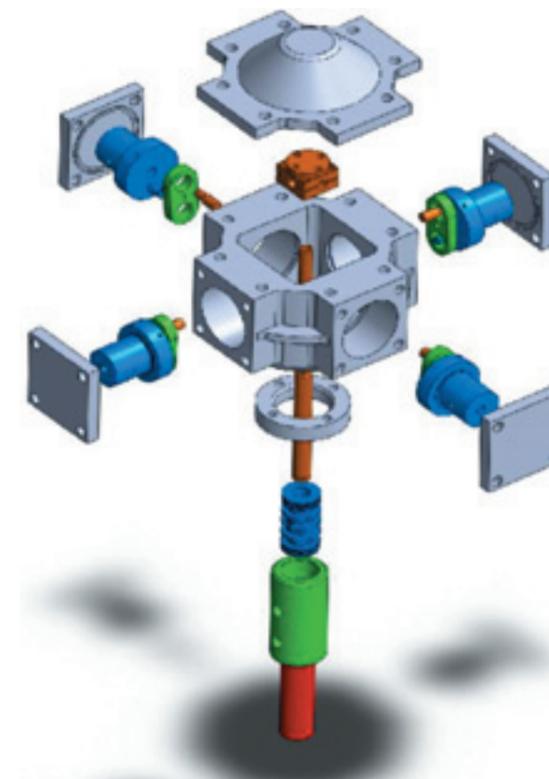


Figure 14: Assembly of the Manson type engine

OBJECTIVES

To develop engine components and engines which are tolerant of bio-liquids and fast-pyrolysis oil.

OUTCOMES

A novel heat engine which can use bio-liquid fuels was developed for mini CHP systems. The engine seems to be an effective alternative to conventional prime movers. The main advantage is its simplicity, that should result in a higher efficiency, increased lifetime and lower cost.

Wide-spread spin-offs of the development are foreseen. The new engine can be used for medium scale power generation systems up to 30 MW_e; as a prime mover for micro-CHP systems for houses; as an automotive exhaust heat recovery unit; and as a compressor or pump. The unit can run on sustainable heat sources.



Fuelling bioliqids in a conventional CI-engine

Liquid fuels can be converted efficiently into electric power in a conventional compression-ignition (CI) engine. When fast pyrolysis oil is used, various engine modifications are required, due to the specific characteristics of this fuel.

- As fast pyrolysis oil is acidic all piping and devices in contact with it should be corrosion resistant. The fuel injection pump and fuel injector should be made from surface treated stainless steel
- Fast pyrolysis oil typically contains 20-25 wt% water, lubrication is poor and small particles (up to 20 µm) might be present. This may cause severe abrasive wear, in particular in the injector, and therefore the fast pyrolysis oil needs to be filtered
- The viscosity of fast pyrolysis oil is higher than that of mineral diesel, and depends strongly on water content and temperature. Reducing the water content would further increase viscosity. The fuels can be preheated to achieve sufficiently low viscosities of typically below 17 cSt
- Fast pyrolysis oil is sensitive to re-polymerisation, in particular, if the temperature rises above 50-60°C re-polymerisation may result in small particles in the oil and increased viscosity
- Fast pyrolysis oil is more difficult to ignite, and higher temperatures are required at the end of the compression stage to achieve complete combustion. This can be achieved by preheating the incoming air. Alternatively the compression ratio can be increased and/or the fuel injection timing can be adapted
- The energy content of fast pyrolysis oil is about half that of mineral diesel, and therefore for the same power output, double the amount of fuel needs to be injected.



Figure 15: Photo of engine test set-up

ENGINE TEST FACILITY

BTG converted a standard CI-engine to allow it to run on fast pyrolysis oil and the other bioliqids considered. The original characteristics of the one-cylinder, 20 kW_e diesel engine are given in Table 3. Three fuel vessels were installed containing engine start-up fuel (mineral diesel), rinsing fluid (e.g. ethanol) and the test fuel. The test fuel can be preheated up to 100°C, and the incoming air can be controlled at temperatures between 20 and 220°C. Two pistons are available, one corresponding to a compression ratio of 17.6 and another one to a ratio of 22.4. A generator connected to the engine converts the mechanical power into electricity. Up to six electrical heaters can be switched on to vary the electrical load in 1 kW_e steps between 1 kW_e and 12 kW_e. The original fuel pump and fuel injector were replaced by a complete, dedicated stainless steel fuel injection system. BTG constructed both parts in-house, as suitable suppliers for such parts could not be identified. Temperatures and pressures can be measured and logged at several positions in the engine. A fast response pressure indicator and oscilloscope were used to measure fuel injection pressure. Analysers were installed to measure gas composition, soot levels and rotational speed. The power output is measured with a smart power analyser.

Table 3: Engine characteristics

| JIANG DONG Engine | |
|----------------------|--------------------------------|
| Model | ZH1130 |
| Piston displacement | 1,592 ml |
| Compression ratio | 17.6 |
| Output | 23.5 kW (at 2,200 rpm) |
| Injection pressure | 200 – 250 bar |
| Fuel Consumption | 240 g/kW _e (diesel) |
| Generator | MECC ALTE – T20FS-160 |
| Max output generator | 10 |

RESULTS

To overcome the poor ignition properties of fast pyrolysis oil, a higher temperature is required in the engine cylinder when the fuel is injected. This can be achieved by increasing the air inlet temperature or the compression ratio. An air inlet temperature of around 100°C at a compression ratio of 17.6 is required for fast pyrolysis oil combustion. By increasing this ratio to 22.4 the air inlet temperature can be reduced by 40°C.

Modifying the fuel injection timing may have some advantages for fast pyrolysis oil combustion. Early injection means that more time is available to ignite the fuel and to achieve complete combustion, however, this resulted in severe operational problems. It appears that the optimal timing for engine operation on fast pyrolysis oil is comparable to that of sunflower oil and biodiesel. For ethanol it was advantageous to inject fuel earlier.

All bioliqids described above (sunflower oil and biodiesel, neat and treated fast pyrolysis oil, blends and emulsions) were tested in the diesel engine. Generally, the upgraded liquids were easier to ignite resulting in lower CO emissions and higher NO_x, whereas the effect on overall efficiency was

less pronounced. The liquids remained acidic, and thus a modified injection system will be required in all cases.

In longer duration tests, the CO emissions and fast pyrolysis oil fuel consumption were monitored while the engine was operated for a period of 40 hours, spread over several days. During the first hours of operation the engine performance improved and then stabilized. Long duration testing will be important for further development.

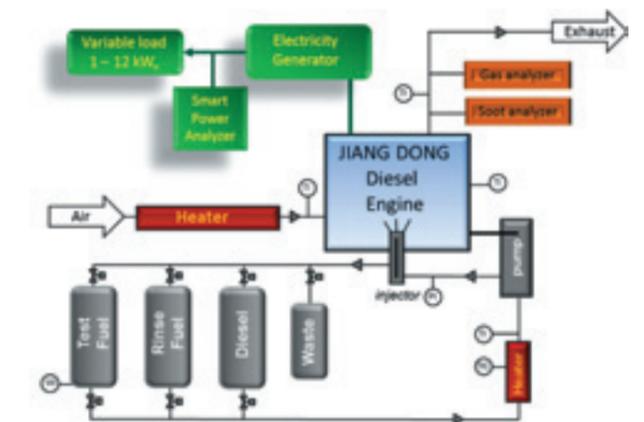


Figure 16: Flow-scheme of engine test unit

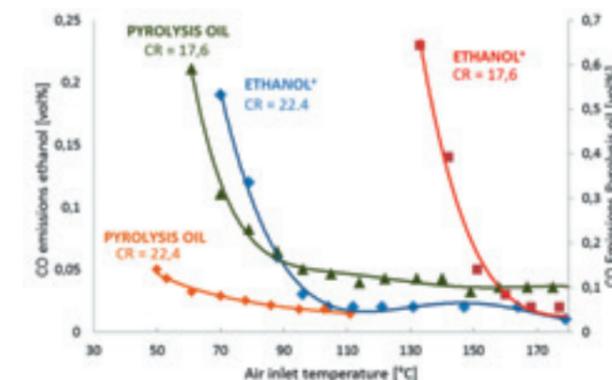


Figure 17: CO emission in the flue gas as a function of the air preheat temperature for fast pyrolysis oil and ethanol for two different compression ratios

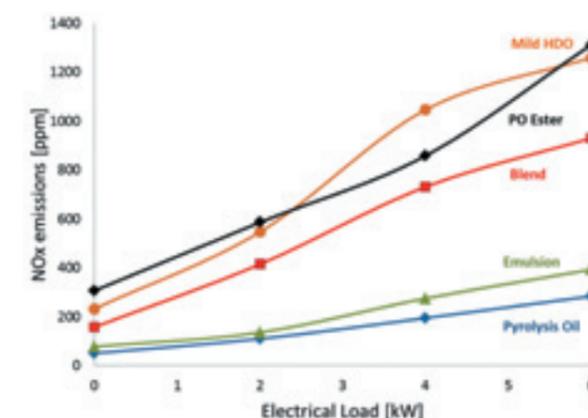


Figure 18: NO_x emissions as a function of the electrical load for different biofuels

OBJECTIVES

Modification of a conventional CI-engine to enable the combustion of fast pyrolysis oil and fast pyrolysis oil derived liquids.

OUTCOMES

- A CI-engine was modified and operated successfully on fast pyrolysis oil and fast pyrolysis oil derived liquids
- Generally, fast pyrolysis oil combustion leads to higher CO and lower NO_x concentrations in the flue gas compared to diesel, biodiesel and sunflower oil
- The ignition properties were improved by upgrading fast pyrolysis oil, but the fuel remains acidic
- The engine was operated for 40 hours on pure fast pyrolysis oil without a noticeable effect on engine performance.



Diesel engine with integrated DeNOx

INTRODUCTION

High NO_x levels in diesel engine exhaust gases represent a serious environmental problem which can be resolved by using several approaches (Figure 19). One approach is based on selective catalytic reduction (SCR) of NO_x by injecting a small amount of reducing gas into the exhaust. The possible reducing gases include unsaturated hydrocarbons, propane, primary diesel fuel, ammonia, urea and synthesis gas (a mixture of hydrogen and carbon monoxide). The synthesis gas can be produced with catalysts by steam reforming, autothermal reforming (ATR) or partial oxidation of diesel fuel or upgraded fast pyrolysis oil. A technology was developed to maximize NO_x reduction in two steps: the first step was reforming of diesel fuel to synthesis gas; and the second step was NO_x reduction by the synthesis gas produced.

CATALYSTS AND REACTOR FOR BIOLIQUID REFORMING TO SYNTHESIS GAS

Three catalysts were identified as more promising for autothermal reforming fuels into synthesis gas: Co₃O₄/MnO₂/BaO/Fechral Net; Rh/Al₂O₃/Net; Ni/BaO/La₂O₃/Al₂O₃/Net. All the catalysts were tested for reforming of diesel and biodiesel under the following conditions: O₂/C = 0.5-0.6, H₂O/C = 1.5-2, contact time 0.3-0.3 s, inlet reactor temperature 200-400°C. The product distribution was as follows (on a dry basis):

A reactor for synthesis gas production was manufactured with dimensions: inner diameter 100 mm; catalyst block dimensions (diameter x length) 100x150 mm; and axial reactor type. (Figure 20)

Table 4: Product distribution

| Feed fuel | H2 | CH4 | CO2 | CO | N2 | Syngas yield NL/g fuel | Syngas yield moles/mole fuel |
|--------------------|----|-----|-----|----|----|------------------------|------------------------------|
| Diesel | 32 | 1 | 12 | 11 | 44 | 2.88 | 18 |
| Biodiesel | 24 | 1 | 15 | 6 | 34 | 1.85-2.2 | |
| Fast pyrolysis oil | 26 | 1 | 14 | 13 | 46 | | |

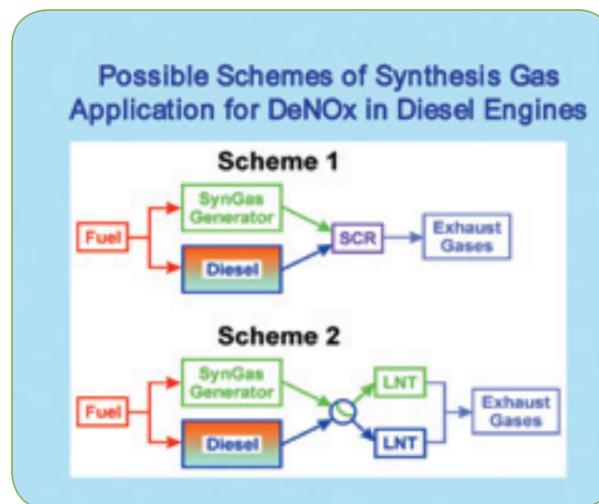


Figure 19: Alternatives for improving diesel engine NO_x emissions



Figure 20: ATR catalyst and reactor

CATALYSTS AND REACTOR FOR SELECTIVE NO_x REDUCTION

25 catalysts were synthesized and tested for selective NO_x reduction. The catalyst with 2% Ag/Al₂O₃ showed the best characteristics and was taken as the most promising one for the development of a selective NO_x reduction module shown in Figure 21. The catalyst consisted of 2-3 mm diameter spheres impregnated with a solution of silver nitrate.

The experiments showed that in order to give high NO_x conversion, autothermal conversion of diesel fuel should be performed so that the reaction products contain synthesis gas, methane and unreacted diesel fuel. This can provide high conversion of NO_x in the temperature range 250-500°C. 60L of a pilot catalyst batch was loaded in a radial deNO_x reactor with dimensions: inner diameter 120 mm; thickness of catalyst bed 100 mm; external diameter 380 mm; and length of reactor 516 mm.



Figure 21: Radial-type DeNO_x reactor

CATALYST MANUFACTURING AND SYSTEM DEVELOPMENT; EXHAUST GAS CLEANING SYSTEM

A system for NO_x cleanup from exhaust gases was developed and assembled (Figure 22). Preliminary experiments gave a satisfactory deNO_x efficiency of 80% in the temperature range 250-350°C. The fuel penalty for synthesis gas production was 3-5% of the input fuel.



Figure 22: A system for NO_x cleanup from exhaust gases

OBJECTIVES

- Development of a system for NO_x removal from diesel engine exhaust gases in two sequential steps of reforming fuel to synthesis gas followed by selective catalytic reduction
- Determining the reactor parameters and the reaction conditions for both steps to maximize NO_x conversion
- Development of catalysts for both steps including synthesis, testing and selection.

OUTCOMES

- Conversion of NO_x reaches 80% in the temperature range 250-500°C
- The fuel penalty for synthesis gas production is estimated as 3-5%.



Bioliqids-CHP assessments and markets

The financial and non-financial benefits of using bioliqids in CHP mode have been evaluated which first required a database of units using biomass for CHP. This was developed for the Netherlands and for the United Kingdom. The database included unit electrical capacity, location, fuel and prime mover. Due to lack of data, it was unfortunately not possible to build similar databases for Russia and Italy. In an attempt to highlight the innovative frame of the project, Parallel Sets diagrams were used for graphical representation

of the database which condensed a conventional set of charts into a single easy to understand diagram (Figure 23).

A model was built to assess the techno-economics of CHP systems based on discounted cash flow analysis in order to estimate the Internal Rate of Return (IRR) for different case studies up to 1MW_e. The model was built as a tool for developers, planners and decision makers, aiming to generate results with little user input. Default values and a standard set of scenarios

are already programmed into the model but can be modified at users will. Internal combustion engines (piston and turbines), as well as Stirling engines and Organic Rankine Cycle systems can be modelled for a variety of fuels, including fast pyrolysis oils, biodiesel and natural gas for comparison. Heat and power production costs are outputs from the model which produces charts containing sensitivity analyses for variations in bioliqid fuel price, labour cost, maintenance cost, power and heat price increases, capital cost, grants and interest rate variations. A number of techno-economic case studies of various CHP systems configurations, capacities and fuels were carried out for each partner countries. The economic evaluation showed that none of the Bioliqids-CHP partner countries will result in a positive IRR without incentives, thus the minimum level of incentives required for a target internal rate of return of 5% was also carried out. The incentive could be either in the form of a feed-in-tariff or as a tradable carbon reduction record. The results in Table 4 correspond to an estimation of feed-in-tariffs compared to estimated power production costs.

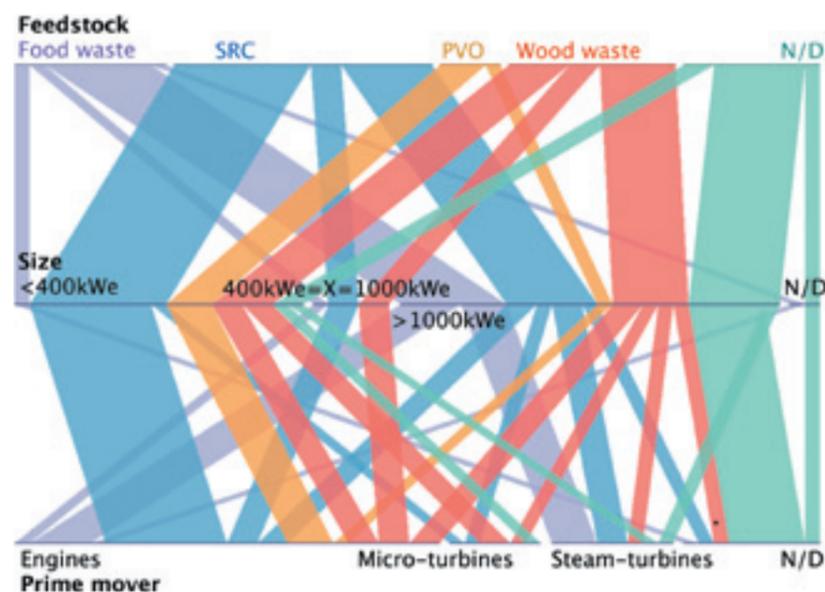


Figure 23: Parallel sets depiction of biomass based CHP systems in the UK

Table 5: Estimated feed-in-tariff required for 5.0% IRR using fast pyrolysis oil in piston internal combustion engines for the Bioliqids-CHP partner countries in 2011.

| Country | Feed-in-tariff value (c/kW _h) | % of power price |
|-----------------|---|------------------|
| The Netherlands | 10.05 | 118.2 |
| Italy | 7.02 | 64.5 |
| Russia | 7.50 | 95.8 |
| United Kingdom | 7.46 | 78.8 |

An environmental assessment for the UK was carried out using the Biomass Environment Assessment Tool (BEAT V2). The tool was developed by AEA Energy & Environment in association with North Energy Associates for DEFRA and the Environment Agency. Although not a full life cycle assessment (LCA), it provides a reliable and standard model that can be used to work through different CHP case studies using bioliqids, including fast pyrolysis oil produced from different sources including straw, forestry

residues and clean wood waste. This enables comparisons on a consistent basis. Although the tool was developed for the UK, the results could be adapted to the other Bioliqids-CHP partner countries with minor modifications in the tool databases. The analysis showed that carbon emissions savings are achievable when using fast pyrolysis oil in CHP schemes of less than 1000kW_e, in line with previous reported literature in which a full LCA analysis was employed. Results are shown in Table 5.

Table 6: Equivalent CO2 emissions increment (savings) when compared to gas in a 1000kW_e piston internal combustion engine using fast pyrolysis oil in CHP mode.

| CHP scheme | g CO2 equivalent/kW _h | % emission changes compared to natural gas |
|-----------------------------|----------------------------------|--|
| Natural gas fired | 617 | 0 |
| Fossil fuel oil fired | 858 | 39 increase |
| 100% forestry residue | 49 | 92 reduction |
| 100% Short Rotation Coppice | 109 | 82 reduction |

Potential markets in which a bioliqid-CHP installation could succeed were identified as follows:

UK the largest opportunities are in the sewage treatment and wood industries,

Netherlands the most promising opportunities are in the agricultural sector, in particular in greenhouse applications and possibly in the development of district heating networks.

Italy there is a marked interest in bioliqids use in the form of pure vegetable oil for power and heat generation, with an estimated increase of over 600% (number of units) for 2020 when compared to the 2007 situation. Reconversion of part of the sugar infrastructure plants into bioenergy power plants is also planned.

The Cogeneration Observatory and Dissemination Europe project (CODE) made its first report available in 2010 on the potential for CHP in the EU with information supplied by the member states. It was envisaged that an additional cogeneration capacity of 122GW_e is economically feasible which could be in operation by 2020. Although this figure encompasses a wide spectrum of sizes (capacities), range of applications and fuels; biomass is expected to make a contribution of about 8% of total growth or 10GW_e, of which 2GW_e could be in the capacity scale of below 1000kW_e.

OBJECTIVES

The main objectives were to perform a technical, environmental and economic performance assessment of bioliqids-CHP installations, and identify market opportunities.

OUTCOMES

- A database of biomass CHP installations was created for the United Kingdom and the Netherlands, which included capacity, location, fuel and prime mover
- The evaluation showed that no country can generate a positive Internal Rate of Return under parameters relevant in 2011. A case study to determine a feed-in-tariff for a fixed 5% IRR was done, resulting in a level for the incentive from 64% to more than double the current power tariff
- The environmental performance was estimated using BEAT V2 and validated with existing data. Depending on the feedstock from which the fast pyrolysis oil is made, there could be CO2 equivalent emissions savings from 82 up to 92% when compared to the same unit using natural gas in a 1000kW_e engine working in CHP mode.



The Consortium & Funding organizations

The Bioliquids-CHP project (2009-2011) was performed by seven partners with complementary expertise in the field of bioenergy-based combined heat and power generation from industry, universities and research institutes from EU Member States and Russia.

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Group photograph of the EU and Russian Partners of Bioliquids-CHP Consortium.

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