PROJECT FINAL REPORT

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Project acronym: **BIOLIQUIDS-CHP**

Project title: **Engine and turbine combustion for combined heat and power production**

Funding Scheme: **Collaborative Project**

Project period: **1 January 2009 - 31 December 2011**

Coordinator: **BTG Biomass Technology Group BV (The Netherlands)**

Project website: **http://www.bioliquids-chp.eu**

Content:

I. Executive summary

The Bioliquids-CHP project involved resarch and technology development (RTD) in the following areas: (a) bioliquids upgrading, (b) modifications of prime movers (engines and turbine) to enable efficient use of bioliquids, (c) pollutant emission reduction, and (d) techno-economic and environmental assessment of the developed systems.

Regarding the research on bioliquids, several batches of biofuels have been produced or purchased, characterised and upgraded. These biofuels included fast pyrolysis oil made from pine and straw, straight vegetable oil (i.e. sunflower oil), and biodiesel. These biofuels were characterised and their ageing behaviour was monitored. RTD activities focused on upgrading fast pyrolysis oil and on preparing blends or emulsions for use in engines/turbine. Different approaches for upgrading fast pyrolysis oil were investigated, including (a) partial dewatering and fractionation, (b) solids removal in a centrifuge, (c) esterification of acidic components with alcohol, and (d) mild hydrodeoxygenation under elevated pressure in the presence of hydrogen and a catalyst. The production of tertiary blends of fast pyrolysis oil, biodiesel and alcohol was also investigated.

RTD on engines/turbine initially focused on identifying and implementing modifications that would enable the use of bioliquids. The engines/turbine considered in the project include two internal combustion (IC) engines, a newly developed external combustion engine and a micro gas turbine (MGT).

BTG ran tests with a Chinese diesel engine (Jiang Dong 1-cylinder 20-kW_e), running it on diesel oil, biodiesel, sunflower oil, ethanol and fast pyrolysis oil. They characterised the engine and identified required modifications and suitable materials to manufacture fast pyrolysis oil resistant engine parts. An extensive testing programme was implemented to understand the combustion behaviour of a range of biofuels and to steer further development and modifications. A significant achievement was the operation of the engine for 40 hrs on pure fast pyrolysis oil without any change of fuel pump or injector, and without significant effect on the flue gas emissions. Similar results are not found in literature.

NAMI modified and extensively tested a Russian diesel engine (YMZ-238M2). It was was assembled on a test bench with a generator, an exhaust gas cleaning system (developed and supplied by BIC), a heat unit and a microprocessor control system. The exhaust gas cleaning system consists of a syngas reactor and DeNox unit. BIC carried out extensive research to identify and select the most suitable catalysts.

The third project partner working on engines is Encontech. They deevelop and modified a Rankine-cycle engine and a Stirling/Manson-type single-piston external combustion engine. First individual engine components were improved and tested, and later the complete engines. The improvements resulted in the design of an unparalleled versatile new heat engine that can use any heat source (including a variety of bioliquids) from 50 to 1000 ^{o}C and is easy scalable in the range 1-1000 kW_e per cylinder.

The University of Florence worked onm a micro gas turbine (Garrett GTP 30-67). The turbine was adapted with minor modifications for vegetable oil and biodiesel, and characterised using diesel oil. Computational fluiddynamic simulations were carried out on the combustor to assess major modifications required for biofuels feeding. This work led to the design, construction and assembly of a modified combustor chamber. Testing with biodiesel and vegetable oil showed a reduction in flue gas emissions, and the modification is considered successful. Test runs with fast pyrolysis oil have not yet been successful mainly due to stability problems with the oil feeding pump.

Finally, the project assessed the developed systems in terms of economic and environmental performance, and identified market opportunities for prospective users of the developed systems. Aston University prepered a partial database of prime movers using bioliquids in CHP mode in partner EU countries, and developed an MS-Excel model for economic evaluation, sensitivity analysis and case studies.

Additional project achievements are the organisation of final dissemination event in Brussels and the preapration and publication of a comprehensive set of training and education materials on bioliquids.

II. Summary description of project context and objectives

Concept and project objectives

Ideas behind the project

The EC has set a target to increase the share of CHP in the European energy supply from the current 10% to 18% in 2010. One of the objectives is to develop distributed energy systems for remote regions with special emphasis on the integration of renewable energy in these solutions. To date the implementation of small-scale (50 to 1000 kW_e), direct biomass-to-electricity CHP-systems has been limited due to:

- Relative high investment and running costs;
- Poor reliability and availability, and
- Low acceptability by the end-user

The reasons causing these *intrinsic* problems are manifold, but main causes are:

- The presence of contaminants in biomass;
- The limited availability of *uniform* types of biomass;
- The non-uniform appearance of biomass, and
- Its general low energetic density (especially in terms of GJ/m^3), causing huge volumes of biomass stocks to be stored near the electricity production unit.

A specific pre-treatment technique, fast pyrolysis, is able to address most of these problems. It can produce clean and energy dense liquids from non-uniform, contaminated and fluffy biomass. In addition, the biomass conversion can be de-coupled (in place, time and scale) from power generatin. The heart of the power production system can then be an engine, viz. either a diesel engine or a gas turbine. Unfortunately, the liquids resulting from fast pyrolysis have rather different characteritics than conventional fossil fuels: they are acidic (pH ~ 3), contain high contents of oxygen and (~25 wt%) water, have low heating content (~18 MJlitre), poor lubrication properties, high ignition temperature (compared to fossil diesel), typically contain fuel bound nitrogen (yielding NO_x) and are susceptible for further polymerisation.

The aim of the project “Bioliquids-CHP” was to develop and demonstrate a cost-effective, biomass based combined heat and power (CHP) system by using liquids derived from fast pyrolysis as intermediate liquid by either modifying the engine, upgrading the fuel or a combination thererof.

The project builds further on the ‘best practice’ pre-treatment technology, producing cheap fast pyrolysis oils (or emulsions in vegetable oils), to be used for high-efficiency engines (diesel and gas turbine). Russian engines, though a bit less efficient than the European ones, are more flexible towards fuel quality. However, it may be very beneficial or even necessary to start from such a robust, and potentially more reliable, engine. Gaps in knowledge to be investigated include the upgrading of fast pyrolysis oils (a.o. de-watering, emulsifying, hydrotreating, catalytic cracking) and effective use in diesel engines and turbines (injector related issues, pumping problems, combustion characteristics). Technical as well as non-technical barriers for further implementation will be identified. Experts from Europe and Russia will be involved in the complete chain, in their own specific part of their expertise, from pyrolysis (upgrading, with / without catalyst), through engine developments (diesel engine and turbine) to electricity production.

Bioliquids-CHP aimed to develop combined heat and power (CHP) system by using liquids derived from fast pyrolysis as intermediate liquid. In this way the biomass conversion is de-coupled from the power production.

Progress beyond the state of the art

Fuel from fast pyrolysis of biomass and other biofuels

The worldwide leaders of processing of biomasses into liquid biofuels through the fast pyrolsyis process include Ensyn/Envergent (Canada/USA), BTG Biomass Technology Group BV, (the Netherlands), and Metso/VTT (Finland). Technologies developed can be classified as:

- Fluidised bed;
- Circulating fluidised bed;
- Rotating cone, and
- Ablative pyrolysis (cone or disc-types);

Fast pyrolysis is a moderate temperature (ca 500 °C) process in which biomass (crops, wood or other organic material) is rapidly heated in the absence of oxygen. As a result, it decomposes to generate mostly vapours and aerosols and some charcoal. After cooling and condensation a dark brown mobile liquid is formed, with a heating value about half of that of conventional fuel oil. While it is related to the traditional pyrolysis processes for making charcoal, fast pyrolysis is an advanced process carefully controlled to give high yields of liquid. The obtained fuel (about 75% wt of the biomass is transformed into a dense oil) turns out to have a cost comparable, although still higher, to that of fossil fuels. There have been significant advances in the science, technology and applications of pyrolysis liquids in recent years, particularly with respect to applications where the crude liquid is increasingly being considered directly for heat and power with minimum upgrading. Compared to the original biomass, fast pyrolysis oil has a significant increase in the energy density on a volumetric basis (5 to 10 MJ/m^3 for wood compared to 18-23 MJ/m^3 for fast pyrolysis oil).

A typical issue of fast pyrolysis oil for application as an engine fuel is its low heat content, the high ignition temperature, its corrosive properties and its low polymerisation temperature (<100 °C) For this reason, fast pyrolysis oil cannot be used in a diesel engine or turbine without some modification to the injection system. It is also not possible to directly use fast pyrolysis oil as an additive to conventional diesel fuel or to biodiesel since it is not miscible with these liquids.

The approach adopted in Bioliquids-CHP is the modification of the prime mover, upgrading the bioliquids or a combination of both to achieve the economic optimum.

Fast pyrolysis oil upgrading

The lack of availability and consistency of fast pyrolysis oil used to be a serious problem in developing engine applications, but significant progress was made tackling this issue in the zeroes. Still, fast pyrolysis oil is high in oxygen content (up to 45 wt%) due to mainly aliphatic and aromatic alcohols, ethers, ketones, carboxylic acids and water. These oxygenated compounds (more than 400 different compounds, including acids, alcohols, aldehydes, esters, ketones and aromatic compounds are identified) are responsible for some deleterious properties of fast pyrolysis oil: high viscosity, non-volatility, poor calorific value, corrosiveness, immiscibility with fossil fuels, thermal instability and trend to polymerisation on storage and transportation. Hence, the pyrolysis oils needs upgrading to reduce the oxygen content. The properties that most negatively affect fast pyrolysis oil fuel quality are low heating value, incompatibility with conventional fuels, solids contents, high viscosity, incomplete volatility and chemical instability. In the Bioliquids project further upgrading the fast pyrolysis oil has been explored to simplify its use in prime movers. Critical properties for use as engine fuel are char content, acidity, poor lubrication and ignition behaviour. Some of the properties can be dealt with by modifying the engine (poor lubrication, ignition behaviour), but this may result in very expensive modifications. It can be much more effective to improve the pyrolysis oil quality; char can be removed by using filtration technologies, ignition improvers and stabilizers can be added etc. A direct feedback and feed forward with engine research should result in the optimum fast pyrolysis oil quality.

Options that were investigated include both physical and chemical upgrading. Options for the latter are in-situ measures (e.g. catalytic cracking using hydrocarbon cracking catalysts) and close-coupled (e.g. partial hydrogenation).

Fast pyrolysis oil engine development

Of all the different fuels to be tested in the project, pyrolysis oil will be the most difficult one to use.The use of latter one in engines/turbines has a lot of technical implications due to different composition, different physical, chemical and technical characteristics visa-a-vis diesel oil. The main issues are:

- Maintenance of power and fuel consumption characteristic on equal level with traditional fuelled engine. It is a problem because fast pyrolysis oil has a modified chemical characteristics and physical characteristics of working body such as low level of calorific value;
- Neutralization of toxic components in exhaust gas especially NO_x;
- Rebuilding fuel injection system due to different viscosity-temperature characteristics;
- Fast pyrolysis oil is more aggressive towards engine materials. This fact requires the replacement of materials (also plastics) used in fuel storage and fuel injection systems especially in gaskets;
- The structure and characteristics of fast pyrolysis oils depend on the initial feedstock;

Summarizing, to develop a successful fast pyrolysis oil CHP development is required on both aspects of the chain, the fuel and the engine: in both tasks European and Russian researchers will collaborate:

Fuel:

- Upgrading the oil to minimize engine modifications: this upgrading will start with physical upgrading, but may include chemical upgrading as well (a.o. catalytic processes); the processes may be done in-bed (during pyrolysis), or ex-bed by modifying the liquid oil after production; additionally blends and emulsions will be prepared.

Engine/turbine:

- Re-design of the injection system, including alternative materials or coatings, injection needle and pump elements. Installation of a water jacket around the tip of the injector may be required to cool it as much as possible.
- Preheating of the combustion air inlet up to 130°C through the use of an in-line heater to overcome the ignition problems or increasing compression ratio;
- Modification of the fuel circulation loop, including the installation of stainless steel mesh filters to capture the char and the particles formed within the system.

Exhaust abatement in bio-fuel and diesel engines

Of the various pollutants emitted by diesel engines and gas turbines, the emission of carbon containing molecules and materials (CO, unburned hydrocarbons, soot and particulate) is strongly dependent on the combustion chamber temperature. When using biofuels, and specifically fast pyrolysis oil, in some cases the low heat content of the fuel has led to the combustion temperature to be not sufficiently high to obtain complete combustion, leading to the emission of pollutants such as CO and particulates. Bioliquids-CHP aimed to address theis problem by proper injection, compression ratios, heat loss reduction etc.

Other typical pollutants emitted by diesel engines are sulphur oxides (mainly SO_2) and nitrogen oxides (NO_x) and sulphur oxides (mainly SO_2). The sulphur content of biofuels is normally negligible, and sulphur oxides do not constitute a problem. Nitrogen oxides result either from the presence of nitrogen in the fuel, or from the formation of "prompt" NO_x. The relatively low nitrogen content of fast pyrolysis ysis oil combined with the application of NO_x abating traps technology may result in NO_xemission levels that for fast pyrolysis oil to be lower than than for diesel oil. Biolioquids-CHP aims to further adopt the NO_x abatement in an effort to achieve a near "zero-emission" device which could be used e.g. in conjunction with electrical motors to provide a near zero pollution hybrid propulsion system. The project considered a NO_x storage/reduction system that would permit near 100% conversion of NO_x over a range of temperatures, and circumvents the current drawback of this system (i.e. sulphur intolerance) due to the absence of sulphur in fast pyrolysis oil. Among others, the reaction of selective catalytic reduction (SCR) of NO_x by injecting small amounts of reducer gas in the engine exhausts was investigsted. Candidate reducers include unsaturated hydrocarbons, propane, primary diesel fuel, ammonia, urea and syngas (CO/H_2 mixture).

Overall project stategy

The aim of the project "Bioliquids-CHP" was to develop and demonstrate a cost-effective, biomass based combined heat and power (CHP) system by using liquids derived from fast pyrolysis as intermediate liquid by either modifying engines, upgrading and/or blending biofuels or a combination thererof. Commercial application of such units is expected in the capacity range of 50-1000 kW_e . The project focuses on three main issues i) the development of the engine, ii) fuel preparation, and iii) emission control (NO_x). Each of the activities have been implemented in a separate work package. Eventually, the different options have been evaluated in an economic, technical and environmental assessment study.

Project structure

The overall structure of the project is illustrated in Figure 1.

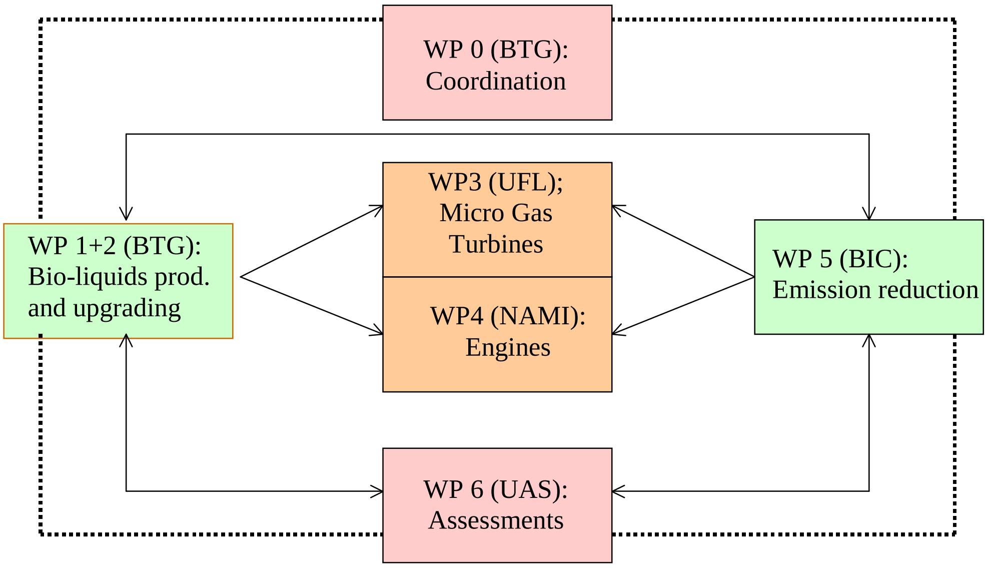


Figure 1: Graphical representation of work packages and their interrelation

Description of the main S&T results/foregrounds

WP1: Bioliquids selection, production & characterisation

The objectives of this WP were to select different types of bioliquids and to produce fast pyrolysis oil from different sources in sufficient quantities as required. All bioliquids used in the project were characterised.

Selection & production of bioliquids

A range of different bioliquids was evaluated for use in prime movers. The ‘primary’ bioliquids are 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 (Figure 2). Two batches of pine derived pyrolysis oil (in total 1,500 kg) and one batch of straw derived oil (~100 kg) were produced and used for the experiments. Additionally, a batch of fast pyrolysis oil was produced from wheat straw. ‘Secondary’ (bio-)liquids used are bio-ethanol and butanol. These were used in a few 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 bioliquids a range of properties were determined and these are summarised in Table I. 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 e.g. the heating value, Cetane number and viscosity. The viscosity of liquids can be lowered by preheating the fuel as illustrated in Figure 4 and Figure 5. For use in stationary diesel engines, the viscosity of the fuel should be below 17-20 cSt.

Figure 2: Pyrolysis pilot plant at BTG

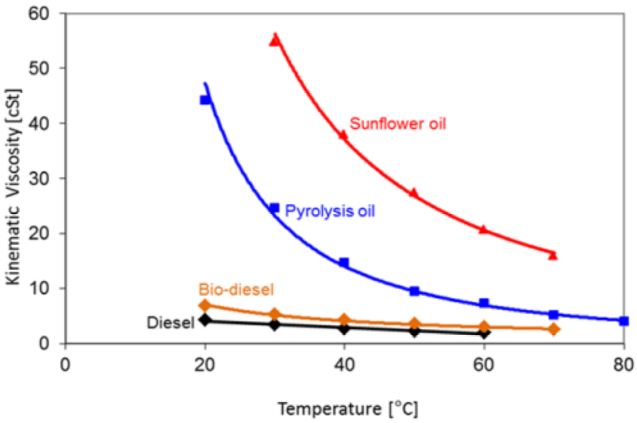


Figure 3: Kinematic viscosity of biofuels as a function of the temperature.

Another important property of any bioliquid -but in particular for fast pyrolysis oil- is its ageing behaviour. A suitable method to study this aspect is the change in kinematic viscosity over time. This change in viscosity was monitored for the different bioliquids during a couple of months. The bioliquids 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 **Error! Reference source not found.**. The relation between aging of fast pyrolysis oil and storage temperature can be described with the following Arrhenius like equation:

$$\Delta viscosity = 3.6 * 10^{11} e_{RT}^{-68,549} \quad (\%/\mathrm{day})$$

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/Ltr	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- 20°C	cSt	6.9	80.7	65.1	-	80.4	1.5	3.6
-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;

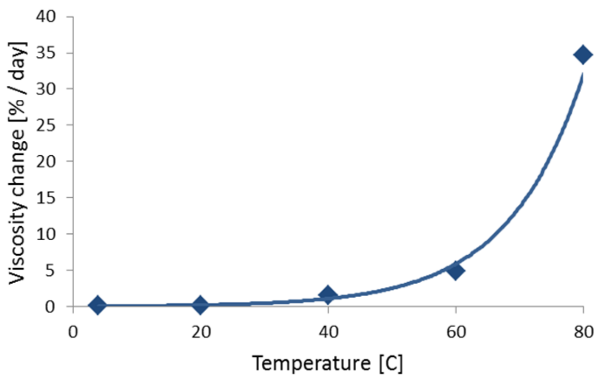


Figure 4: Change in viscosity of fast pyrolysis oil as a funtion of the storage temperature

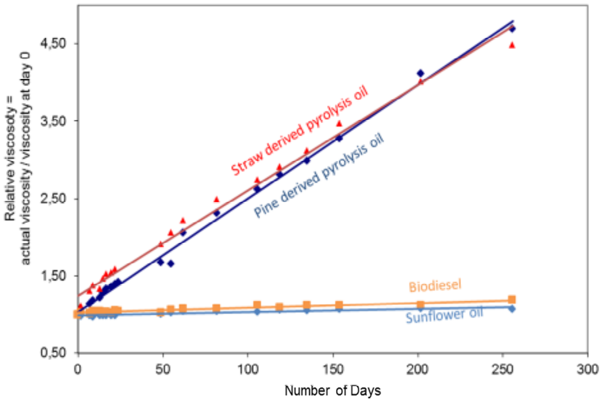


Figure 5: Change in viscosity as a function of storage time for different fuels at 40C

WP2: Bioliquids upgrading & blending

Fast pyrolysis oil (sometimes also refered to as bio-oil) is considered the most difficult fuel of the bioliquids tested. It has been tested in engines in the past with limited success. Fast pyrolysis oil has poor combustibility, requiring a pilot fuel or additives for successful engine combustion. In addition, fast pyrolysis oil could have adverse effects on engine components due to its acidic characteristics and the presence of particulates. It is not possible to upgrade fast pyrolysis oil with conventional fuels as they are immiscible.

A series of tests were designed to attempt the upgrading of fast pyrolysis oil to enable or simplify its application in prime movers. The main objective of WP2 is the production of biofuels with improved fuel characteristics through i) physical treatment, ii) chemical treatment, iii) preparation of emulsions using different bioliquids or iv) preparation of blends using different bioliquids.

Physical treatment

Removing water from fast pyrolysis oil

Fast pyrolysis oil from biomass typically contains about 25wt% water. This high water content reduces the energy content value and has a negative impact on ignition properties. Therefore, partial removal of water may be advantageous. In Figure 6 a picture is shown of the film evaporator used in the laboratory. Typical throughput is 1-2 kg/hr of oil, a pressure of 100-200 mbar, and a temperature of 50-60 °C. Inconveniently, removing water leads to an increase in oil viscosity (see Figure 7) and oil ageing becomes more severe. For low water contents (< 10 wt%) it is hardly possible to obtain sufficient lower viscosity at an acceptable fuel preheat temperature. Adding ethanol to the dewatered fast pyrolysis oil can offset these detrimental impacts.

Figure 6: Lab-scale film evaporator to remove water from fast pyrolysis oil

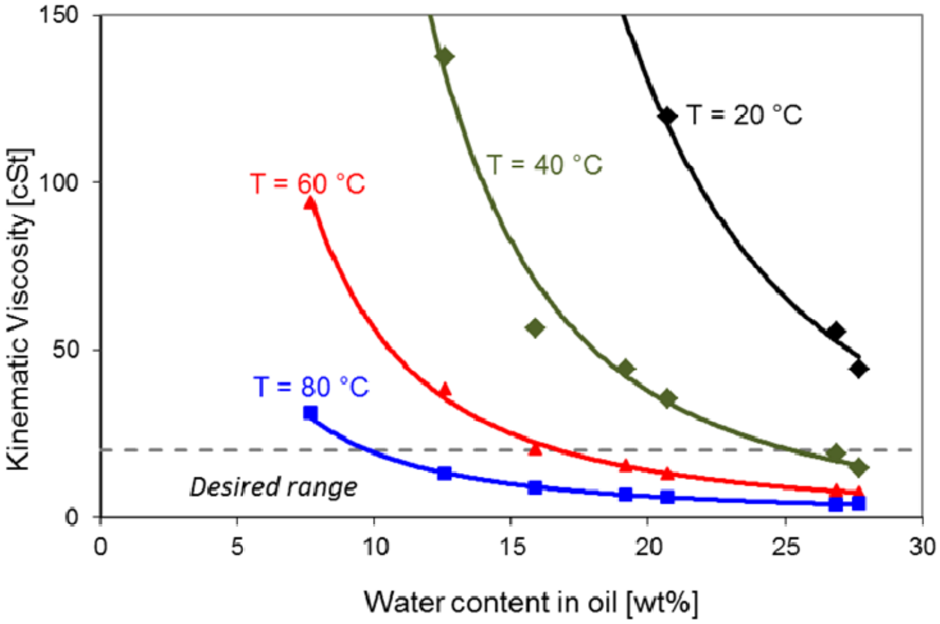


Figure 7: Kinematic viscosity as function of the water content in fast pyrolysis oil and for different temperatures.

Reducing solids content in fast pyrolysis oil

Untreated fast pyrolysis oil can have a high solids content. When applied in prime movers this can easily lead to plugging and wear of e.g. fuel pump and injector. Devices tested on different scales on 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 (high solids removal, easy operation and limited oil loss) were obtained with the self-cleaning centrifuge (see Figure 8).

Figure 8: GEA Self-cleaning centrifuge

Table 2: Results with GEA centrifuge

	Flowrate [kg/h]	Cleaning freq. [minutes]	Ash content [wt.%]
1	246	8	0.06
2	171	15	0.033
3	180	15	0.041
4	n.d.	5	0.019

Chemical treatment

Through chemical treatment specific fast pyrolysis oil properties can be changed. Two approaches were explored, i.e. mild hydrotreatment and reactive distillation with an alcohol.

Mild hydrotreatment of fast pyrolysis oil

Mild hydrotreatment implies catalytic treatment of fast pyrolysis oil in the presence of hydrogen at elevated pressure. The resulting fast pyrolysis oil has reduced acidity, increased energy content and improved ignition and thermal stability properties. The hydrotreatment is performed in BTG's hydrogenation unit (Figure 9), applying a patented catalyst developed jointly with the Boreskov Institute of Catalysis (BIC) and Rijksuniversiteit Groningen (RUG). The operating pressure is typically around 200 bar, and reactor temperatures can be up to 350 °C. The hydrogen consumption is about 10-20 gram/kg oil. The fuel produced is referred to as "Mild-HDO".

Reactive distillation of fast pyrolysis oil

Fast pyrolysis oil was treated with an alcohol in a reactive distillation process and in the presence of a catalyst. The resulting fast pyrolysis oil has a lower acidity and water content, and a 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 reactant and applying 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 via the vapour phase. This fuel is referred to as "PO-Ester". Besides butanol also octanol and glycerol have been tested. With glycerol no useful results were obtained. In Table 3 some further information on these tests are given.

Figure 9: HDO test unit at BTG

Table 3: Process conditions for reactive distillation / esterification of fast pyrolysis oil

	Alcohol/amount (g)	Bio-oil amount (g)	Catalyst (g)	T (°C)	TAN (mg KOH/g)	Viscosity (40 °C)
Sample 1	1-butanol / 12.9	100.2	2.95	100-110	50.5	61.4
Sample 2	1-butanol / 12.7	103.0	2.95	80-85	43.0	127.5
Sample 3	1-octanol / 12.0	101.6	3.03	80-85	26.1	160.9

Emulsification and blending

Emulsification

Emulsification of fast purolysis oil with diesel fuel was investigated as an economic solution for improving and upgrading fast purolysis oil properties. The emulsion of biodiesel in fast purolysis oil was prepared starting from a batches of EN14214-compliant biodiesel supplied by Novaol (Italy) and 25 liters of fast pyrolysis oil from fast pyrolysis of pine by BTG (The Netherland). Atlox 4912 was selected as the emulsifying agent (surfactant) after the screening phase among almost 40 polar and apolar surfactants.

The procedure for the emulsification was as follow:
1. The surfactant Atlox 4912 was dissolved in biodiesel at about 45˚C;
2. The biodiesel/surfactant solution was cooled down to room temperature;
3. The solution is emulsified with BCO under vortex mixing for 5 minutes at room temperature.

The final composition of the emulsion was: bio-oil 94.75 wt.%, surfactant 0.25 wt.%, biodiesel 5 wt%. Once the emulsification process was completed, a dense phase, referred to as “cream”, floated at the top of the main phase, i.e. the emulsion, which could be easily removed by mechanical means.

Blending

A series of tests was designed to blend fast pyrolysis oil with biodiesel in the presence of an alcohol in order to overcome some of the disadvantages of use of either fuel by itself. Fast pyrolysis oil is immiscible with biodiesel, however, the presence of an alcohol allows the blend to stabilize and form a single homogeneous phase. The alcohols used as co-solvent were ethanol, 1-butanol or 2-propanol. As the alcohol is bio derived, the use of a 100% renewable liquid fuel in engines could take advantage of incentives potentially available for renewable power.

Experiments were carried out in which variable proportions of the three components were planned and tested in order to build three phase diagrams (one per alcohol used), with the objective to identify the boundary between a homogeneous one phase blend and a multiple phase blend. Tests were designed to cover a wide spectrum of proportions for all three alcohols, using the sample homogeneity (visual aspect) after 48h as the main criteria.

The tests were documented through the characterization of selected homogenous samples, the estimation of particular properties such as heating value and elemental composition for all samples, while at the same time photographic evidence was gathered for all samples. Three-phase charts were prepared for each of the alcohols highlighting the area in which the blend is a homogeneous one-phase liquid (see Figure 10). Blends using butanol showed the largest area of stable one-phase blends, followed by mixtures using propanol while blends containing ethanol showed the smallest homogeneous one-phase area. A new development was achieved during the upgrading through blending as the concept proved to be successful.

The most important feature of this achievement is the ability to, within the component limitations, tailor the blend to target the end user requirements if necessary, e.g. heating value, viscosity or flash point. A number of homogeneous one-phase blends were tested for stability, viscosity, pH and density. A patent has been applied for, for the blending concept and the concept was nominated among the best 10 ideas in the Cleantech Open UK 2011 competition.

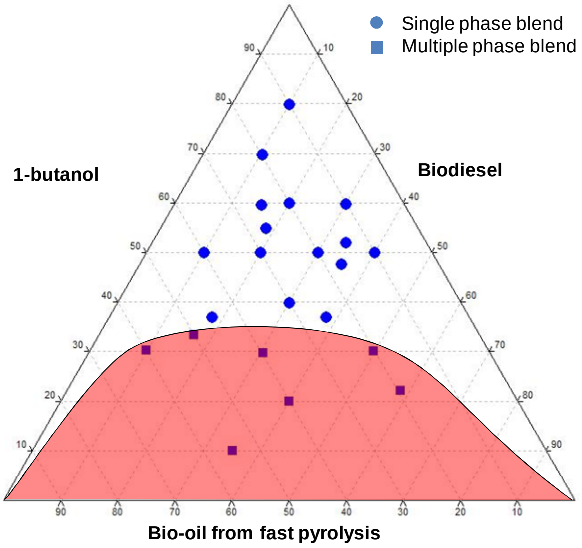


Figure 10: Three phase chart for bio-oil/biodiesel/butanol blends, showing homogenous blend and phase separation

Properties of upgraded bioliquids

In Table 4 the properties of upgraded fast pyrolysis oils are presented. As starting point the first batch of fast pyrolysis oil (Pine I) was used. Clear differences can be observed for e.g. heating value, water content, viscosity and carbon residue. In all cases the fuel remained acidic.

Table 4: Properties of modified fast pyrolysis oils

Property	unit	Emulsion	PO-Ester	Mild HDO	Blend
C	wt%	44.4	58.4	67.6	54.5
H	wt%	6.4	7.4	8.1	8.7
N	wt%	<0.1	<0.1	<0.1	<0.1
O (balance)	wt%	49.2	34.2	24.2	36.8
Water content	wt%	22.8	6.6	6.7	17.2
Ash content	wt%	0.298	0.018	0.017	0.01
Solids content	wt%	-	-	-	0.02
Density	kg/m^3	1,198	1,158	1,106	998
LHV, calculated	MJ/kg	16.3	24.0	27.0	23.8
LHV	MJ/ltr	19.5	28.0	29.9	23.8
pH	-	2.1	3.0	3.1	3.0
MCRT	wt%	18	20	11	8
Kinematic viscosity (40 °C)	cSt	36	115	149	7
Acid number	mg KOH/g	-	22	-	53
Carbonyl number	mg BuO/g	133	112	10	-

Which of the investigated upgrading techniques is the best depends on the end-use of the pyrolysis oil. In CHP application (engine or turbine) a low solid, homogeneous fuel is required. Filtration/centrifuging will always be required to obtain and guarantee sufficient low solids content. Solids removal has a limited effect on pyrolysis oil price (< 5% change). Depending on the feedstock used for the PO some dewatering may be required. This is e.g. the case with straw-derived pyrolysis oil. Generally, the chemical upgraded pyrolysis oil fuels, emulsions and blends showed a somewhat improved combustion behaviour in the engine compared to crude pyrolysis oil (see WP4). However, in all cases the pyrolysis oil remained acidic and a full retrofit of the engine is still required. In parallel it was demonstrated that the engine could run on pure pyrolysis oil (filtrated not chemical treated). Therefore, it is concluded that chemical upgrading the oil does not improve the overall economics.

WP3: Micro Gas Turbine

The main objective of WP3 was to develop micro gas turbine components (and eventually turbines) that are tolerant towards the bio-liquids mixtures and the upgraded fast pyrolysis oils. The engines should be applicable for CHP systems in a power range of 50 to a few hundred kW$_e$.

Modification of the micro gas turbine

A Garrett GTP-3067 micro gas turbine (MGT) was selected based on three main requirements: robustness, simple design and silo-shaped combustion chamber. A test rig, comprising the engine itself, auxiliary and instruments, was built. The performance of the MGT was compared with a reference turbine i.e. a Capstone C30 MGT modified to run on straight vegetable oil as feedstock.

A parametric study was carried out on the Garrett turbine to assess the necessary modifications to the fuel line to make it capable of working on a variety of biofuels, i.e. vegetable oil, biodiesel, bio-ethanol and fast pyrolysis oil. With the aid of RE-CORD personnel, a detailed survey of the scientific literature on the possible material compatibility issues related with the use of fast pyrolysis oil and first generation biofuels was carried out to select the proper materials for the pump. RE-CORD also assisted with analytical determinations on biofuels and material selection. A gear pump with AISI 316 shafts and body and PEEK gears was selected and installed on the MGT fuel line circuit because these materials were found to be among the most tolerant toward fast pyrolysis oil aggressiveness, and the pump could supply the required head and flow rate. Testing of the pumps with “conventional” biofuels and diesel was successfully passed.

A preliminary set of adaptations was made to the engine, and a test campaign carried out with “conventional” biofuels (bio-ethanol, biodiesel, vegetable oil). The test campaign yielded sufficient understanding of the problems that could arise operating the MGT on fast pyrolysis oil, and the necessary modifications were carried out on the test rig (see Figure 3 for the final test rig layout).

The modification of the MGT combustion chamber, needed to accommodate fast pyrolysis oil burning, was assisted by 0 and 3D computational fluid dynamics (CFD) simulations carried out on both cold and reactive environment; see Figure 11 and Figure 12 for illustrations of the output from these simulations. The new combustor (Figure 14) features several modifications compared to the original one, e.g. a different air repartition among combustion zone, less air entrance in the primary zone, a diminished jet penetrations, and increased flame temperature and temperature homogeneity.

After these preliminary tests, it was decided to proceed to fast pyrolysis oil testing. A specific switch procedure was studied and adopted in order to avoid an abrupt modification of fuel flow rate and combustion conditions inside the combustion chamber. When a mixture of ethanol (80%) and fast pyrolysis oil (20%) was fed to the MGT, the engine could be operated for approx. 3 minutes; during this interval, it was necessary to increase the pump flow rate because the engine could not maintain a constant rotational speed, and after three minutes a sudden decrease of the engine rotational speed happened, causing the shut-down of the system. It was tried to recover the full speed state by re-operating the start-up procedure five times, but it was not possible to operate the pump. An inspection of the pump was then carried out, and it was found that the graphite buckles that sustain the gears during normal operation were eroded (see Figure 15), causing the stop of the pump. No damages were found on the PEEK gears, nor on the AISI 316 shaft (see Figure 16). The pump was sent back to the supplier, repaired, mounted again on the test rig and tested, but showed the same behaviour.

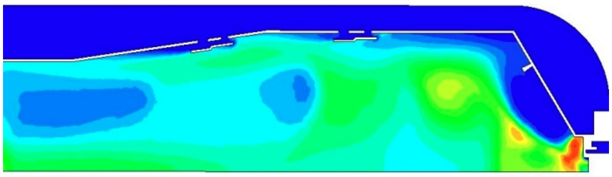


Figure 11: temperature field of the original combustor (same scale of figure 2).

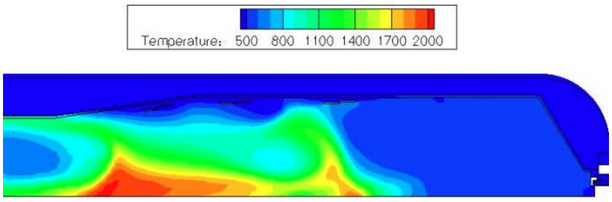


Figure 12: temperature field of the original combustor (same scale of figure 2).

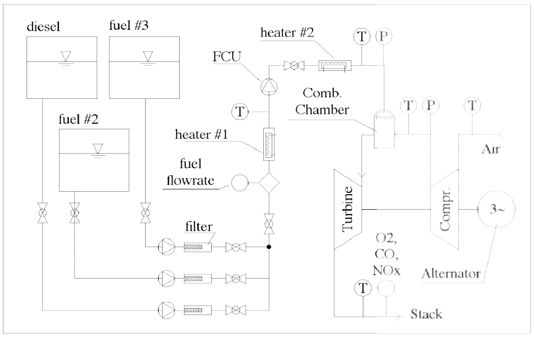


Figure 13: Layout of the MGT with highlighted the new measurement point and the tanks for biofuels testing.

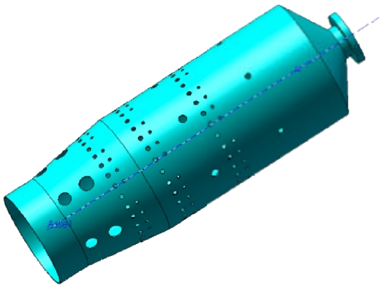


Figure 14: Layout of the modified combustor.

Figure 15: Damages on the graphite buckles on the left side of the NAX10 pump.

Figure 16: PEEK gear and shaft. Both elements withstood contact with fast pyrolysis oil perfectly.

Testing of the micro gas turbine

Testing of the MGT was varied out with the help of RE-CORD personnel at both the Montepaldi premise and Tagliaferri company mechanical workshop in Scarperia. In the first test campaign, the MGT was first characterized when running with diesel and then tested with vegetable oil, biodiesel and their mixtures, and the respective performance (e.g. hourly consumption, fuel injection pressure and temperature, exhaust gases temperature, O_2, CO and NO_x concentrations at the stack) compared to the baseline reference values on diesel. The effect of fuel preheating on CO concentration in the exhaust was investigated between 80°C and 120°C. Biodiesel preheating largely effects the CO concentration: at 80°C a reduction of CO concentration of approx. 37% compared to diesel at 20°C, and 51% compared to biodiesel at 20°C could be measured. 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 preheating at 120°C and with a minimum load of 5 kW; preheated vegetable oil generates CO emissions very similar to diesel at 20°C. CO emission of mixtures were found midway between and vegetable oil and biodiesel at the same preheating temperature; NO_x emission resulted to be always of few ppm for all fuels. Some results with the original combustor are reported in Figure 17 and Figure 18. During this test phase it was determined that the re-designed combustor performed far better that the original one when fed with diesel, leading to an almost six-fold reduction of the CO concentrations, confirming that the combustion conditions were largely improved; conversely, NOx increased two-fold, see Figure 19 and Figure 20.

Evaluation and assessment

The experiences gained during this project led to the a remarkable advancement in the know-how on the use of bioliquids in micro gas turbine; the basic project of a retrofit package was carried out, including a guide for the selection of proper materials and the development of a newly designed combustor, that can be potentially adapted to a wide range of existing engines that are characterized by the same geometry of the combustion chamber.

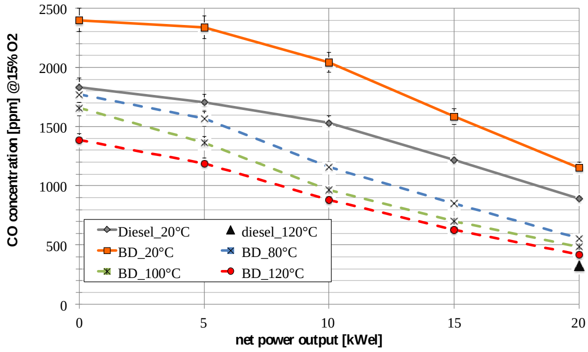


Figure 17: CO concentration in the exhaust (referred to 15 vol.% oxygen) for diesel oil (at 20 and 120°C) and biodiesel (at 20, 80, 100, 120°C).

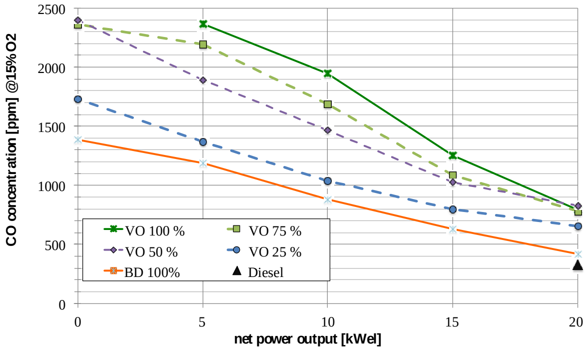


Figure 18: CO concentration in the exhaust (referred to 15 vol.% oxygen) for pure vegatable oil and several mixtures with biodiesel.

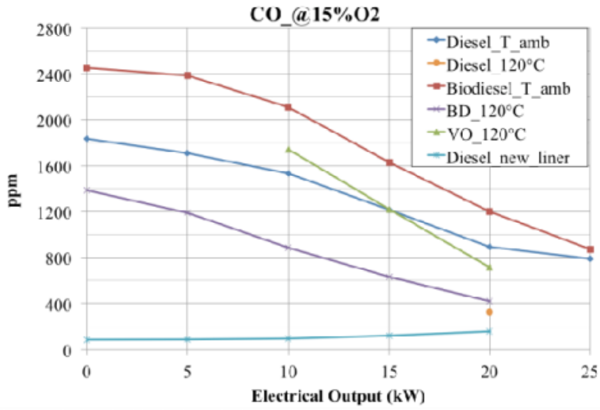


Figure 19: CO concentration (referred to 15 vol.% oxygen) in the exhaust for the modified combustor fed with diesel (light blue line); for comparison are reported the previous measured values.

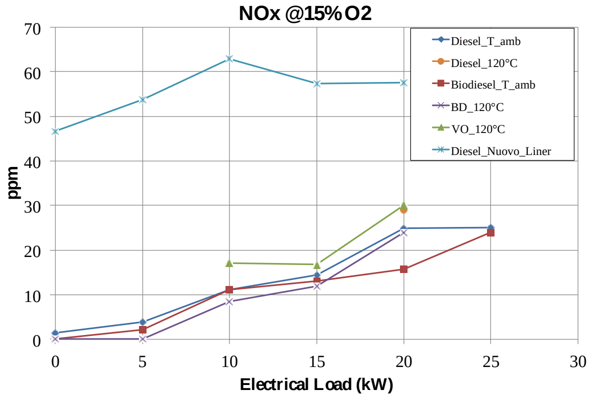


Figure 20: NO_x concentration (referred to 15 vol.% oxygen) in the exhaust for the modified combustor fed with diesel (light blue line); for comparison are reported the previous measured values.

WP4: Diesel Engines

The main objective of WP4 was to develop engine components (and eventually engines) that are tolerant towards the bio-liquids mixtures and the upgraded fast pyrolysis oils. The engines should be applicable for CHP systems in a power range of 50 – 1000 kW_e.

To attain this challenging objective three different approaches that are in line with the expertise of the participants were implemented:

- Modification of a conventional diesel engine to enable fuelling of fast pyrolysis oil and fast pyrolysis oil derived liquids.
- Development of a CHP system based on a conventional diesel engine operated on mixtures of fast pyrolysis oil derived liquids and diesel fuel.
- Development of new energy efficient external combustion engines capable of operation on a variety of bioliquids, including fast pyrolysis liquids.

The developments were led by BTG, NAMI and ECT (Encontech) respectively.

Modification of a conventional CI-engine to enable fuelling of fast pyrolysis oil (FPO) and FPO-derived liquids (BTG)

Introduction.

Diesel engines are internal combustion engines operated on the basis of a Diesel (compression ignition, CI) cycle. In this type of volumetric machines, finely pulverized combustible is injected inside the cylinder or an adjacent chamber, where it vaporizes and self-ignites, due to the temperature of the compressed air. Due to the characteristics of the combustion process, diesel engines are more tolerant towards a lower quality fuel, as well as generally more efficient, when compared to gasoline engines.

Diesel-cycle engines have a wide range of applications; and are widely used for commercial freight, construction, heavy truck, agricultural machines, and infrastructure maintenance. The diesel-cycle's inherent combustion efficiency advantage over Otto-cycle engines (powered by gasoline), and diesel fuel's dominant position in the refined petroleum products market, make this kind of engines a key technology for the introduction of liquid biofuels in the energy market.

Modification required.

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

- Fast pyrolysis oil is acidic and therefore all piping and devices in contact with fast pyrolysis oil 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 (< 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 filtrated;
- The viscosity of fast pyrolysis oil is higher than that of mineral diesel, and strongly depends on water content and temperature. Reducing the water content would further increase viscosity. To achieve sufficient low viscosities (< 17 cSt) the fuels can be preheated;
- Fast pyrolysis oil is sensitive to re-polymerisation, in particular, if 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 is achieved by preheating the incoming air. Alternatively, the compression ratio can be increased. Additionally, 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 output double the amount of fuel needs to be injected.

Engine test facility

BTG converted a standard Jiang Dong CI-engine to allow it to run on fast pyrolysis oils (and all other biofuels considered). Three fuel vessels are installed containing engine start-up fuel (mineral diesel), rinsing fluid (e.g. ethanol) and test fuel, respectively (see Figure 21). The test fuel can be preheated to about 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.

At several positions in the engine temperatures and pressures can be measured and logged. A fast response pressure indicator and oscilloscope are applied to measure fuel injection pressure. Two analysers are installed, measuring gas components , and soot and rotational speed respectively. The actual power output is measured with a smart power analyser.

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. For fast pyrolysis oil fuelling an air inlet temperature of around 100°C is required at a compression ratio of 17.6. By increasing this ratio to 22.4 the air inlet temperature can be reduced with 40°C.

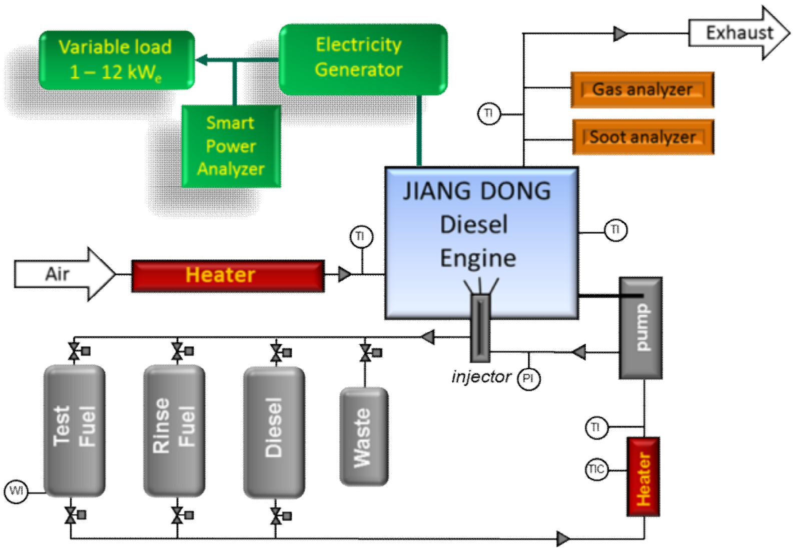


Figure 21: Engine test facility

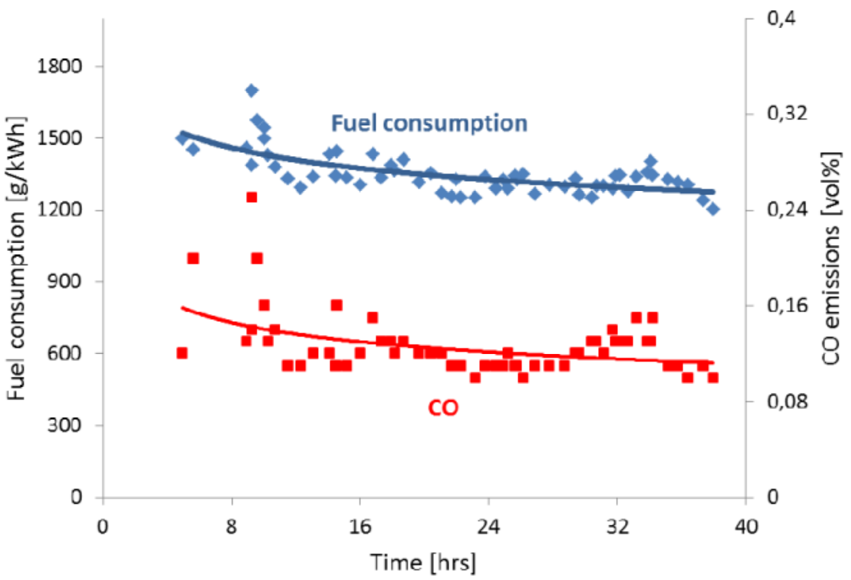


Figure 22: Fuel consumption and CO emissions as a function of time on stream for fast pyrolysis oil fuelling

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

In duration tests, the CO emissions and fast pyrolysis oil fuel consumption were monitored when the engine was operated for a period of 40 hours, spread over several days (a couple of hours each day, see Figure 22). In the first hours of operation the engine performance improved somewhat and then it stabilized. Obviously, for further development real long duration testing will be important.

All bioliquids described before (sunflower oil and biodiesel, neat and treated fast pyrolysis oil, blends and emulsifications) were tested in the diesel engine. Generally, the upgraded liquids were easier to ignite resulting in lower CO emissions and higher NO_x (see Figure 23), whereas the effect on overall efficiency was less pronounced . The liquids remain acidic, and thus a modified injection system will be required in all cases.

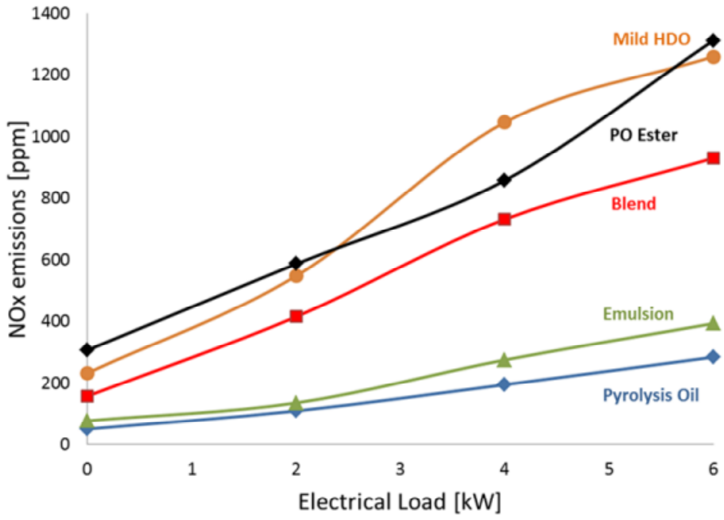


Figure 23: NOx emissions for the different fuels tested at 4 kWe load

Development of a CHP system based on a conventional diesel engine operated on mixtures of fast pyrolysis oil derived liquids and diesel fuel (NAMI)

A Russian made diesel engine, typeYMZ-238M2, was selected as the basis for the cogeneration (CHP) plant. This engine is assembled on a test bench with a generator, an exhaust gas cleaning system, a heat unit and a microprocessor control system; and extensive testing of the resulting CHP plant has been carried out.

The exhaust gas cleaning system consists of a syngas reactor and DeNox that were both developed by BIC. For this purpose, extensive catalyst research was carried out in WP5 in order to identify and select the most suitable catalysts.

Since the physical and chemical properties of bio-liquids differ from those of standard IC-engine fuels, engine modification was necessary to achieve long term operation of the engine without substantial reduction of the energy efficiency. Therefore first the influence of bioliquids on (the performance of) the individual engine components was studied. The study included the compatibility of the engine materials (elastic materials, alloys of non-ferrous metals such as brass, bronze, copper, lead, tin, and zinc) with bioliquids, the quality of the fuel filtration, wear of the fuel supply system components, and energy requirement for the injection of the fuels.

Based on the results of this study the following modifications were implemented in the fuel supply and gas exchange systems:

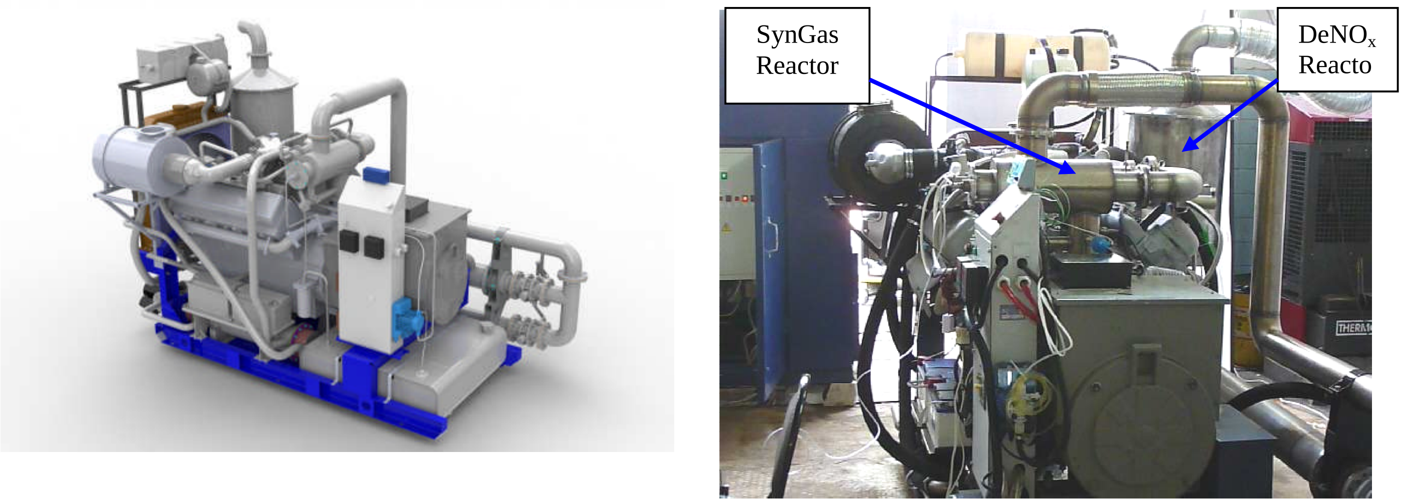
- Application of new materials (stainless steel, aluminium allows, plastics) in the fuel storage and supply sections including fuel pump.
- Application of various coatings in the fuel storage and supply sections.
- Upgrade of the fuel filters.
- Upgrade of gaskets.
- Optimizing the working parameters of the fuel injection system.
- Increase of the fuel supply pressure.
- Preheating of fuels for e.g. effective cleaning/ filtration.
- Adjustment of the control of the fuel supply system (upgrade of the fuel injection timing).

These modifications were deemed necessary due to different viscosity of bio-liquids and its dependence on temperature, presence of particulates, different fuel and air flow rates and undesired corrosive properties with respect to the materials of the engine.

Modifications of the gas exchange system were made to maintain the energy efficiency of the engine and included:

- Air filter.
- Geometry of the air supply lines.

The modified engine was assembled together with an electrical alternator of 30-100 kWe, an exhaust gas cleaning system, a heat supply/exchange system and a microprocessor control system. Figure 24 shows the constructed CHP plant, called AVTAB-1.



(a) **(b)**

Figure 24: AVTAB-1 CHP plant at NAMI (a) 3D Model (b) picture

An essential future of the modified engine is that synthesis gas is generated from the biofuel and used as an additive to the fuel for the engine. A reactor for synthesis gas production from biofuel will be developed by BIC. In addition the engine was equipped with a fuel preheating system, powered by accumulator for the engine start up.

Extensive tests of the modified engine, all its components and eventually of the entire CHP plant were performed. The tests confirmed the AVTAB-1 CHP plant meets all the originally set requirement. Its main characteristics are summarised below.

Electric power at nominal rating	100 kW
Highest possible heating power	150 kW
Efficiency of transformation of fuel energy to electricity	15,1 - 33,3 %
Efficiency of transformation fuel energy to heat	36,9 - 47,1 %
Overall energy efficiency of the plant	52,0 - 75,6 %
Reduction of NOx components in the exhaust gas	80,0 - 82,3 %
Hydrogen content in the synthetic gas	35 % vol
Sulphur dioxide content of in the exhaust gas	$(2 – 4)\cdot 10^{-4}$ kg/h

Development of new energy efficient external combustion engines (ECT)
The strength of external combustion heat engines vis-à-vis internal combustion engines is compatibility with a wide variety of fuel sources, low emissions and low noise.

In the course of the project three new types of heat engine were developed and tested at ECT: 1) Rankine cycle piston engine; 2) Stirling type single-piston (or Manson type) engine; 3) ECT engine.

The results obtained show that the engines each is an effective alternatives and supplements to the established methods of energy conversion - internal combustion engines, micro turbines, Stirling engines and fuel cells.

Rankine cycle piston engine

The Rankine cycle piston engine which resembles piston steam engine was developed based on the experience with the pulse compression reactors. It covers applications (temperature range of the heat sources) not suitable for the Stirling type engines. The engine principles are:

- a full absence of oil lubrication; side forces are eliminated by an especially designed crank gear and not by a lubricated guiding mechanism;
- an accurate linear motion of a self-centered, self-aligned piston is maintained by gas bearing generated by an insignificant leakage of working fluid through the clearance between the piston and cylinder;
- the gas lubricated piston plays a role of a slide valve delivering a working fluid to the cylinder.

Figure 25 shows a sketch of the engine and the assembled engine. The inner diameter of the engine cylinder is 40 mm, the piston stroke is also 40 mm.

During the engine tests the engine was driven by compressed air at pressure up to 20 bar instead of steam. The power and efficiency were estimated by measuring the angular acceleration of the flywheels (with the moment of inertia of 0.46 kg•m2 and 0.80 kg•m2) and the consumption of the compressed air during idle starting. The compression/expansion ratio was varied in the experiments. Figure 26 shows an example of the measurements.

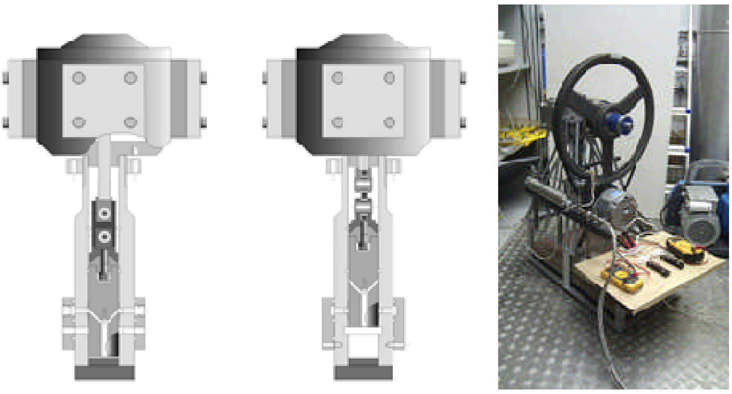


Figure 25: Sketch of the Rankine cycle piston engine (left) and the assembled engine with the permanent magnet alternator connected to incandescent lamps (right).

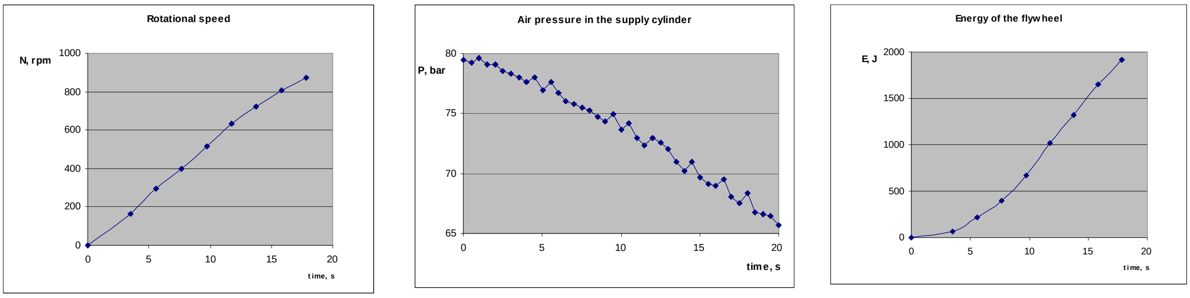


Figure 26: Engine speed, air pressure in the gas supply cylinder and energy of the flywheel as function of time during engine starting; moment of inertia of the flywheel 0.46 kg·m2, air pressure 17 bara.

For the tests at higher driving pressure the engine (crank gear) was connected to a permanent magnet alternator (Wind Blue Power DC-500) with electrical power up to 15 kW.

Based on the results obtained it can be predicted that without any optimization the current engine can generate about 5 kW by the use of hot steam at the pressure of about 100 bar. By making larger cylinders e.g. 120 mm diameter, and without further optimization, the power will have to increase to 45 kW per cylinder. This means that very compact multi-cylinder engine fuelled with bio-liquids can be made for mini-CHP systems with electrical power in the range of 50 – 1000 kW.

Stirling/Manson type single piston external combustion engine

Novel external combustion engine was proposed. It can be viewed as a Stirling engine utilizing Manson cycle[1]. The fundamental difference compared with Stirling engines is that the engine has only one moving part (piston). It can be called Stirling type Single Piston External Combustion (SSPEC) engine. Another important feature of the SSPEC engine is that the amount of the working fluid changes in the cycle.

Figure 27 explains the principle of the engine. In operation four stages can be distinguished. These stages are:

- A – Maximum amount of the working fluid in the cylinder; the pressure in the cylinder is higher than the pressure outside the cylinder, the piston/displacer moves up and more working fluid is coming to the hot part of the cylinder; the heating of the working fluid leads to the pressure increase which occurs faster than the pressure decrease due to the increase of the free volume in the cylinder.
- B - The valve opens, the pressure of the working fluid equalizes with the pressure outside the cylinder, and the amount of the working fluid in the cylinder becomes minimum.
- C - The piston/displacer starts to move down; this stage is similar to stage A, the difference is that now the amount of the working fluid in the cylinder is minimal and the pressure in the cylinder is less than the pressure outside it.
- D - The valve opens, the pressure of the working fluid equalizes with the pressure outside the cylinder, and the amount of the working fluid in the cylinder becomes maximum.

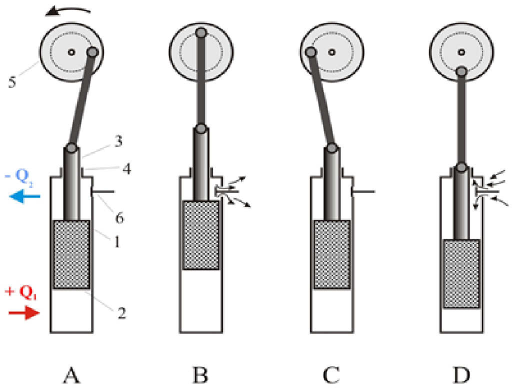


Figure 27: SSPEC engine principle: 1 –cylinder, 2 - displacer with regenerator, 3 – piston, 4 - piston seal, 5 - crank gear with alternator; 6 - valve.

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[1] Manson A.D. A Novel Hot-air Engine, http://www.stirlingengines.org.uk/work/cyc2.html

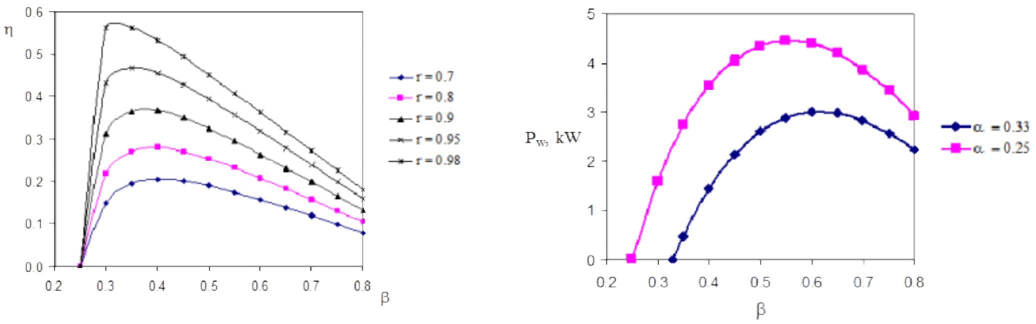


Figure 28: Thermodynamic efficiency (left) and mechanical power (right) of the engine as a function of geometrical parameter β = (S-Sp)/S for different regeneration efficiencies r and α = TC/TH= 0.25 and 0.33; d = 40 mm; P = 100 bar, speed 1200 rpm.

The thermodynamic analysis and detailed modelling of the engine were performed. Figure 28 shows examples of the thermodynamic analysis (where S and Sp are cross sectional areas of the cylinder and piston, and TC and TH temperatures of the cold and hot parts.)

For realistic geometric and operating parameters and the regenerator efficiency of about 95% the ultimate energy conversion efficiency of the engine proposed can be as high as 40 – 50%.

Several versions of the engine, all with inner diameter of the cylinder of 20 mm, were constructed and tested. Figure 29 shows the engine assembly with the crank gear and the assembled modified engine (without crank gear). The engine was equipped with a flywheel.

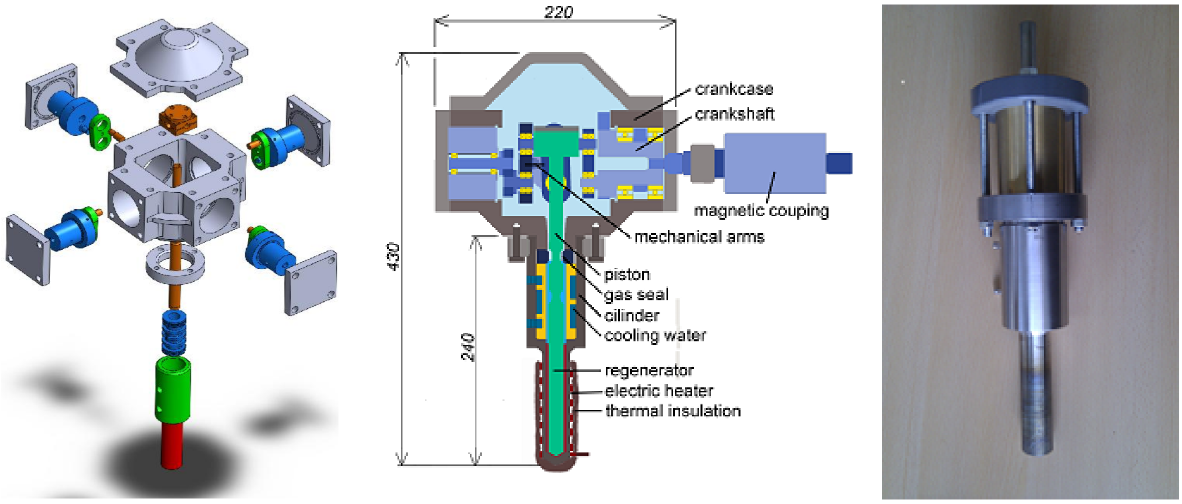


Figure 29: Engine assembly with crank gear and engine without crank gear

During the test a 1 kW electrical heater was used for heating of the engine cylinder from ambient temperature to 700 0C. Cold part of the engine was kept at constant temperature by flowing tap water. Air was used as the working fluid. Its pressure varied in the range 1 – 20 bar.

Most of the results obtained were qualitative. The power and efficiency were estimated by connecting the alternator to incandescent lamps with a nominal power of 100 W_e.

The engine developed has a number of advantages compared to state-of-the-art Stirling engines. The main advantage of the engine proposed is its simplicity. A power piston is integral with a displacer and a heat regenerator. It allows solving the problem of the high-temperature sealing of the piston and the displacer typical of all types of Stirling engines. In addition the design proposed provides ideal use of the displacer volume eliminating heat losses from outside gas circuit. Both strokes of the piston are working ones. The engine can be considered as maintenance-free as it has no piston rings or any other rubbing components requiring lubrication. The only seal is contactless and wear free. It is located in the cold part of the cylinder. As a result the gas leakage rate can be one-two orders of magnitude as small as that in Stirling engines. Balancing of the engine is much easy compared to Stirling engines.

A remarkable feature of the SSPEC engine is that according to its principle any working fluid can be used in the engine. To confirm the expectation water was used as a working fluid. The engine with water started running at the set temperature of the heater of 300 ^{0}C. This discovery extends substantially capabilities of the engine, in particular for bio-liquid applications. It has also cleared the way towards fundamentally new engine concept which combines all the advantages of the Stirling type and Rankine cycle piston engines.

ECT heat engine

Combination of the ideas behind the Rankine cycle piston engine and SSPEC engine resulted in a new heat engine, temporally called ECT engine, which combines all the advantages of its predecessors and has no parallels.

The basic principle of the ECT engine is similar to that of the SSPEC engine. However the design of the ECT engine is very much different. In particular: a) in the SSPEC engine the gas exchange stages B and D are not accompanied with useful work, whereas at ECT engine they do; b) the piston of the ECT engine is not connected directly to the crank gear; c) the regenerator of the ECT engine is decoupled from the piston.

Figure 30 shows the ECT engine parts and the assembled engine.

The engine tests confirmed that the novel engine has a number of advantages compared to conventional prime movers. The main advantage is its simplicity resulting in a higher efficiency, increased lifetime and low cost.

According to the concept the novel engine, in contrast to any other known engine, can use any heat sources from 50 to 1000 ^{o}C and easy scalable in the range 1 W - 1 MW$_e$ per cylinder. It suits ideally for CHP systems operated on a variety of bioliquids and is applicable for various other purposes, e.g. for pumping, compression and propulsion. Exhaust heat recovery systems for cars is another unlimited market for the engine developed. The engine can also be used for vehicle propulsion. This would permit to substantially decrease level of CO, NO_x and C_xH_y pollution.

Figure 30: ECT engine parts (left) and assembled engine (right).

Determing which engine type/class is best suited for difficult bioliquid fuels is not straightforward. There is a large number of economic and technical factors that influence the suitability. For instance, from one side stationary combustion is easy to arrange and therefore external combustion engines look more attractive; from other side IC-engines are widespread and various versions are available. One should also realise that new achievements in the fields of new materials and automation can change cardinally the engine ranking.

WP5: Emission reduction

Introduction

High NO_x content in the diesel exhaust gases represents a serious ecological problem which is addressed now by using several approaches. One of them is based on the reaction of selective catalytic reduction (SCR) of NO_x by a reducer gas injected to the exhausts in a small amount. Unsaturated hydrocarbons, propane, primary diesel fuel, ammonia, urea and mixture of hydrogen and carbon monoxide (synthesis gas) to be an efficient NOx reducer as well. The synthesis gas can be produced with catalysts by the reactions of steam reforming, autothermal reforming (ATR) or partial oxidation of upgrading fast pyrolysis oils or diesel fuel. WP5 therefore aims at the development of catalysts and a system for NO_x removal from diesel engine exhaust gases; through ATR of diesel fuel to synthesis gas followed by NO_x reduction by synthesis gas in SCR or LNT regimes.

Catalysts and reactor for fossil diesel and bioliquids autothermal reforming to synthesis gas.

The following most promising catalysts for ATR of fuels into syngas were synthesized and tested:

- A3: $Co_3O_4/MnO_2/BaO$/Fechral Net;
- A5: Rh/Al_2O_3/Net+
- A6: $Ni/BaO/La_2O_3/Al_2O_3$/Net.

All catalysts were tested in the reactions of ATR of diesel fuel and biodiesel fuel under the following conditions: $O_2/C = 0.5\text{-}0.6$, $H_2O/C = 1.5\text{-}2$, contact time 0.3-0.3 s, inlet reactor temperature 200-400°C. Respective product distribution was as follows (on dry basis): for ATR of diesel fuel $H_2 = 32\%$, $CH_4 = 1\%$, $CO_2 = 12\%$, $CO = 11\%$, $N_2 = 44\%$, syngas yield was 2.88 NL per 1 g of diesel fuel, hydrogen yield – 18 moles per 1 mole of diesel fuel; for ATR of biodiesel: $H_2 = 24\%$, $CH_4 = 1\%$, $CO_2 = 15\%$, $CO = 6\%$, $N_2 = 34\%$, syngas yield was 1.85-2.2 NL per 1 g of biodiesel fuel; ATR of fast pyrolysis oil: $H_2 = 26\%$, $CH_4 = 1.2\%$, $CO_2 = 14\%$, $CO = 13\%$, $N_2 = 45.8\%$. Reactor for synthesis gas production was manufactured (see Figure 32). Its parameters are as follows: inner diameter, 100 mm, catalyst block dimensions (diameter x length), 100x150 mm, and reactor type - axial.

Catalysts and reactor for selective NOx reduction

In total 25 different catalysts for selective NO_x reduction were synthesized. All catalysts were tested for the reaction of selective NO_x reduction. Catalyst 2% Ag/Al_2O3 showed the best characteristics. The catalyst consists of 2-3 mm diameter spheres impregnated with a solution of silver nitrate. This catalyst was taken as the most promising one for the development of selective NO_x reduction module. The experiments showed that in order to provide high reaction degrees of NO_x, autothermal conversion of diesel fuel should be performed so that the reaction products contain synthesis gas, methane and unreacted diesel fuel residue. In this case, the as-prepared multicomponent reducing agent can provide high conversion of NO_x in the temperature range 250-500 ^{o}C.

Pilot catalyst batch (60 liter) and radial type DeNOx reactor were manufactured (see Figure 31). Parameters of radial type DeNOx reactor: inner diameter 120 mm, thickness of catalyst bed 100 mm, external diameter 380 mm, length of reactor 516 mm.

Catalyst manufacturing and system development; Exhaust gas cleaning system

A system for NO_x- cleanup from exhaust gases was developed and assembled. Tentative experiments proved sufficient DeNOx efficiency: NO_x conversion was 80% in temperature range 250-350 ^{0}C; fuel penalty for synthesis gas production 3-5%.

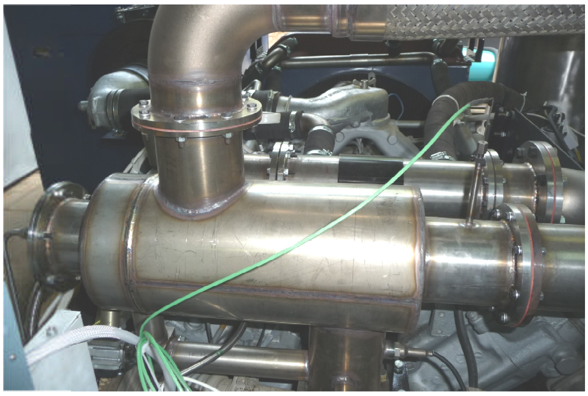
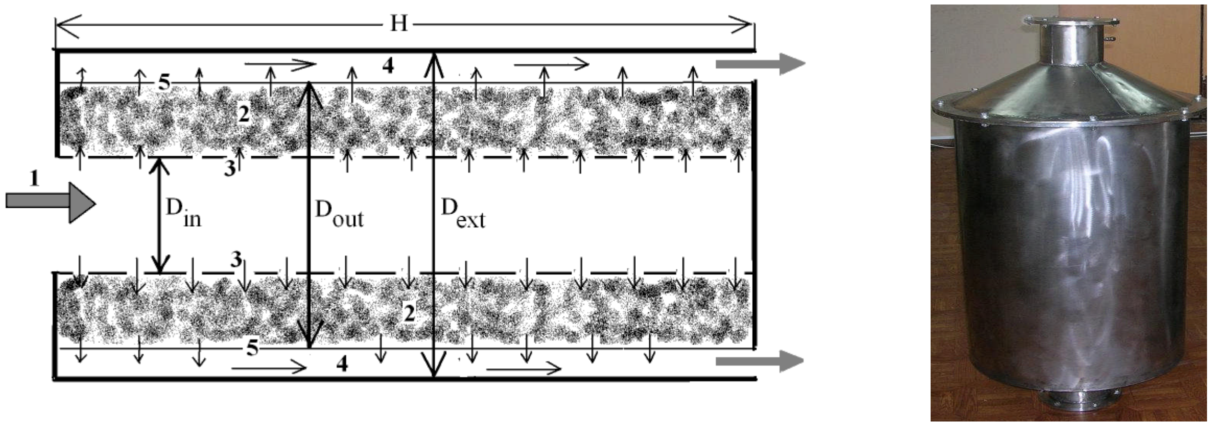


Figure 31: General view of synthesis gas reactor



(a) (b)

Figure 32: Schema (a) and general view (b) of the DeNO$_x$ reactor. Legend: 1- Exhaust gas inlet; 2-Catalyst; 3-Pseudoseptum; 4- Outlet gas reservoir; 5- Clean gas after DeNO$_x$.

Discussion of emission reduction system performance

The project aimed to develop a multi-component NO$_x$ reducing agent on the base of the vehicle fuel to provide 80% conversion of NO$_x$ in the temperature interval of 250-500°C. The fuel penalty for deNOx process should not exceed 3% of total fuel consumption in the engine. Direct use of hydrocarbons for deNOx purposes is inappropriate as it causes 5-6% fuel penalty and requires high reaction temperatures. Urea is an efficient single-component reducer at temperatures of 370-500°C. Its application is limited because of relative toxicity and inability to be used at temperatures below minus 18-19°C (which are common in Siberia in winter). In fact, urea appears additional reagent onboard a vehicle. In this regard, the use of fuel (diesel+ biofuel) reforming products for deNOx purposes is much more appropriate. The fuel reforming products consist of syngas, methane and unsaturated hydrocarbons. This multi-component mixture allows NO$_x$ reduction at 250-500°C; fuel penalty with this approach is below 3%. In case of LNT, fuel penalty is below 1.5%.

WP6: Assessments

In the last WP the benefits of using bioliquids in CHP (cogeneration) mode were evaluated in a number of assessments including:

- State of the art
- Environmental performance
- Technical and economic performance
- Information for developers

State of the art

A preliminary study of the current prime mover technologies, in addition to a database, was completed in order to establish a starting point and used to illustrate the state of the art and the advantages and disadvantages of the technologies. The prime mover technologies review included piston internal combustion engines, turbines, organic Rankine cycle (ORC) systems and Stirling engines from the economic (capital cost) and performance (efficiency) point of view. More information on the technologies can be found in the Technologies Summary incluided in the Promotion Pack handed out during the project completion workshop.

As information for CHP units below 1000kW$_e$ using bioliquids is scarce, a decision was made to expand the scope and include CHP units using biomass for the partner countries. The making of the database was hindered by the lack of reliable and detailed information. A database of units using biomass for CHP was developed for the Netherlands and for the United Kingdom but unfortunately it was not possible to build a similar database for Russia and Italy. The database includes unit electrical capacity, location, fuel and prime mover, among other items of information.

In an attempt to highlight the innovative frame of the project, Parallel Sets diagrams were used for the database graphic representation, condensing the conventional set of charts normally used for database representation into a single easy to understand diagram. The tool allows the visualization of large amounts of categorized data in a simple interactive chart as a step to identify the market and correlate to past and present experiences. The number of horizontal bars (categories) is variable. Each horizontal bar has sub-categories from which the data is further expanded. Although this is an interactive tool, a modified print out can be made and is included in Figure 33. The figures have three categorized horizontal bars:

- **Feedstock**: With Food waste, Short Rotation Coppice (SRC), Vegetable oils, Wood waste, Other waste and an additional sub-category for items with no details.
- **Size**: Disaggregated as units below 400 kW$_e$, units between 400 kW$_e$ and 1000 kW$_e$, units above 1000 kW$_e$ and units with no details as sub-categories.
- **Prime mover**: For information regarding the specific prime mover, piston internal combustion engines, gas turbines, steam turbines and no details.

The link between each category is a coloured ‘ribbon’. The value of any individual ribbon within any category is displayed with the cursor. It is also important to note that the width of each ribbon is proportional to the number of units in each category.

Environmental performance

A number of pollutants are produced during the combustion of fuels. Carbon monoxide (CO) is emitted during (inefficient) combustion, nitrogen oxides (NO_x) are very much fuel and combustion conditions specific, sulphur dioxide (SO_2) is released when using fuels with sulphur content and combustion plants are also responsible for the emissions of particulates. A reduction in overall emissions when exploiting biomass as fuel is expected by 2030 when compared to the situation in 2005 (European Environment Agency, 2008, ‘Maximizing the environmental benefits of Europe’s bioenergy potential’), as shown in Table 5:

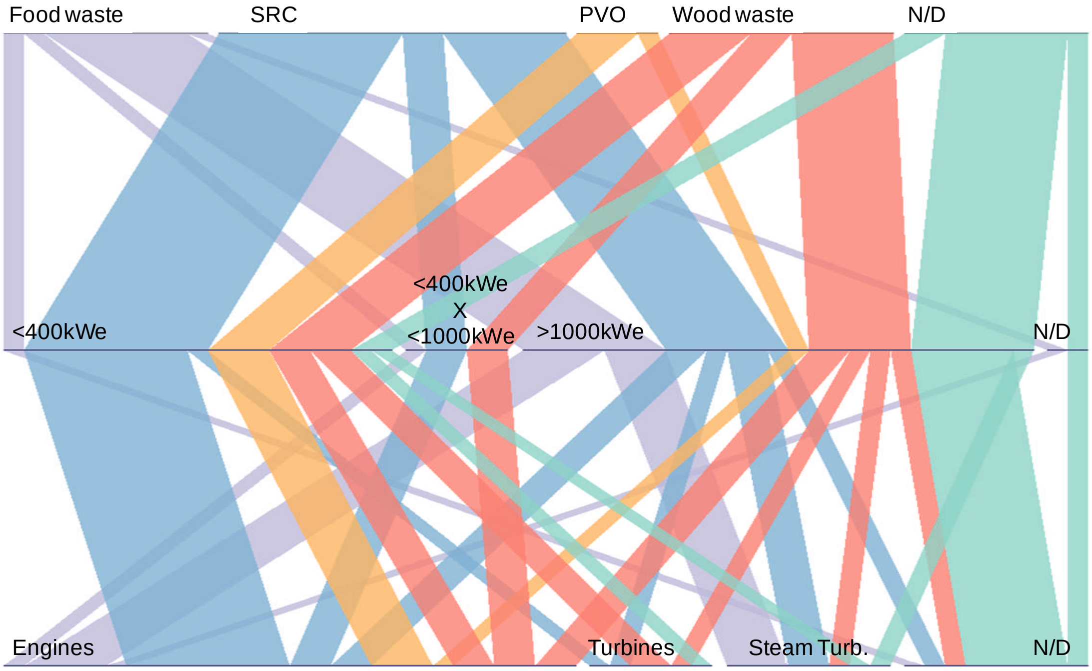


Figure 33: Parallel sets visualization of the biomass fired CHP units in the United Kingdom.

Table 5: % increase or reduction in pollutants in 2030 when compared to 2005 figures for a 100% biomass use scenario.

Pollutant	% Increase (Reduction)
CO_2	(86%)
SO_2	30%
Particulate matter	(20%)
NO_x	41%

In terms of conversion technology, the literature shows a well documented tendency of better environmental performance for gas turbines when compared to piston internal combustion engines. The low values exhibited by the gas turbine are a consequence of the longer residence time and good fuel-air mixture.

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 bioliquids, including fast pyrolysis oil produced from different sources with straw, forestry residues or clean wood waste among others. This enables comparisons between the results on the same estimation basis. Although the tool was developed for the UK, the results could be adapted to the Bioliquids-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 1000 kW_e, in line with previous reported literature in which a full LCA analysis was employed. **Error! Reference source not found.** 6 summarizes the results:

Table 6: Equivalent CO_2 emissions increment (savings) when compared to gas in a 1000kWe piston internal combustion engine using fast pyrolysis oil in CHP mode.

CHP scheme	g CO_2 equivalent/kWh	% emission increment (saving)
Gas fired	616.90	0.0
Oil fired	857.60	39.0
100% forestry residue	48.93	(92.1)
100% SRC	109.46	(82.3)

The diversity of use of biomass for energy and the diversity of conditions in each country has limited the number of LCA studies for fast pyrolysis oil as fuel for CHP, especially when compared to the number of LCA studies of biomass for transportation.

The savings in CO_2 emissions for the different bioliquids developed during the Bioliquids-CHP project are expected overall to be similar to that of fast pyrolysis oil, however, each particular upgrading methodology will have an impact that will lower the savings expressed in **Error! Reference source not found.**. Although this impact has not been quantified, it can be expressed in qualitative terms referenced to the energy used to make fast pyrolysis oil, as shown in Table7:

Table 7. Overall impact of selected bioliquids when compared to pyrolysis oil

Bioliquid	Items to consider in addition to the production of bio-oil	Overall impact compared to bio-oil
30/30/40 butanol blend	• Production, transport and storage of biodiesel and butanol. • Mixing energy for the production of the blend.	Biodiesel has a higher environmental impact than bio-oil due to higher production inputs. Butanol impact is also higher than bio-oil but less than biodiesel again due to high biomass production and distillation requirements. Quantitative data is not feasible due to dependency on feedstock and process for both biodiesel and butanol.
FPO ester	• Production, transport and storage of butanol • Catalyst production • Distillation process energy consumption	Slightly higher impact than bio-oil production due to higher impact of butanol production as defined above. Catalyst production and process energy are relatively insignificant.
Mild HDO	• Catalyst production • Hydrotreatment process energy consumption	Slightly higher impact than bio-oil production because of hydrogen requirement. Catalyst production and process energy are relatively insignificant.

Therefore the increase in emissions and its impact on CO_2 saving potential is expected to be slightly higher when using any of the bioliquid produced by the Bioliquids-CHP project.

Technical and economic performance

The technical performance of the different bioliquids has been detailed in previous WP. The limited amount of data does not provide enough information to determine accurately performance indicators such as efficiency, reliability or durability. With further testing it will be possible to gather more information and increase the confidence in the reported values, but at this stage, there is no information beyond establishment of feasibility.

For the assessment of the techno-economics of CHP systems, a model was built incorporating discounted cash flow analysis in order to estimate the internal rate of return (IRR) for different case studies. The scope was to make a flexible and easy to use model for comparison between:

- Prime movers
- Bioliquids
- Capacity
- Location

It was developed in order to require minimum input from the user and provide quick results for both the internal rate of return and power production cost. In the model it is assumed the fuel is a commodity to be purchased in the market, thus fuel production costs are not considered. The model was built as a tool for developers, planners and decision makers, aiming to generate results with little user input. Default values and scenario evaluations are already programmed into the model but can be modified at users will. A number of scenarios are built into the model. These are:

- Fuel price
- Labour cost
- Maintenance cost
- Capital cost and depreciation
- Power and heat prices
- Grants availability
- Interest rate changes

The advantage is that the results are both numerically and visually accessible in the form of bar charts, thus allowing the user to make a quick analysis and perform changes if required. The scenarios work making higher (+10% and +5%) and lower (-10% and -5%) assumptions for the base case. Thus, the labour cost scenario will assume higher and lower labour cost.

A number of techno-economic assessments of various CHP systems configurations, capacities and fuels were carried out for each of the partner countries. The economic evaluation showed that none of the project partner countries will result in positive IRR without incentives, thus illustrating the difficulties associated with an economically attractive bioliquid CHP installation. An assessment looking into the minimum level of incentives required for a target internal rate of return of 5% was carried out for all partner countries. The incentive could be either in the form of a feed-in-tariff or as a tradable carbon reduction record. When using a feed-in-tariff, the results are as shown in Table 8:

Table 8: Estimated feed-in-tariff required for 5.0% IRR using fast pyrolysis oil in piston internal combustion engines for the Bioliquids-CHP project partner countries.

Country	Power retail sales price (c€/kWh)	Feed-in-tariff value (c€/kWh)	Feed-in-tariff % of power retail price
Italy	14.80	3.78	25.54%
The Netherlands	9.90	8.82	89.09%
Russia	9.12	6.39	70.07%
United Kingdom	10.10	6.88	68.12%

The level of incentive requires basically that the price of power is almost doubled from the current local prices. The sensitivity analysis shows that, for all countries, the largest impact on the IRR is the fuel price, as illustrated in Figure 34 for the UK:

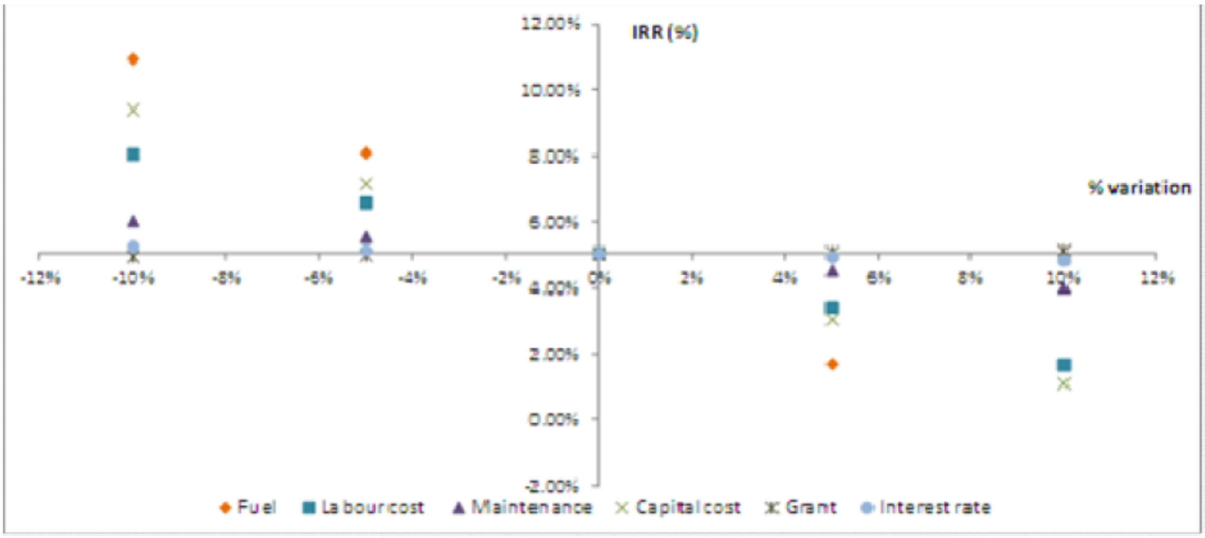


Figure 34: Sensitivity study for the UK using fast pyrolysis oil in piston internal combustion engines.

The economic performance comparison of different prime movers using different bioliquids in the partner's countries was limited to those bioliquids with the highest heating value, as the heating value and heat and power output are directly associated. In order to simulate the bioliquid price, this was linked to the increase in heating value relative to bio-oil. The different bioliquids heating values and difference relative to bio-oil are detailed in Table 9. The bioliquids selected for economic evaluation comparison and their price are shown in Table 10.

Table 9. Bioliquids heating value and heating value increase factor

Bioliquid	Heating value (MJ/kg)	Heating value increase factor
Bio-oil	17.0	1.00
30/30/40 butanol blend	25.9	1.52
Dry FPO + ethanol	18.7	1.10
FPO emulsion with 5% biodiesel	16.3	0.96
FPO ester	23.5	1.38
FPO sugars	18.4	1.08
Mild HDO	27.0	1.59

Table 10. Selected bioliquids assumed price per country

Bioliquid	Price (Euro/GJ)			
	Italy	Netherlands	Russia	UK
Bio-oil	7.92	8.14	7.04	7.65
30/30/40 butanol blend	12.06	12.40	10.72	11.65
FPO ester	10.94	11.25	9.73	10.57
Mild HDO	12.57	12.93	11.18	12.15

An estimation of the feed-in-tariff required for a 5.0% IRR was carried out for the Bioliquids-CHP partner countries for each of the bioliquids detailed in Table , using the three main prime movers and is shown in Figure 35:

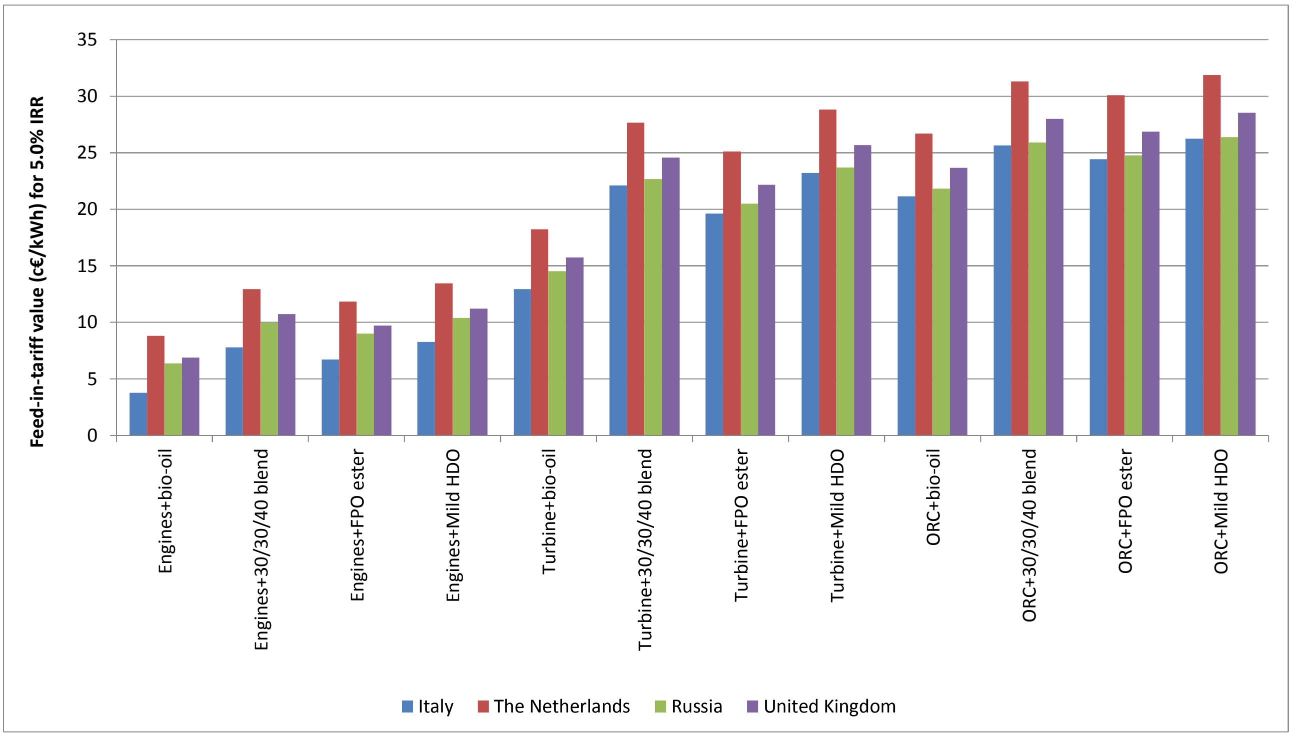


Figure 35: Value of the feed-in-tariff for a 5.0% IRR in different prime movers using different bioliquids in the Bioliquids-CHP partner countries

The figure illustrates several important details:

- The more mature the prime mover technology requires lower feed-in-tariff incentive for a target 5% IRR, thus, engines require lower incentives when compared to turbines, and turbines require less feed-in-tariff incentives when compared to ORC systems. The maturity of the prime mover technology is then a major factor to consider and future efforts should be targeted primarily to developing engines to achieve commercial viability.
- The figure also shows that the basic bioliquid, bio-oil, is financially more attractive that the bioliquids derived from it. This is only true if the price assumptions are as projected in this exercise. Although some of the bioliquids produced for this project have enhanced properties, e.g., lower viscosity, bioliquids with increased heating values would require larger incentives when compared to bio-oil.
- The Netherlands consistently require the highest level of incentives when compared among the Bioliquids-CHP partner countries, whereas Italy regularly requires the lowest level of feed-in-tariff. A combination of local parameters (fuel price, power and heat sales price, labour wages) has a larger impact on the market in the Netherlands when compared to the other partner countries.

Information for developers

Most legislation associated with planning and regulation that would affect small scale CHP are contained within the scope of local administration powers. The best advice we can offer to anyone looking into small scale bioliquid CHP is to refer to the local authority in which the scheme will be installed. In the UK, local authorities are responsible for determining planning application for renewable energy projects below $50MW_e$ and planning permission is always required except for units of $<50kW_e$ or $<45kW_{th}$

When looking at the potential markets in which a bioliquid-CHP installation could succeed, it is necessary to segregate by location, thus:

- For the UK the largest opportunities are in the sewage treatment and wood industries. Buildings are also potential large customers; however this would require the development of new heat distribution infrastructure.

- In the Netherlands the most promising opportunities are in the agricultural sector, in particular in greenhouse applications and possibly in the development of district heating networks. Both the food and chemical industries, with current low to medium intake of CHP installations, are the sector with the largest market potential.
- For Italy there is a marked interest in bioliquids 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. The reconvention of part of the sugar infrastructure plants into bioenergy power plants is also in plans. The food industry is among the largest potential users, followed by the chemical industry (both in terms of capacity and number of units).

Availability of biomass materials on site is an important factor for biomass cogeneration, but the use of heat as an energy source is the limiting factor. Thus, opportunities for installing biomass cogeneration in sites without the feedstock or with related activities are narrow. The Cogeneration Observatory and Dissemination Europe project (CODE) made available in 2010 its first report on the potential for CHP in the EU with information supplied by the member states. It is envisaged that an additional cogeneration capacity of 122 GW_e is economically feasible which could be in operation by 2020. Although this figure encompasses a wide spectrum of size (capacity), range of applications and fuels, biomass is expected to make a contribution of about 8% of total growth or 10 GW_e, of which 2 GW_e could be in the capacity scale of below 1000 kW_e.

IV. Potential impact

Impact

Impacts can be evaluated in terms of a variety of criteria as listed below. Areas where BioliquidsCHP have contributed are underlined and discussed below:

- Policy (government and agencies) – advice, information, consultation
- Industry – companies, trade associations, training future technologists, commercialisation, developing advanced technologies, solving industrial problems
- Economy – exploitation of IPR, new technology, exports, competitiveness, new and/or growing markets
- Public – engagement, education, promotion
- Society – sustainability, CO2 reduction, quality of life
- Research – academic community, new research projects, publications
- Strategic and Social – Bio-liquid producers, plant manufacturers, SMEs, investment, local domestic and small industrial applications, regulations, education and training, rural development, farming and agriculture

Policy

Information has been provided to policy makers through publications and meetings, notably the project completion seminar held in Brussels in November 2011. The important contributions have been in promoting the use of bioliquids, promoting small power and heat generation technology and producing fact sheets on performance and cost.

Industry

Information has been provided through publications and meetings, notably the project completion seminar. The important contributions have been in promoting the use of bioliquids, promoting small power and heat generation technology and producing fact sheets on performance and cost. These will enable industry to become aware of bioliquids as a commercial renewable energy source and the availability of suitable small scale CHP plants to utilise these renewable liquids in cost effective applications. It is believed that the additional information will encourage existing market players to become more active and encourage new entrants both in bioliquids supply and in small scale CHP systems. In addition, there has been extensive contact with many of the players in the EU, especially in Italy, Netherlands and the UK, which has also served to provide information and encouragement.

Economy

The market for energy and power in Europe is vast. As the targets for renewable energy become more focussed and pressures to displace fossil fuels grow, policy makers and industry will increasingly look to decentralised small scale CHP to provide more efficient and cost effective energy supplies. Estimates of the size of this market sector suggest an increase from 2GWe in 2000 to 20GWe in 2020. With investments ranging from 300 to 800 € per kW, this represents a massive potential growth area.

Public and society

As CHP provides a greater proportion of the heat and power needs in a more decentralised economy, there will be substantial impacts on users, i.e. the public. They will be involved more in local decision making and derive more benefits from locally sited heat power units, and this will improve their sense of ownership and involvement, as well as a greater awareness of their contributions to sustainability and carbon reduction.

Research

A number of significant developments have emerged from the research concerning both bioliquids production and their use in engines and turbines. Several new ideas would benefit from further development and these are being explored by several partners as discussed in the Exploitation Plan and other reports.

Market analysis of CHP

Early assessments[2] in 2004 estimated that the only way to reach the cogeneration target set by the EU from 9% in 1997 to 18% in 2010 was including micro-generation (less than 1MWe) in the CHP mix, albeit with a range of fuels from natural gas, biomass and waste. In the same study biomass based CHP was expected to increase its presence from 2GWe in 2000 to 20GWe in 2020, of which it is assumed small scale biomass fuelled would contribute with 3.6GWe.

BIOCOGEN[3] reported in 2003 that the contribution of biomass to cogeneration could be of 11 GWe by 2010 with an additional 9GWe for 2020. The forecast shows that the domestic sector could grow to 28% of the EU cogeneration capacity by 2020 from virtually zero contribution in 1999, however, this can only be possible if technological improvements and policy changes are implemented.

The EU-funded Cogeneration Observatory and Dissemination Europe[4] project (CODE) releases in 2010 its first report on the potential for CHP in the EU with information supplied by the EC Member Sstates. In here it is envisaged that an additional cogeneration capacity of 122 GW_e is economically feasible and which could be in operation in by 2020. Although this figure encompasses a wide spectrum of size (capacity), range of applications and fuels, biomass is expected to make a contribution. If a similar assumption to the previous report is made, this is, about 8% of total growth as biomass based CHP or 10 GW_e, of which 2 GW_e could be in the capacity scale of below 1000 kW_e.

Strategic and social

Much attention in renewable energy has focussed on large scale applications and opportunities, while small scale local applications have been largely neglected due to relatively poor economics and poor appreciation of the potential and opportunities at domestic, local and regional levels. The focus of the project on CHP up to 1 MW_e has enabled SMEs and organisations involved in promotion and development of small power and heat to become aware of the technologies and opportunities for this sector. The communities who can contribute to the deployment of the technologies range from the farming and agricultural communities who provide the basic raw materials of biomass for fast pyrolysis to produce bio-oil; and vegetable oils and vegetable oil upgrading into biodiesel, followed by distribution of these bioliquids. A major contribution to rural development can therefore be anticipated. Another sector can develop and market small scale CHP systems based on these bioliquids with benefits for manufacturing, equipment suppliers and consultancy, as well as local and regional government through planning and regulations. The small scale of the proposed developments mean that SMEs are well placed to exploit all stage of the bio-energy-CHP chain and thereby to derive synergies and collaborations that would otherwise be more difficult to establish. The novel development in liquids, emulsions, blends and their utilisation in a variety of heat and power generation devices will benefit bioliquid producers and plant manufacturers and create employment and new investment especially for SMEs. One of the major byproducts or side benefits has been directly in education and training of all the researchers engaged on the project and indirectly through their subsequent employment and the range of publications from the project.

Exploitation

Exploitation has been evaluated through questionnaires sent to all partners and these are reported in the Exploitation Plan. While each partner is responsible for their own exploitation, a summary of the opportunities identified is shown in Table 11 on the next page.

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[2] Lymberopoulos, N (2004). ‘Microturbines and their application in bio-energy’. Centre for Renewable Energy Sources. Greece. Available from: http://ec.europa.eu/energy/efficiency/studies/doc/industry/microturbines_bioenergy.pdf [Accessed on 24 May 2010]

[3] BIOCOGEN (2003). ‘Final Technical Report’. Centre for Renewable Energy Sources. Available from: http://www.cres.gr/biocogen/pdf/market_analysis.pdf [Accessed on 24 May 2010]

[4] Cogeneration Observatory And Dissemination Europe (2009). ‘European potential for cogeneration’. Brussels, Belgium. Available from: http://www.code-project.eu/wp-content/uploads/2011/02/290110-CODE-European-summary-report.pdf [Accessed on 19 May 2010]

Table 11: Summary of exploitation plans in relevant areas.

Technology	Patent(s) planned	Licensing planned	Publications planned
▪ DeNOx system	P	L	
▪ Stirling cycle	P	L	
▪ Rankine cycle	P	L	
▪ Engine fuel system	P		J
▪ BO-BD emulsions	P		
▪ Micro turbine			J
▪ CHP power plant	P	L	
Products			
▪ Bio-liquid blends	P	L	J
▪ TEA CHP model			J
▪ CHP database			J
▪ DeNO$_x$ catalysts	P	L	
▪ Piston engine	P	L	
▪ Rankine engine	P	L	
▪ CHP power plant		L	
Know-how			
▪ All partners have know-how which they plan to exploit	P	L	J

Main Dissemination Activities

Brochure

An English language project brochure was produced early in 2010 and this was then translated into Russian. The brochure provides an overview of the project, the partners, their experience and facilities and contributions to the project. It is a useful summary of the project and has been used by partners as promotional material and disseminated at conferences and events.

Website

The project website has been available at www.bioliquids-chp.eu since the first year of the project and has been regularly updated with information, news, deliverables, training and education materials, promotional materials and details of project events.

Promotional Packs

A promotional pack was distributed to around 60 delegates at the Final Workshop and 140 further copies are being sent to partners for distribution to relevant Target Groups. The packs included several publicity brochures and publicity information for the BioliquidsCHP project; partner summary sheets; fact sheets on bioliquids, environmental performance, case studies and technologies.

Workshop

The final joint dissemination event was organised on 8 November 2011 in Brussels entitled "*Symposium on using bioliquids in engines and turbines in CHP applications*" and attracted a very encouraging audience of over 55 attendees from industry, government and academia. The event included reports from all project partners on their achievements. There were also presentations from the EC and Russian Ministry of Science and relevant case studies and experience from Industry.

Final Project Brochure

A final project brochure is being finalised for bulk distribution to partners for re-distribution to their stakeholders. This will include a report on the project and the activities and results from the partners.

Publications

Peer reviewed journal and book publications

1. Alcala A and Bridgwater AV, "Biomass fuelled combined heat and power -situation in the UK and the Netherlands", Proceedings of the Bioten conference on biomass bioenergy and biofuels, Bridgwater AV (Editor) 2011, CPL Press,
2. Bridgwater, AV, Alcala A (2011). Biomass-based small and micro combined heat and power (CHP) systems: application and status in the United Kingdom. In: Beith, R Small and micro combined heat and power (CHP) systems: Advanced design, performance, materials and applications. Cambridge: Woodhead Publishing. p427-458.
3. Bridgwater AV, “Upgrading biomass fast pyrolysis liquids”, Accepted for publication in Environmental Progress and Sustainable Energy (2012).
4. Beld, B van der, “The use of pyrolysis oil and pyrolysis oil derived fuels in diesel engines for CHP applications”, Accepted for publication in Applied Energy (2012).

Planned publications

A number of joint publications with both EU and Russian partners have been agreed and the scope of three possible joint articles are detailed below:

Table 7: Planned publications

Scope/Topic	**Partners and primary Responsibility**
Use of bio-liquid blends in engines and micro-turbines and comparison of engines and turbines running on bio-liquids - results	CREAR, BTG, Aston
Comparison of properties of upgraded bio-oil and blends with bio-oil	Aston, BTG, BIC, CREAR. A draft is being circulated in March 2012
$DeNo_x$ catalysts for engines	BIC, NAMI

Papers submitted for review in peer reviewed journals

Bridgwater AV, Alcala A, "Blends of bio-oil and biodiesel for heat and power applications", Paper submitted to Fuel, February 2012

Figure 36: The project's scientific coordinator, Dr. Bert van de Beld, at the tcb conference in Chicago (September 2011)

V. Website and contact details of project partners

Project website www.bioliquids-chp.eu

Project coordination

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Partners

- EnConTech BV (NL)
- University of Florence, CREAR (Italy)
- Boreskov Institute of Catalysis, Siberian Branch of Russian Academy of Sciences (Russia)
- Federal State Unitary Enterprise 'Central Scientific Research Automobile and Automotive Engines Institute' - FSUE 'NAMI' (Russia)
- Aston University (United Kingdom)
- The Likhachev Plant (AMO ZIL) (Russia)