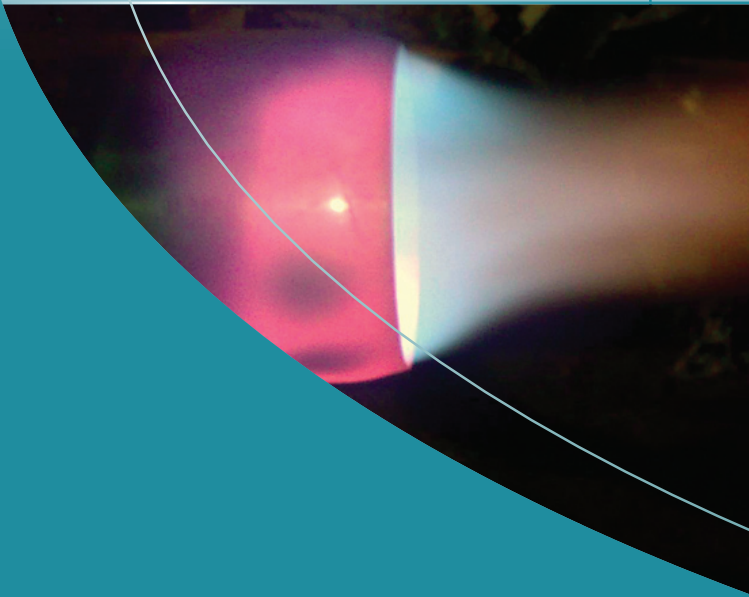


Ulla Lassi and Bodil Wikman (ed.)

BIOMASS GASIFICATION TO HEAT, ELECTRICITY AND BIOFUELS

HighBio Project Publication



BIOMASS GASIFICATION TO HEAT, ELECTRICITY AND BIOFUELS

HighBio Project Publication

Edited by Ulla Lassi and Bodil Wikman

HIGHBIO-INTERREG NORD
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Biomassan kaasutus lämmöksi, sähköksi ja biopolttoaineiksi
Förgasning av biomassa till värme, el och biobränslen
Gasification of biomass to heat, power and biofuels



Gränslösa möjligheter



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Kokkola 2011



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PREFACE

Renewable energy and the use of biomass in energy production promotes sustainable development and decreases the use of fossil fuels. Biomass, e.g. wood chips can be used in the production of heat and electricity, as well as being used as a biofuel component and novel product for the chemical industry. Efficient utilisation of biomass requires a high level of knowledge and the development of new processes to create a new way of thinking. In this process, international co-operation plays a significant role.

The aim of the HighBio project was to produce new information on biomass gasification and the utilisation opportunities of product gas in biofuel and biochemicals production. The project was also aimed at studying utilisation properties of biogasification ashes in distributed energy production. Small-scaled CHP plants can be used for simultaneous heat and power production by gasifying wood chips and by burning energy intensive product gas. Compared with thermal combustion, particulate emissions from gasification are lower, which also contributes to the EU's ever tightening emission legislation. Several small and middle scale companies in the Northern part of Finland and Sweden have worked with biomass gasification, and during the project, the birth of new ones has been seen. In this development stage, researchers of the HighBio project have also been strongly involved.

Increased use of renewable energy opens up new possibilities for entrepreneurship and the birth of new companies, especially in rural areas. In order to enable these opportunities, we need research data from the universities, novel innovations, and especially their successful commercialisation. The HighBio project has also contributed to tackling those challenges by arranging research seminars and meetings to companies and other interest groups, as well as by establishing research activities and collaborations. Regional collaboration combined with national and international research networks has made a strong basis for this activity.

Finally, we would like to express our deepest gratitude to all of you who have participated in the HighBio project; researchers, companies and other interest groups, financiers and active participants in our seminars and meetings. You have made this project very interesting and challenging, but most importantly having made the project have a significant effect upon our society.

Kokkola, 12th of May, 2011

Ulla Lassi
Professor, Applied Chemistry
Leader of HighBio project

Bodil Wikman
Project coordinator



Within the HighBio project seminars and study tours have been arranged by different partners. The picture presents the Finnish HighBio delegation visiting Smurfit Kappa kraftliner and bioenergy production site in Piteå, Sweden within the framework for a project seminar in May 2010.

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DECENTRALISED ENERGY PRODUCTION

DECENTRALISED ENERGY PRODUCTION

Ulf-Peter Granö

In terms of national energy production, it is important in the future that small-scale decentralised solutions come closer to the raw materials and consumers. Unfortunately, in Finland big companies are still making use of their resources to hamper small-scale local solutions. Hopefully, common sense will prevail and decentralised energy production can be developed in small units. In particular, small-scale CHP units (combined heat and power) can contribute to the development of sustainable energy production.

DECENTRALISED CHP-REFINING OF BIOMASS

Finland and Sweden possess large amounts of unused biomass resources in the form of forests. These resources could be exploited in the production of electricity and heat. In addition, they offer raw materials for the production of transportation fuels and chemicals. Due to rapid progress in technical development, the research is globally focused on the simple and robust solutions for the refining processes.

Small-scale solutions with regards to the refining of biomass for consumers in a nearby region do not have the desirable resources required for development. The financial support from national and EU sources of funding are often awarded to the big actors due to their better visibility. The authorities and decision-makers have not been interested or have not had the competence to see the considerable potential of small-scale energy production, such as thermal power production.

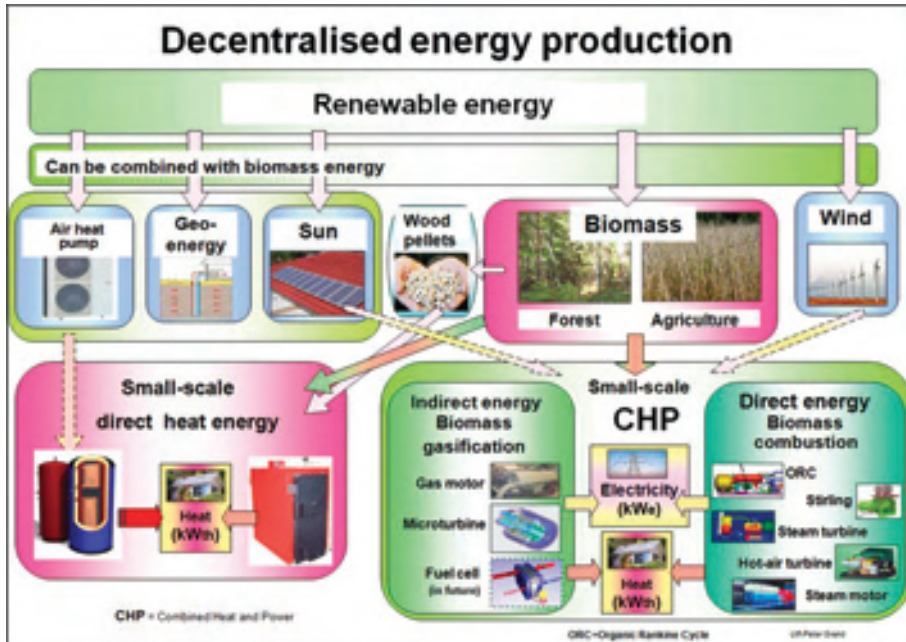


FIGURE 1. Decentralised energy production.

SUMMARY – REFINING OF BIOMASS BASED RAW MATERIAL

The scheme illustrated below describes in general the refining of biomass-based raw materials.

Biomass-based raw material can originate from forest, agriculture, manure or agricultural waste, municipal waste, or wastes from the process industry.

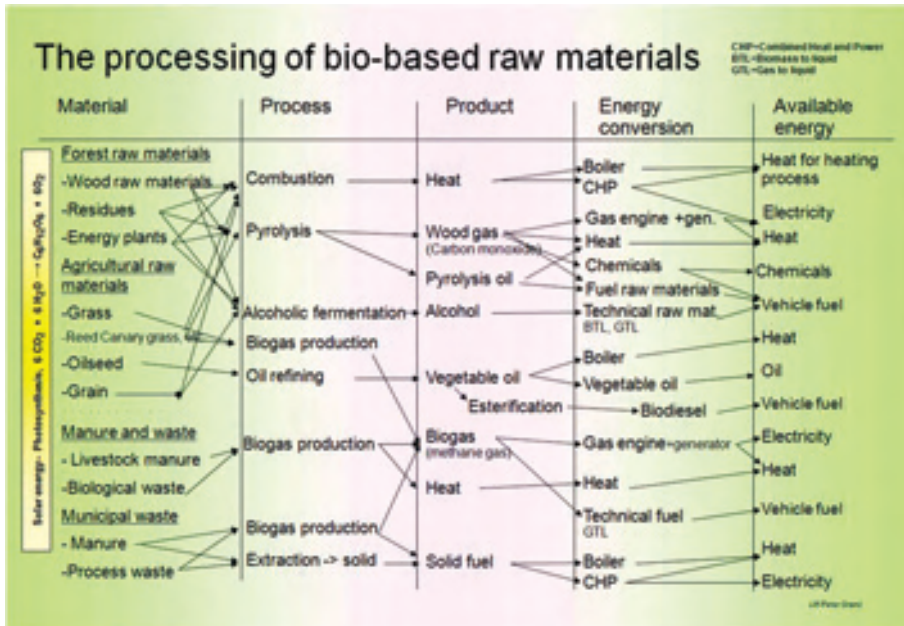


FIGURE 2. Processing of biomaterials.

CHP – COGENERATION

Decentralised CHP units for heat and electricity can be comprised by many different ways depending largely on the volume of the electricity to be generated. An important factor is the cost of electricity or an electricity subsidy.

Examples of different types of units:

- Direct combustion of wood chips/pellets + Stirling engine
- Direct combustion of wood chips/pellets + Organic Rankine Cycle (ORC)
- Direct combustion of wood chips/pellets + Small steam turbine
- Gasification + Direct combustion + Gas engine or micro turbine
- Gasification + Direct combustion + ORC
- Gasification + Gas engine (piston engine)
- Gasification + Micro turbine
- Biogas + Gas engine
- Biogas + Micro turbine
- Combination of bio-syngas and biogas + Gas engine or micro turbine

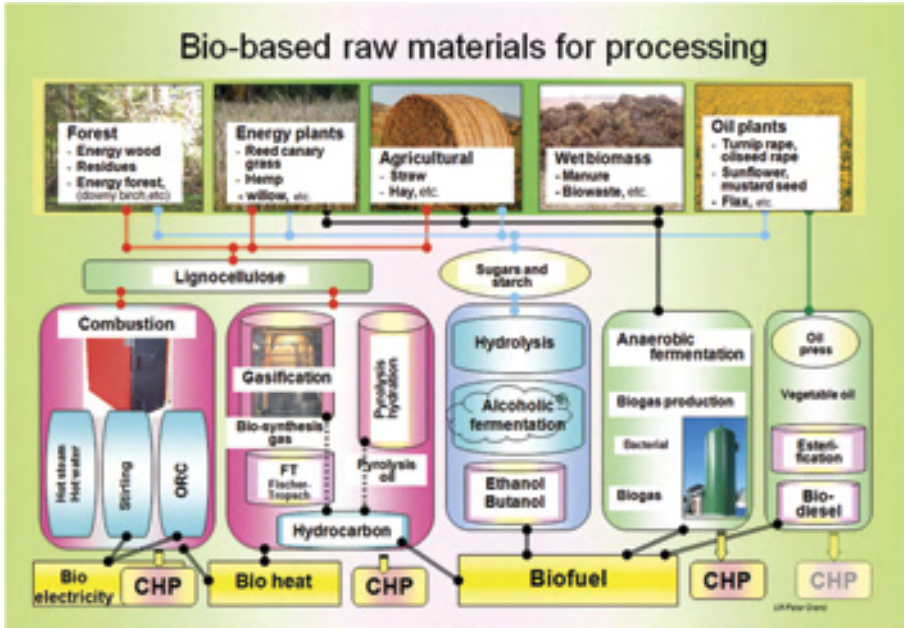


FIGURE 3. Bio-based raw materials for processing.

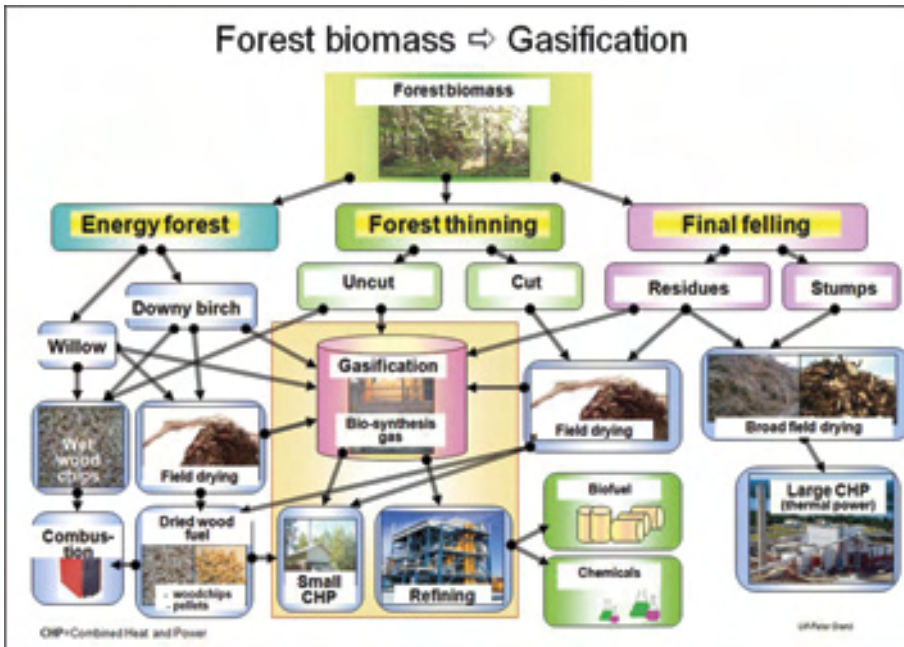


FIGURE 4. Forest biomass for gasification.

BIOMASS AND OIL PLANTS

Forest and agricultural based raw materials for green energy can originate from several different resources, as described below:

In general, **biomass from forest** contains:

- **Fuel wood**, different size wood from forest clearance and thinning
- **Logging residues**, branches and tops from a logging area
- **Energy forest**, or short rotation forestry, e.g cultivation of downy birch

Energy plants cultivated in fields

- Reed canary grass, hemp (fibre hemp for biomass), elephant grass etc.
- Willow, brittle willow, cultivated mainly in fields; is an intermediate form of energy forest

From agriculture

- straw, grass and other plants cultivated for biogas production

Wet biomass

- Manure and bio waste, such as spoiled silage in bales or from silo

Oil plants

- Turnip rape, oilseed rape, sunflower, mustard, flax etc. yield bio-oils, which can be converted to biodiesel by the esterification process

GREEN ENERGY – INTEGRATED REFINING OF THE BIOMASS

The concept of small-scale decentralised refining of biomass has the potential to exhibit a key role in the regional environmental thinking. The study of novel technologies suitable for decentralised refining processes enables the refining of the biomass-based raw material for customers and consumers in local and neighbouring areas. A growing interest for the integration of different refining processes exists, to increase the consolidation and create positive synergy effects.

GASIFICATION OF WOOD

Gasification of biomass produces useful product gas which is an interesting gaseous resource. It can be utilised as a fuel in direct combustion or as a raw material for further processing. Amongst all the available gasification options in terms of production of fuels and chemicals, forest-based

biomasses as raw materials is the most interesting. Synthesis gas (syngas) or product gas can be used in further processing after purification and conditioning.

Application areas include:

- Direct combustion for heat production
- Direct combustion in CHP unit for heat and electricity production
- Gas fuel for electricity production – CHP with:
 - piston engine/gas engine
 - gas turbine
 - fuel cell (in the future)
- Processing and upgrading to
 - transportation fuels
 - chemicals

INTEGRATION POSSIBILITIES

Coordination of activities between operators of heating units in the region can be performed in different ways and evolve over time. Therefore it is already important in the planning phase to try to locate units so that future plans can be implemented easily. This includes suitable land area, logistics as well as cables and pipe lines for electrical and thermal connections respectively.

Some examples of the possible activities for integration include:

- Drying of the wood chips
- CHP unit
- Energy terminals, with integrated treatment of biomass raw material and processed material
- Gasification of biomass
- Solar energy
- Geo energy
- Manufacturing of pellets
- Production of biogas from farms
- Production of biogas from nearby communities
- Processing of raw materials for the production of transportation fuels

Activities depend primarily on local development and interests.

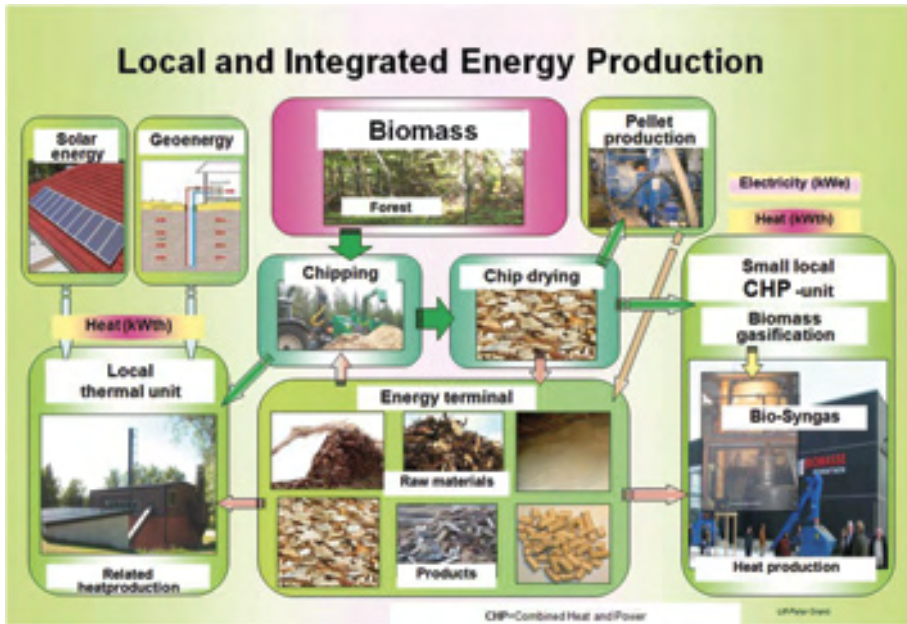


FIGURE 5. Local and integrated energy production.

Often integration evolves gradually, and is dependent on what stage the pieces that are used in the development of local activities will be introduced. The priority is mainly due to, for example, needs and demands of the local energy cooperation and neighbouring area.

GREEN CHEMISTRY

By a chemical refining of syngas or product gas it is possible to produce a variety of raw materials and products. The greatest expectations are associated to the transportation fuels as a replacement for fossil fuels. This is beneficial for the utilisation of forest-based biomass as a raw material since it does not compete with food production.

Through the development of green chemistry it is possible to reduce the dependence of oil products. In addition, as local resources are exploited more efficiently it can only improve the employment and self-sufficiency in the region.

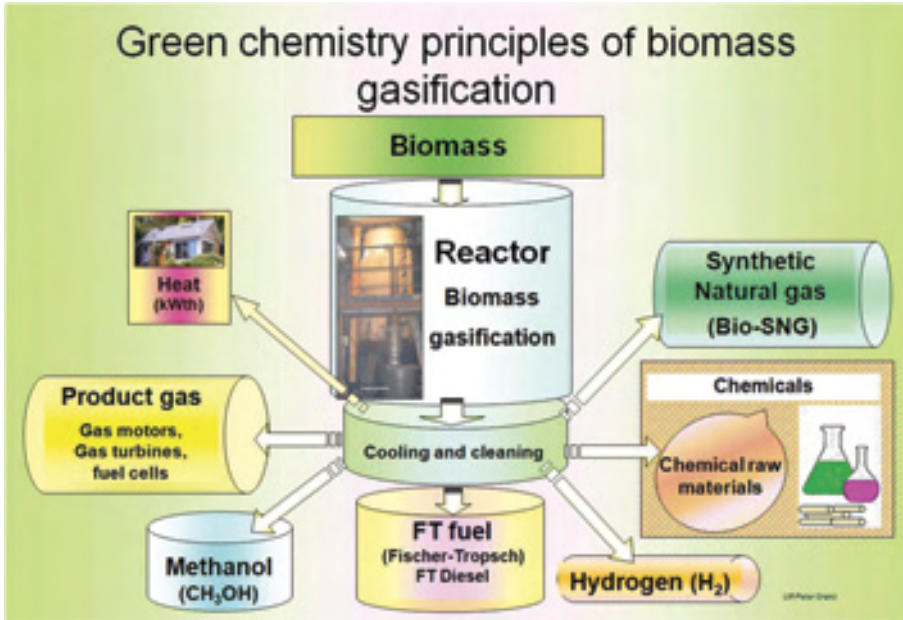


FIGURE 6. Green chemistry - potential of gasification of biomass.

SMALLER UNITS FOR REFINING

A good alternative is to locate gasification and refining units close to a CHP plant, which allows the efficient utilisation of heat and distribution of product gas obtained from the gasification process. It ensures that product gas of low quality and heat can be exploited in a CHP unit and district heating network respectively.

It is appropriate for smaller gasification units based on biomass gasification to combine with local CHP plants, especially if the gasifiers, that can use moist or dry biomass to produce product gas free of tar particles, are available. In order to produce product gas economically, a CHP unit, which requires the drying of fuels and efficient purification of tars, must be large enough.

Decentralised energy production already offers considerable potential to utilise local bioenergy resources through small-scale refining, promoting a sustainable development.

BIOMASS GASIFICATION

ETC-HIGHBIO CONTRIBUTIONS

Magnus Marklund and Olov Öhrman

ETC, Piteå, Sweden

PILOT-SCALE ENTRAINED FLOW GASIFICATION

An increase in the use of biomass based energy resources, both nationally and globally, will help to reduce the demand of fossil fuels and limit long-term greenhouse effects. Besides the generation of electricity and heat, biomass can efficiently be converted into valuable materials, such as chemicals and biofuels through so-called biorefinery concepts. Material flow of the annual logging of biomass in Sweden, where about 45% is in the form of logging residues (equivalent to approximately 70 TWh), is presented in Figure 1.

Energy Technology Centre in Piteå (ETC, Piteå, Sweden) is currently working on a pilot project for the gasification of biomass which has also been a part of the HighBio project. The project has involved the design, construction and commissioning of the pilot plant, which is based on Pressurised Entrained flow Biomass Gasification (PEBG) for the production of synthesis gas from wood waste and other biomass that the industry has no use for. The technology concept is based on high temperature (> 1200 °C) gasification of powdered biomass in a pressurised entrained down flow gasifier with a low production of tar and other hydrocarbons. The disadvantage of this concept in comparison with gasification at low temperatures and a long residence time is that the fuel must be ground to a fine powder (<1 mm) and the enclosing material is exposed to high heat loads and ash and slag. The main technological challenges for the plants are fuel processing and supply, control of slag formation and the optimal design of the burner and quench cooler to ensure a smooth and stable operation.

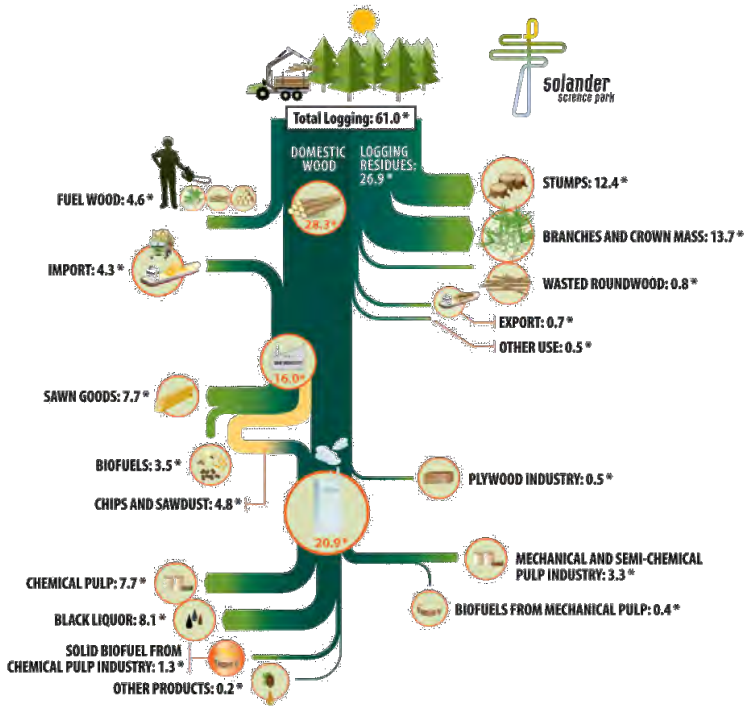


FIGURE 1. Harvested annually material flow of biomass in Sweden in 2004.

Concerning the slagging issue, Table 1 shows the different features which make up the tree. It clearly shows that the proportion of extractives and ash is higher in the needles and bark in comparison with ordinary wood. This means that logging residues from forestry has a higher content of extractives and ash content due to increased amounts of needles and bark that comes with this material.

TABLE 1. Approximate percentages of cellulose, hemicellulose, lignin, extractive and ash in Pine and Spruce.

	Cellulose	Hemi-cellulose	Lignin [wt-%] dry basis	Extractives	Ash
Pine (about 70 years)					
Stem wood	41	27	28	3	1
Bark, inner	36	26	29	4.5	2
Bark, outer	25	20	48	3.5	2
Branches	32	32	31	3.5	1
Wood needles	29	25	28	13	5
Spruce (about 110 years)					
Stem wood	43	27	28	0.8	1
Bark	36	20	36	3.8	4
Branches	29	30	37	1.7	2
Wood needles	28	25	35	6.1	5

The PEBG plant at ETC was inaugurated as the 'IVAB gasifier' at the Solander Symposium in November 2010 (see Figure 2 for a side view of the plant). The facility is currently being commissioned (April 2011) where all subsystems have been systematically tested, and initial combustion tests have been carried out.



FIGURE 2. PEBG pilot plant at ETC (titled "IVAB gasifier") was put into operation in April 2011.

The initial gasification experiments will focus on atmospheric gasification of stem wood with a synthetic air mixture to ensure safe operation. Further on, experimental campaigns will be focused on pressurised conditions and with an increased oxygen concentration for various fuels (bark, stumps and other wood residues). The plant is designed for a load and pressure of 1 MW_{th} and 10 bars respectively. The nominal operation conditions will be $500 \text{ kW}_{\text{th}}$ at 5 bar absolute pressure.

FEEDING POWDER FROM BIOMASS

Supply of biomass in powdered form can be problematic due to the fibrous structure of the biomass. Powder from biomass is mainly in the form of small chips that tend to stick together and form arches and bridges when the powder is transported. A robust and reliable feeding system is a necessity for all types of processes that handle powders from biomass, especially when biomass is used for combustion and gasification (e.g. in PEBG process). In these applications, a steady and stable supply of powder is required. There are a variety of pneumatic powder transport systems available on the market for atmospheric processes, but these are not suitable for pressurised conditions due to the large amounts of transport gas required. The most suitable powder supply for pressurised gasification is a lock hopper based concept with dual fuel storage tanks that can alternate with filling and feeding to maintain a continuous operation. For the PEBG plant, such a concept has been constructed and demonstrated with good performances in the initial tests.

The first tests of the feeding system in the PEBG plant were carried out with three different fuels (a bark powder and two stem wood powders with different size distributions) under atmospheric conditions. The feeder was calibrated by the use of a scale that could log the rate of fuel powder being transported every second. The linearity of the weight increase in proportion to the feeding rate can be used as a stability measure of the powder feeder. Furthermore, impact of fuel type, size distribution and choice of fuel on the stability were also examined. Figure 3 shows the linear relationship between the measured fuel flow and the used feeding rate for a powder originating from stemwood.

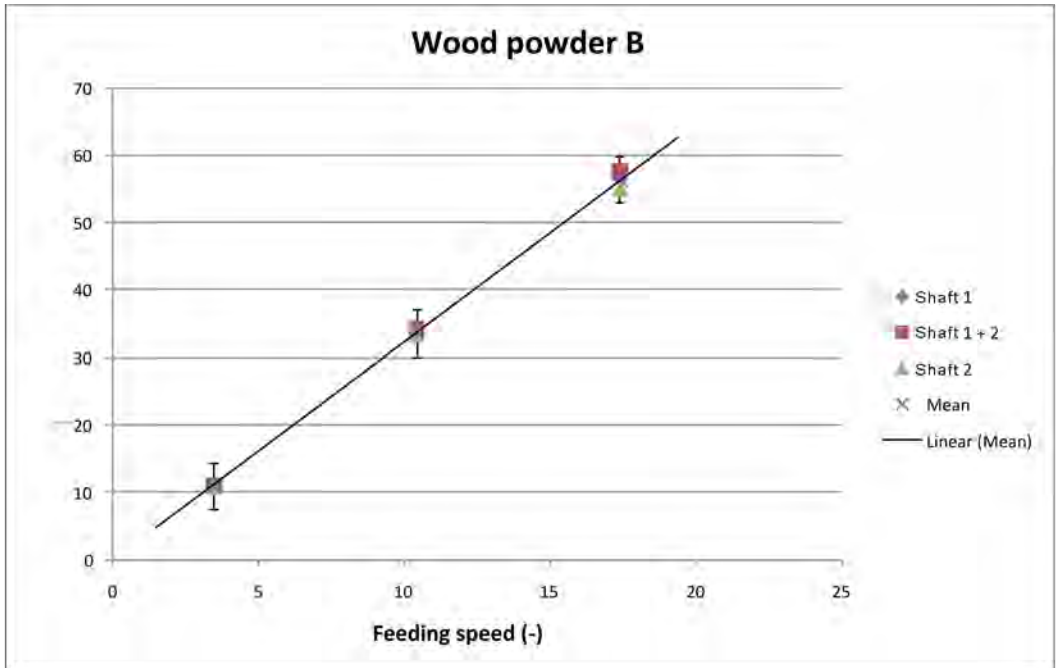


FIGURE 3. Relation between the measured flow of feedstock and the feeding rate.

FUEL PREPARATION

In recent decades, pellet manufacturing and powder combustion has steadily increased. In both processes, a significant issue is the grinding of biofuels. This also applies to biomass gasification in plants where wood powder is used, e.g. in a cyclone gasifier or entrained flow gasifier. The requirements for the powder, however, differ between these applications. For example, pellet production is suitable for particles with a diameter up to 3 mm whilst this size must be reduced to less than 1 mm in powder combustion and gasification. Furthermore, another requirement is that a portion of the particles, about 10% of the powder, should be less than 100 μ m. This is an important requirement considering flame stability.

The grinding of biofuel is a more complicated process and requires more energy than coal grinding. This is because coal is more brittle, and therefore, more easy to break down. Previous studies have shown that coal grinding requires 7-36 kWh/t of energy, which is less than the energy reported for biomass (20-200 kWh/t). The grinding of pellets for pulverising normally requires most powders to be less than 1 mm, and

a certain amount below 0.2 mm. Table 2 shows a number of pelletising companies operating in Sweden. Bionorr distinguishes themselves with a high energy consumption of about 74 kWh / t. This is due to the fact that Bionorr uses a special process where grinding takes place before drying. Normally, drying is carried out before grinding and as a result reduces the demand for electricity. Values presented in Table 2 are partly based on estimates (e.g. grinding capacity and engine efficiency), and therefore, results presented are not comparable directly. It is, anyhow, reasonable to assume that the average energy consumption for milling of biomass is 25 kWh/t (moisture content of biomass being 10-12%).

It is widely known that energy consumption increases markedly with the moisture content of biomass. Bionorr uses about three times as much energy for grinding compared with the maximum energy consumption at any other facilities. Bionorr uses 'raw' chips with a moisture content of about 50 % whereas other facilities grind dried wood chips or sawdust with a moisture content of about 12 %. Previous experience has shown that the following factors, in addition to moisture, impact the energy consumption in grinding:

1. Sieve density
2. Sieve plate area
3. Structure of the materials

Another pre-treatment technology is torrefaction, which is a thermal pretreatment process of biomass to convert it from hydrophilic to hydrophobic materials. The process takes place at 250-300 °C in an inert environment (fumes). At these temperatures during the heat treatment of dry wood, the connecting structure between the cellulose, hemicellulose and lignin (wooden main components) changes. Hemicellulose is the least heat stable component of wood and is the source of most of the substances produced by torrefaction. The degradation of hemicellulose also initiates some structural changes in the lignin, the cellulose, however it is not significantly affected.

Table 3 shows a list of various references that report mass and energy exchanges in torrefaction and the boundary conditions that were used in the trials. Table 3 also shows that the mass exchange varies between 43 and 87 % depending on the wood type, temperature and reaction time. Energy output also possesses wide variations. The lowest energy yield is 50 % while the highest is about 93 %. However, there are some results whose values that are even higher than these.

TABLE 2. Various milling techniques used in Sweden.

Owner	Mark	Sieve (mm)	Production (t/h)	Motor effect (kW)	Energy (kWh/t)	Type of raw material	Moisture content %
1. Glommers	Russian (unknown)	6	1,6	25	15,6	Dry chips	9-15
2. SCA Bionorr	ABB	wind term	10	736	73,6	Green chips	45-55
3. Laxå Pellets	Andritz Sprout	2,5	8	200	25,0	Pine / spruce scip	10
4. Luleå Bioenergi	Buhler	3	(7-10)		24,7	Chips	10-15
5. Derome Bioenergi	Buhler	4-6	5	118	24,0	Sawdusts	12
6. Lantmännens Agroenergi Ab	Andritz Sprout	4-6	10	315	31,5	Processed chips (max 15 mm)	11
7. Vida Pellets	Andritz Sprout	5	16	200	12,5	Chips	12

TABLE 3. Mass and energy exchange from torrefaction.

Material	Mass exchange (%)	Energy output (%)	Calorific value (MJ/kg)	Temp (°C)	Reaction time (min)
Wheat straw	72.0	77.0	20.7	270	30
Reed canary grass	71.0	78.0	20.8		
Willow	80.0	86.0	21.7		
Wheat straw	55.1	65.8	22.6	290	30
Reed canary grass	61.2	69.0	21.8		
Willow	72.0	79.2	21.9		
Willow	87.0	95.0	19.4	250	30
Willow	67.0	79.0	21.0	300	10
Wood waste	56.0	65.0	22.8		30
Wood waste	54.0	62.0	23.0	270	60
Wood waste	43.0	50.0	23.1		90
Birch	68.9	88.3	21.1	280	120
Pine	72.1	92.9	22.3		
Bagass	64.7	82.8	19.8		

Wood possesses three main components: cellulose, hemicellulose and lignin. These three substances are polymers with weak chemical bounds. During the heat treatment of dry wood at temperatures above 200 °C, the structure of these chemical bonds changes. There are also differences in hemicelluloses between soft and hard wood. For example, hemicellulose present in hardwood contains 80-90 % xylan, while softwood contains 60-70 % glucomannan and 15-30 % arabinogalactan. Xylan is more heat sensitive than the other wood components, and this explains the higher mass loss during torrefaction of hardwood and straw.

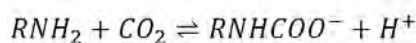
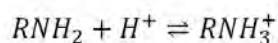
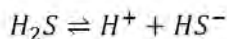
PRODUCT GAS COMPOSITION

The gasification of biomass produces a synthesis gas consisting of H₂, CO and CO₂. In addition to these components, 'raw' synthesis gas can contain small amounts of pollutants such as H₂S, COS, mercaptans, heavy hydrocarbons (tar) and particulates. It may also contain traces of halides and HCN. Depending on the application where the synthesis gas is to be used, demands for purification differ. In general, if synthesis gas is used for catalytic synthesis of transportation fuel it requires a higher level of treatment compared if the gas is used for power generation. Many different gas purification technologies exist today. The techniques that can be relevant for purification of synthesis gas from a biomass gasifier are as follows:

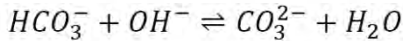
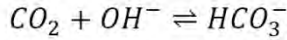
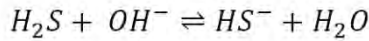
- Physical and chemical scrubbers (absorption)
- Adsorption
- Thermal or catalytic conversion
- Membranes

ABSORPTION

When a gas dissolves in a fluid absorption takes place. There are two types of absorption, chemical and physical. An example of chemical absorption is amine wash that can be used to clean synthesis gas from H₂S and CO₂. There are many different types of amines used. The general reactions that take place are:



Alkaline solutions can also be used to clean synthesis gas. Often the solutions are Na_2CO_3 or K_2CO_3 at pH 9-11. The reactions that take place are:



An example of purification of H_2S from synthesis gas produced from gasification of black liquor is shown in Figure 4. The graph shows the amount of H_2S and CO_2 that can be removed from the synthesis gas by means of short-term contactors containing dilute liquor, which is a kind of alkaline wash. In the experiment 78 % of the H_2S was removed from the synthesis gas with three short term contactors.

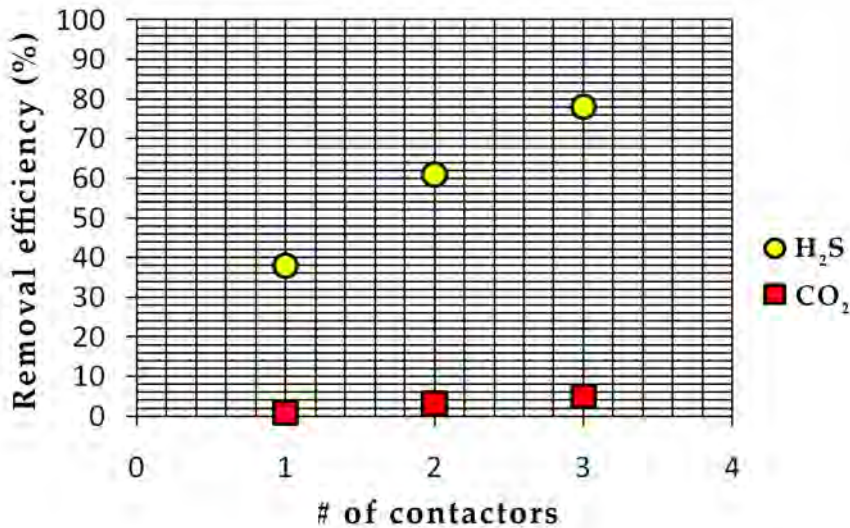


FIGURE 4. Treatment of H_2S using diluted liquor at 50 °C.

Examples of commercial processes that use alkaline solutions include Benfield, Catacarb, Flexsorb, Giammarco-Vetrocoke, Seaboard, Vacuum Carbonate, Vacasulf and Alkacid etc.

When large amounts of impurities have to be removed from the gas phase, a natural absorption might be more appropriate. For example, organic solvents such as methanol are used to absorb impurities. Furthermore, purified synthesis gas as well as clean gas streams consisting

of e.g. H_2S and CO_2 , are readily available from the plant. Examples of commercial technologies are Selexol, Sepasolv, Purisol and Rectisol.

Sulfinol and Amisol are two different processes in which both chemical and physical absorption takes place. The physical absorption is used to remove most of the impurities and the chemicals to purify the final content. In such Amisol processes methanol is used for physical absorption and alkyl amine as a chemical solvent.

ADSORPTION

Adsorption usually takes place at low temperature, and can either be physical or chemical in nature. The adsorption of a gas bounds to the surface of a material with high surface area e.g. $500 \text{ m}^2/\text{g}$. Examples of materials used in adsorption are activated carbon or zeolites. Activated carbon is used to adsorb heavier hydrocarbons from a gas stream whilst zeolites can be used to remove CO_2 from the synthesis gas. Regeneration of adsorbents can be achieved by heating or using pressure. For example, ZnO can be used to remove H_2S from a gas stream since H_2S reacts with ZnO to form ZnS at elevated temperatures. However, ZnS is difficult to regenerate. For this reason it is used only to remove small amounts of pollutants before the gas is injected into the catalysts for the production of transportation fuels.

THERMAL OR CATALYTIC CONVERSION

Contaminants can also be removed via thermal or catalytic conversion. Odours and volatile organic impurities can be oxidised thermally whilst via catalytic conversions, impurities are removed at lower temperatures.

MEMBRANE

More recently, membranes have been used in gas purification. A zeolite membrane or polymer electrolyte membrane is used to selectively separate out a particular component into a gas stream. ETC in Piteå, Sweden, has successfully tested CO_2 selective zeolite membranes at high pressure. The membranes have great potential to be used in biofuel production because the synthesis gas from a biomass gasifier needs to be purified from CO_2 .

SYNTHESIS GAS TO HIGH VALUE PRODUCTS

Several research projects are underway in this area. In the BioDME project, currently performed at ETC in Piteå, DME is produced on a pilot scale (4 tons/day) from synthesis gas that is produced from gasification of black liquor, which could also easily be further converted into gasoline. Similarly, diesel can be produced from synthesis gas. In Finland there are on-going research and development activities around this process. Synthesis gas has for a long time been converted into many different products. For biomass gasification, it is important that the formed synthesis gas can be purified to a suitable quality for existing technologies. In addition, there should be room for innovations in gas cleaning and catalytic synthesis of custom synthesis gas from biomass gasification, such as zeolite membranes for the purification of synthesis gas.

ETC has a bench scale plant for the catalytic synthesis of methanol and DME. During 2010, the first synthesis of methanol was achieved from synthesis gas via black liquor gasification. The gas from the black liquor gasifier was purified first from benzene with a carbon filter (adsorption) and then from sulphur components with a layer of zinc oxide. The clean gas was then introduced into a catalytic reactor where the gas was converted into methanol. Figure 4 shows the plant used for methanol synthesis. Totally, approximately 0.6 dm³ of liquid bio-methanol was produced, see Figure 6.

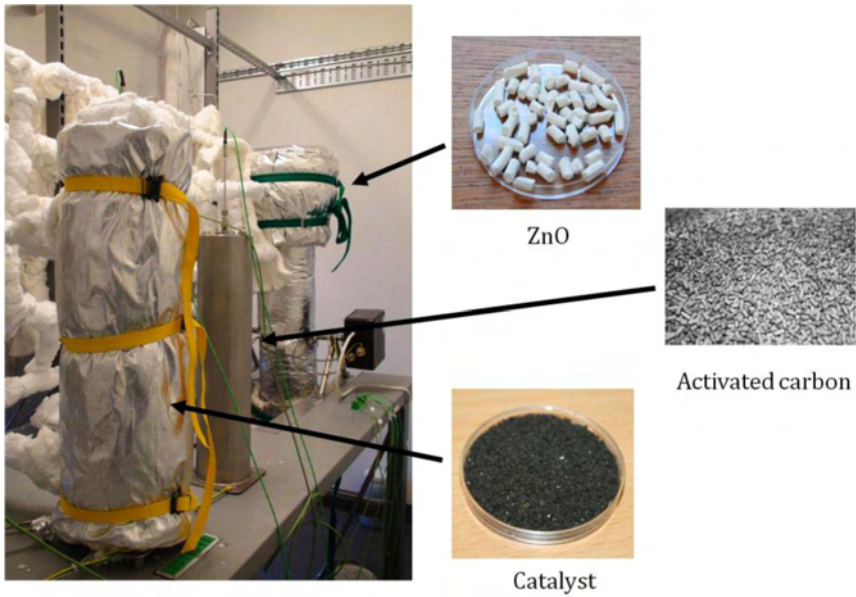


FIGURE 5. Plant used for the catalytic synthesis of methanol from syngas. The plant includes the reactor with the addition of carbon, zinc oxide and a catalyst.



FIGURE 6. Methanol is drained from the facility, made from gasified black liquor.

CENTRIA DOWNDRAFT BIOMASS GASIFIER FOR SMALL SCALE CHP PRODUCTION

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During the past few years, gasification of biomass has become a popular topic of industrial and scientific interest. Product gas or synthesis gas, as a result of biomass gasification, can be used in small-scale CHP (combined heat and power) units for heat and power (electricity) production. Moreover, the product gas can also be used in production of biofuels and chemicals. Small-scale CHP can be defined as combined heat and power generation systems with electrical power less than 100 kW. Micro-scale CHP is also often used to denote small-scale CHP systems with an electric capacity smaller than 15 kW_e (Dong L. 2009).

The Centria downdraft gasifier studied in the HighBio research project, as shown in Figure 1, is based on patented EK gasifier technology. Thermal and electrical output power of the Centria research gasifier is 100 kW_{th} and 50 kW_e respectively.

The Centria downdraft gasifier consists of a feeding system for wood chips, air pre-heater and supply, gasifier with ash removal and a gas cleaning system (Figure 1). Centria research gasifier is based on a traditional wood gasification process, but it has some distinct technical improvements that make it unique and more versatile in distributed CHP production. In the EK-technology based biomass gasification process the quality of the fuel is not as critical as in traditional gasifiers and (for example) in air dried (moisture content 30–40%) wood chips (containing bark) made from birch, pine etc which can be fed in to the gasifier.



FIGURE 1. CENTRIA downdraft gasifier is based on patented EK gasification technology.

Process conditions during the stable operation of the Centria downdraft gasifier is presented in Table 1 and the process flow diagram in Figure 2.

TABLE 1. Process conditions during the stable operation of the Centria downdraft gasifier

Property	value
Feedstock mass flow, kg/h	45
Air flow, Nm ³ /h	52
Air temperature, °C	16
Reactor temperature, °C	1200
Bottom ash removal rate, kg/h	0.4
Product gas flow, Nm ³ /h	78

Research at the Centria R&D renewable energy laboratory aims to provide a more comprehensive understanding of the operational conditions, produce different gas or syngas compositions and study the heat and electricity coproduction (CHP) optimisation from syngas generated by gasification of renewable energy sources. This includes wood chips and small size thinnings as well as other agricultural biomasses. The aim of the study is in good accordance with the EU strategy to reduce the dependence

on fossil fuels, reduce greenhouse gas emissions and meet the tough CO₂ reduction targets.

In biomass-fuelled CHP systems combustion and steam turbine technologies are the most widely used, particularly for large and medium-scale biomass-fuelled CHP systems (Table 2). Gasification based CHP systems can potentially have a higher electricity efficiency than a direct combustion CHP. The gas obtained by gasification can be utilised in diesel, gas, Stirling or “dual fuel” engines, or in a gas turbine. (Verigan 2009)

TABLE 2. Major energy conversion technologies for biomass-fuelled CHP systems (Dong L., 2009)

Primary technology	Secondary technology
Combustion producing steam, hot water	Steam engine; steam turbine; Stirling engine; Organic Rankine Cycle (ORC)
Gasification producing gaseous fuels	Internal combustion (IC) engine; micro-turbine; gas turbine; fuel cell; Stirling engine
Pyrolysis producing gaseous and liquid fuels	Internal combustion engine
Biochemical/biological processes producing ethanol, biogas	Internal combustion engine
Chemical/mechanical processes producing biodiesel	Internal combustion engine

Downdraft gasification can be considered as one of the most suitable technologies for distributed small-scale biomass based combined heat and power production up to about 1 MW_{th}. All together there are about 50 commercial gasification plant manufacturers in Europe, the United States, and in Canada from which 75% uses a fixed-bed downdraft design, 20% fluidised-bed systems, 2.5% updraft and the remaining 2.5% are various other designs (H. Knoef 2000).

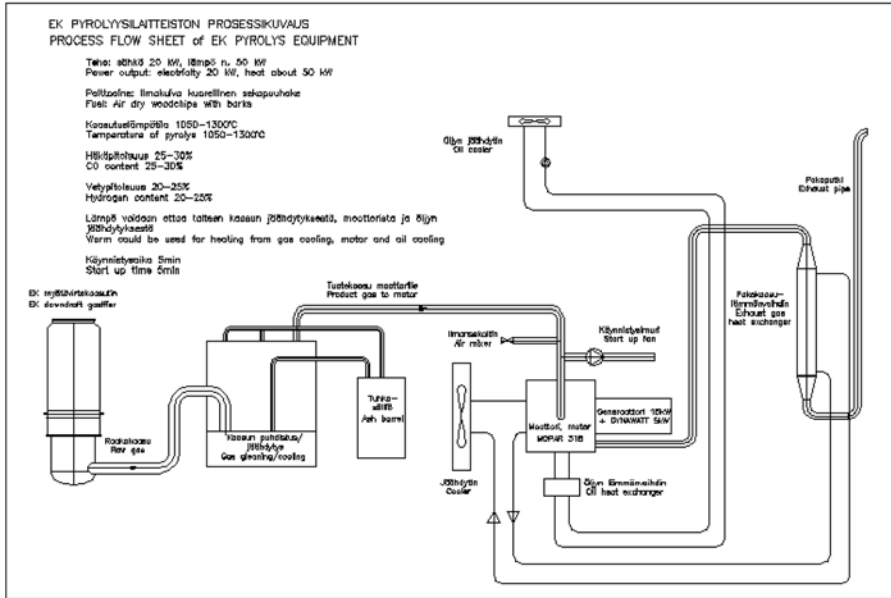


FIGURE 2. Process flow diagram of the Centria R&D renewable energy laboratory gasifier

SPECIFIC FUEL CONSUMPTION AND SPECIFIC LOAD ESTIMATION OF THE GASIFIER

Specific gas production of the Centria R&D renewable energy laboratory gasifier and wood gas fuel consumption of the modified IC engine was determined using different electric loads of 9 kW, 18 kW and 27 kW (Figure 3).

Moisture content and measured higher and lower heating values of the wood chip used in this study are represented in Table 3. Moisture of chips was rather high at 44.6 %.



FIGURE 3. Study of the gas production and fuel consumption of the modified 8 litre 6 cylinder IC engine. Electrical power loads of 9 kW used in the experiment (left) and IC gas engine (right)

TABLE 3. Measured properties of the wood chips used in the experiment

Wood chip property	Unit	Measured Value
Moisture as received	%	44.6
Ash (dry basis)	%	1.9
Higher heating value (HHV(dry))	MJ/kg	19.71
Lower heating value (LHV(dry))	MJ/kg	18.3
Lower heating value as received (LHV)	MJ/kg	9.5

Specific gas and wood consumption of the IC engine was determined by increasing the electric load from a no-load situation to 27 kW by 9 kW steps using 9 kW electric heaters (Figure 3). Specific gas consumption of the IC engine in a no-load situation is rather high at 70.4 Nm³ of wood gas to produce 1 kWh of electrical energy compared to an under load situation where 2.6–3.0 Nm³ is required to produce 1 kWh of electrical energy. (Table 4)

TABLE 4. Measured data for the determination of wood gas consumption of the IC engine

Measurement	Unit	Test run 1	Test run 2	Test run 3	Test run 4
Average product gas volume flow rate	Nm ³ /h	70	94	124	151
Wood chip consumption	kg/h		39.78	-	58.84
Heat power	kW	22		45	52.5
Electric energy	kWh	0	9	18	27
Specific gas consumption	Nm ³ /kWh	70.4	2.6	3.0	3.0

Specific wood chip consumption was estimated from measurements presented in Table 4 to be 1.06 kg/kWh whilst the specific gas production was calculated to be 2.45 - 2.83 Nm³/kg.

Wood chip consumption was also determined using an Oilon natural gas burner modified for wood gas usage. The same burner can also be used in a Sterling engine CHP unit (Figure 6). According to collected measurements air dry (moisture 35 %) wood chip consumption was 57 litre / h, which equates to about 16 kg / h (approx specific gravity: 280 kg/m³). (Figure 4) Wood gas production was measured using a gasometer and found to be 7.49 Nm³/h, which according to this measurement, would produce 3.6 Nm³ for 1 kg of wood chips. This is rather high compared to values presented in Table 5.



FIGURE 4. Evaluation of specific gas production using a gas burner. Wood gas fuelled gas burner (left) and test facility (right).

Measured wood chip consumption of the Centria CHP unit as a function of electrical energy produced is presented graphically in Figure 5.

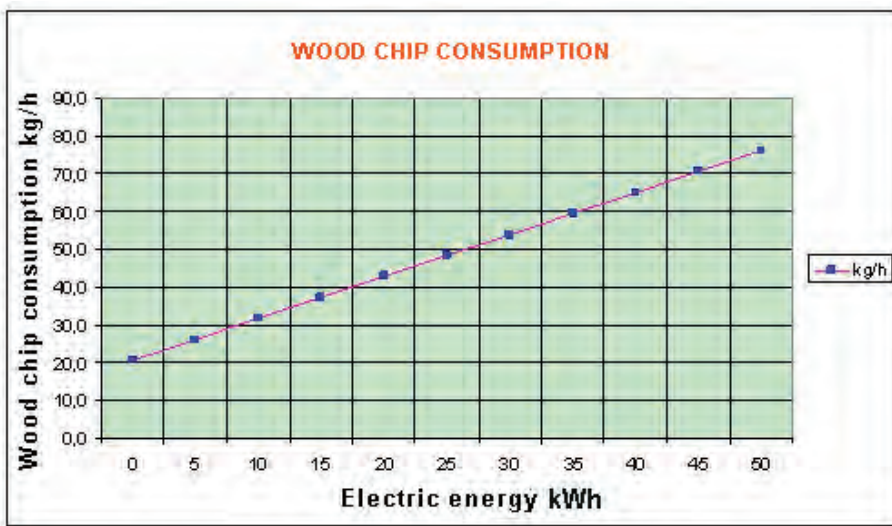


FIGURE 5. Wood chip consumption (kg/h) as a function of electrical energy (kWh).

Measured specific gas production and fuel consumption are in good agreement with the values presented in literature (Table 5)

TABLE 5 Measured gasification parameters compared to typical values presented in literature

Gasification parameter	Unit	Measured Values (Centria gasifier)	Typical Values (Knoef 2005)
Specific gas production	Nm ³ /kg	2.5–2.8	2–3
Specific gas production	Nm ³ /kW _e	2.6–3.0	2–3
Specific fuel consumption	kg/kW _e	1.06	1–1.3
Specific load	kg/m ² .hr	2510	500–2000

It should be noted that the moisture content of wood chips used in this experiment was about 45 %, which is much more than the literature value given for the highest acceptable moisture content (25 %) for a downdraft gasifier (H. Knoef 2005). Lower heating value of the wood chips used in this experiment was about 9.0 MJ/kg, which is considerably lower than

the literature value provided (13.5 MJ/kg) for wood chips with a moisture content of 25 %.

UTILISATION OF PRODUCT GAS

High temperature biomass gasification (1200 – 1400 °C) results in biosyngas (H_2 to CO ratio 2:1), a raw material that can be used in the chemical industry to produce liquid fuels (e.g. ethanol, methanol, and FT-diesel), to generate heat and power or synthesise other chemicals and produce H_2 .

Low temperature biomass gasification (800 – 1000 °C), on the other hand, results in product gas that contains mainly CO, H_2 , CO_2 , H_2O , CH_4 , N_2 , some higher hydrocarbons and tars, which can be used as fuel for gas or in a Stirling engine to produce electricity along with heat. After tar cracking, cleaning and reforming, product gas can be used like biosyngas in several applications e.g. as a feedstock for synthetic natural gas (SNG) production.

The addition of steam or oxygen to the biomass gasification process results in steam reforming and produces a biosyngas, which can be used as the feed to a Fischer-Tropsch reaction to make higher hydrocarbons, or to a water gas shift reaction (WGS) for hydrogen production. Currently, hydrogen is primarily used in the chemical industry, but in the future it could become a significant fuel used in cars for example. (Holladay, et al. 2009).

STIRLING ENGINE BASED MICRO-CHP UNIT IN CENTRIA R&D RENEWABLE ENERGY LABORATORY

A Stirling engine coupled with a biomass gasifier is the latest installation in the Centria R&D renewable energy laboratory.

A Stirling engine is a heat engine which operates by cyclic compression and expansion of air or other gas, the working fluid, at different temperature levels such that there is a net conversion of heat energy to mechanical work. The Stirling engine is noted for its high efficiency compared to steam engines, quiet operation, and the ease with which it can use almost any heat source. This compatibility with alternative and renewable energy sources has become an increasingly significant method for reducing the dependence on fossil fuels and to reduce CO_2 emissions. (http://en.wikipedia.org/wiki/Stirling_engine)



FIGURE 6. Installation of the SOLO Stirling 161 Combined Heat and Power to the Centria R&D renewable energy laboratory

The heat from the combustion of fuel is transferred from the outside to the working gas at a high temperature (typically 700°C - 750°C) and the extra heat, which is not converted into work on the shaft, is rejected into the cooling water at 40°C - 85°C.

There are some important benefits from using the Sterling micro-CHP units compared to conventional IC engine combined heat power production. For instance service intervals for Stirling engines are much longer compared with Otto engines, being typically 5000 to 8000 hours whilst the emission of harmful substances from current Stirling burners can be 10 times lower than the emission from gas-fired Otto engines with a catalytic converter. (SOLO STIRLING GmbH version 1.9, July 2003) The capacity of the Stirling engine is 9 and 26 kW for electric power and thermal power respectively, whilst a total efficiency of over 95 % can be achieved.

REFERENCES

- Dong L., Liu H. and Riffat S. "Development of small-scale and micro-scale biomass-fuelled CHP systems –A literature review." *Applied Thermal Engineering* 29, 2009: 2119–2126.
- Holladay, J.D., J. Hu, D.L. King, and Y. Wang. "An overview of hydrogen production technologies." *Catalysis Today* 139. 2009. 244 – 260.
- Knoef, H. *Inventory of biomass gasifier manufacturers and installations*. Enschede: Final Report to European Commission, Contract DIS/1734/98-NL, Biomass Technology Group BV, University of Twente, 2000.
- Knoef, H.A.M., ed. *Handbook Biomass Gasification*. BTG Biomass Technology Group BV, The Netherlands, 2005.
- SOLO STIRLING GmbH. *Technical Documentation. Solo Stirling 161 Combined Heat and Power (CHP) Module*. Sildeffingen: www.stirling-engine.de, version 1.9, July 2003.
- Verigan, H.J. "Advanced Techniques for Generation of Energy from Biomass and Waste." *ECN publication.*, 2009: Available from: http://www.ecn.nl/fileadmin/ecn/units/bio/Overig/pdf/Biomassa_voordelen.pdf.

GASIFICATION AND ANALYSIS OF THE PRODUCT GAS

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BIOMASS GASIFICATION

Gasification is a thermal treatment process based on drying, pyrolysis, oxidation, and char gasification, which results in gaseous products and small quantities of organic impurities, char and ash. Gasification is performed at high temperatures in order to optimise gas production. The resulting gas, known as the producer gas or product gas is a mixture of carbon monoxide (CO), hydrogen (H₂), and methane (CH₄), together with carbon dioxide (CO₂), nitrogen (N₂) and some organic impurities (tar) along with dust, HCl, H₂S, NH₃ ect. (Figure 1)

biomass + O ₂ (or H ₂ O)	→	CO, CO ₂ , H ₂ O, H ₂ , CH ₄ + other hydrocarbons
	→	tar+char+ash
	→	HCN, NH ₃ , HCl, H ₂ S + other sulphur gases

FIGURE 1. Product gas formed from biomass gasification.

Pyrolysis is the first step in all thermochemical biomass conversions. Conventional slow pyrolysis (carbonisation) has been utilised for thousands of years primarily for the production of charcoal. Fast pyrolysis produces mainly liquid bio-oils (60–75 wt%), some solid char (15–25 wt%), and non-condensable gases (0–20 wt%). Flash pyrolysis is considered to be an improved version of the fast pyrolysis, with reaction times of few to several seconds. (Table 1)

TABLE 1. Pyrolysis conditions in slow, fast and flash pyrolysis

	Slow pyrolysis	Fast pyrolysis	Flash pyrolysis
Pyrolysis temperature (°C)	300–700	600–1000	800–1000
Heating rate (°C/s)	0.1–1	10–200	>1000
Particle size (mm)	5–50	<1	<0.2
Solid residence time (s)	300–550	0.5–10	<0.5

The organic impurities range from low molecular weight hydrocarbons to high molecular weight polynuclear aromatic hydrocarbons (PAHs), which are known as tars (Figure 2). Along with the increasing temperature a secondary reaction starts to occur in the gas phase and oxygenated tar components are converted to light hydrocarbons, aromatics, higher hydrocarbons and finally to larger PAH compounds in tertiary processes. Tar conversion from primary products to aromatic hydrocarbons as a function of temperature is presented in Figure 2. (Li C. 2009)

**FIGURE 2.** Tar formation scheme proposed by Elliot (Elliott, 1988)

Tar compounds can be divided into five groups according to the molecular weight, as shown in Table 2.

TABLE 2. Tar compounds can be divided into five different classes (Li C., 2009)

Tar class	Class name	Property	Representative compounds
1	GC-undetectable	Very heavy tars, cannot be detected by GC (Gas Chromatography)	Determined by subtracting the GC-detectable tar fraction from the total gravimetric tar
2	Heterocyclic aromatics	Tars containing hetero atoms; highly water soluble compounds	Pyridine, phenol, cresols, quinoline, isoquinoline, dibenzophenol
3	Light aromatic (1 ring)	Usually light hydrocarbons with single ring; do not pose a problem regarding condensability and solubility	Toluene, ethylbenzene, xylenes, styrene
4	Light PAH compounds (2–3 rings)	2 and 3 rings compounds; condense at low temperature even at very low concentration	Indene, naphthalene, methylnaphthalene, biphenyl, acenaphthalene, fluorene, phenanthrene, anthracene
5	Heavy PAH compounds (4–7 rings)	Larger than 3-ring, these components condense at high-temperatures at low concentrations	Fluoranthene, pyrene, chrysene, perylene, coronene

Gasification, even at high temperatures of 800-1000 °C produces a significant amount of tar, which is still the main problem in gasification processes and therefore tar removal is regarded as one of the greatest technical problems for the development of gasification technology.

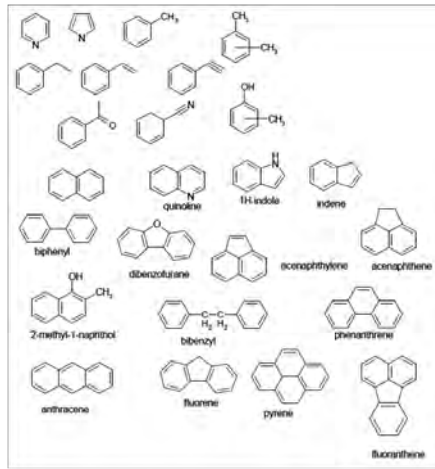


FIGURE 3. Example of some common tar compounds

Composition and the amount of tar, which has been defined as a collection of organic contaminants with a molecular weight larger than that of benzene, depends on the biomass type, gasifier and operation conditions of the gasifier. Average concentration of tars are approximately 100 g/Nm³ in an updraft gasifier, 10 g/Nm³ in a fluidised bed gasifier and 1g/Nm³ in a downdraft gasifier (Neeft J. 1999) (Figure 3)

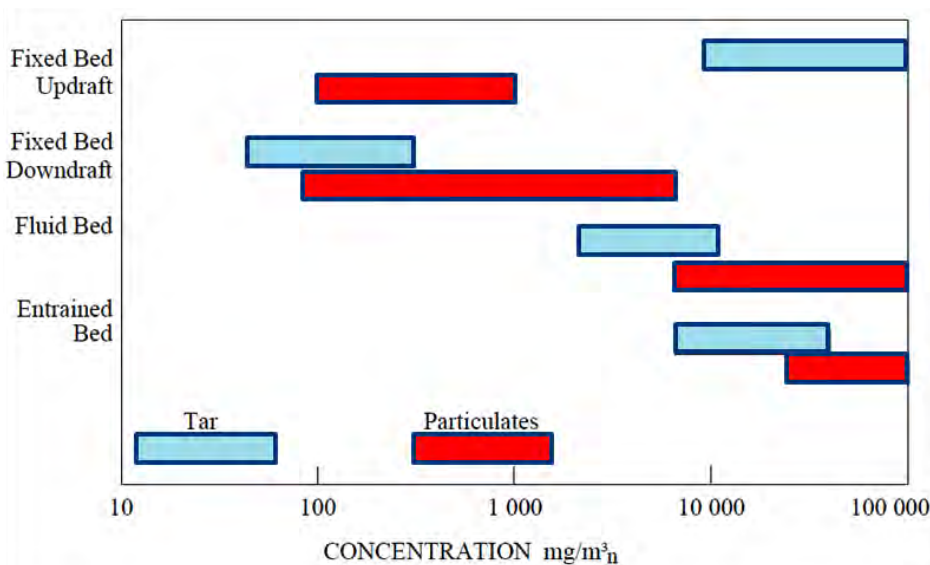


FIGURE 4. Typical particulate and tar loadings in biomass gasifiers (tar B.P. > 150 °C) (Stålberg P. 1998)

Most important tar decomposition processes are cracking, steam and dry reforming (Figure 5).

Cracking: $p \text{ C}_n\text{H}_x \rightarrow q \text{ C}_m\text{H}_y + r\text{H}_2$.

Stream reforming: $\text{C}_n\text{H}_x + n \text{ H}_2\text{O} \rightarrow (n + x/2) \text{ H}_2 + n \text{ CO}$

Dry reforming: $\text{C}_n\text{H}_x + n \text{ CO}_2 \rightarrow (x/2) \text{ H}_2 + 2n \text{ CO}$.

Carbon formation: $\text{C}_n\text{H}_x \rightarrow n \text{ C} + (x/2) \text{ H}_2$.

C_nH_x represents tar, and C_mH_y represents hydrocarbon with smaller carbon number than C_nH_x

FIGURE 5. Most important tar decomposition processes.

Tar can be reduced in the gasifier itself by modifying the gasification conditions or gasifier design (*primary measures*) or by mechanical separation or through thermal or catalytic cracking after the gas formation (*secondary measures*). In the EK gasifier technology tar is reduced primarily by a novel gasifier design while secondary measures for gas cleaning involves only a wet scrubber.

ANALYSIS OF TARS AND PRODUCT GAS

The analysis of impurities of the product gas such as tars is most often performed by *gas chromatography* (GC) or *gravimetrically*. Sampling of the tar analysis methods are most often based on trapping the tar in an organic solvent or by adsorption on a suitable sorbent. (Li C. 2009). Traditional tar sampling methods are based on cold trapping coupled with solvent absorption in impingers. Various solvents are used to sample tar, but 2-propanol was recommended by the Tar Protocol (Neef 2005). (Figure 6)

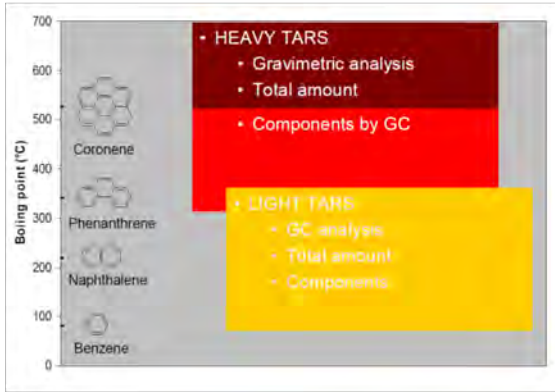
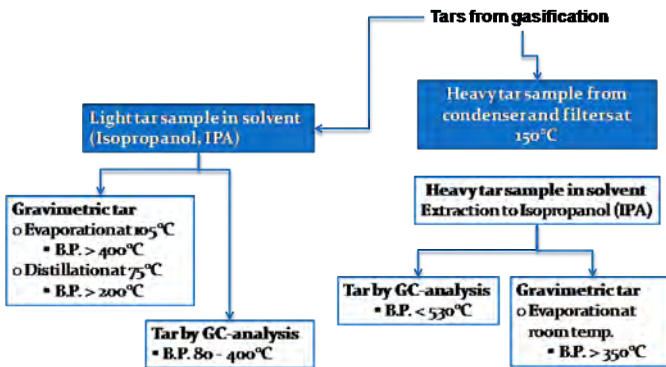


FIGURE 6. Light tars can be analysed by gas chromatography while heavy tars are analysed gravimetrically (Reinikainen 2009)



In addition to the tar protocol, we have used a SPA (Solid Phase Adsorption) method for the determination of the total tar content of the product gas from the gasifier in CHP production. Biomass used in this experiment was in the form of wood chips possessing a moisture content of about 30 %. Tar samples were adsorbed on the solid sorbent (XAD) and the sorbent was extracted with DCM (dichloromethane) using the Soxhlet apparatus. DCM extract was evaporated and the resulting residue was weighed via the gravimetric method. Measured tar content of the producer gas during half and full load was 143 g/Nm³ and 138 mg/Nm³ respectively (Table 3).

TABLE 3. Total tar concentration of the Centria R&D pilot gasifier product gas before and after cleaning

Power	Tar content of the product gas mg/m ³ n (dry, STP: 0°C, 1 atm)
50 %	143
100 %	138



FIGURE 7.
Centria R&D renewable energy
laboratory FTIR gas analyser Gaset
Dx4000N

Product gas from the gasifier contains mainly permanent gases CO, H₂, CO₂, CH₄ and N₂. Permanent gas concentrations and quality of the product gas can be continuously followed by measuring CO, CO₂, CH₄ contents and ethane and ethylene concentrations together with benzene by a FTIR gas analyser (Gaset Dx4000N). Fourier Transformed Infra Red spectroscopy (FTIR) is a spectroscopic method that compares the absorbed energy from an infra red source of light. Diatomic gases (hydrogen and nitrogen) can be analysed continuously by micro-GC. Hydrogen can also be measured by a Dräger X-am 3000 flue gas analyser after dilution of the product gas since the measuring range of the flue gas analyser is only up to 0.5 vol % of H₂.

During the total tar sampling (Table 3) the product gas was also continuously monitored by the FTIR gas analyser and the measured concentrations of the permanent gases are given in Table 4.

TABLE 4. FTIR analysis of the Centria R&D gasifier product gas (STP 0°C, 1 atm). Concentration of the main gaseous components (permanent gases)

Power	H ₂ O vol%	CO ₂ vol%	CO mg/ Nm ³	CH ₄ mg/ Nm ³
50 %	7.0	11.0	138	9
100 %	6.3	9.4	171	11

Typical composition and concentrations of the product gas from the Centria research gasifier are presented in Table 5. Typical gas composition was measured by gas chromatography after sampling in Tedlar sampling bags.

TABLE 5. Typical composition and concentrations of the product gas from Centria R&D pilot gasifier.

Product gas component	vol-%	g/Nm ³ (STP 0°C, 1 atm)
CO	15	187
H ₂	15	14
CH ₄	2.5	18
CO ₂	15	295
N ₂	50	
Other gaseous compounds	2.5	

During the total tar sampling (Table 3) the *emissions of the internal combustion engine* (IC engine) was continuously monitored by measuring O₂, CO₂, CO, NO_x and SO₂ concentrations in the flue gas. Continuous emission measurements on dry basis, were based on paramagnetism (O₂), IR absorption (CO, CO₂), UV- fluorescence (SO₂) and chemiluminescence (NO_x). Results of the continuous emission measurements with the estimated combined uncertainty are presented in Table 6.

TABLE 6. Composition and concentration of the flue gas main gaseous components during the tar sampling along with the estimated total combined uncertainty

Measured flue gas component	Measured flue gas composition	Concentration (dry, STP: 0°C, 1 atm))
O ₂	0.4 ±0.04 vol%	-
CO ₂	17±2 vol%	-
CO	568±63 ppm	170 ±19 mg/Nm ³
SO ₂	8±1 ppm	25 ±4 mg/Nm ³
NOx	162±37 ppm	332 ±37 mg/Nm ³



FIGURE 8.
IC gas engine emission measurement

REFERENCES

- Elliott, DC. "Relation of reaction time and temperature to chemical composition of pyrolysis oils." *Proceedings of the ACS symposium series 376, pyrolysis oils from biomass*. 1988.
- Li C., Suzuki K. "Tar property, analysis, reforming mechanism and model for biomass gasification—An overview." *Renewable and Sustainable Energy Reviews*, 2009: 594–604.
- Neeft, J.P.A. "Rationale for setup of impinger train as used in the Technical Specification of Sampling and Analysis of Tar and Particles in the Product Gases of Biomass Gasification." *Technical background document CEN BT/TF 143. Organic contaminants("tar")*. January 2005. <http://www.tar-web.net/>.
- Neeft J., Knoef H., Onaji P. J. Neeft, H. Knoef, P. Onaji, *Behaviour of Tar in Biomass Gasification Systems, Tar Related Problems and Their Solutions*. Report No. 9919, Energy from Waste and Biomass, 1999.
- Neeft, J.P.A., "Rationale for setup of impinger train as used in the Technical Specification of Sampling and Analysis of Tar and Particles in the Product Gases of Biomass Gasification." *Technical background document CEN BT/TF 143 "Organic contaminants ("tar")*, 1999.
- Reinikainen, M. "Synthesis Gas Characterization at VTT laboratories and test facilities." VTT Finland , 2009.
- Stålberg P., et.al. *Sampling of contaminants from product gases of biomass gasifiers*, VTT Research Notes 1903. Technical Research Center of Finland, 1998.

FUTURE OF GASIFICATION TECHNOLOGY

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In Finland biomass gasification has been studied for the last 30 years (Salo, 2009) with an increased focus in the early 1990s on heat and power (CHP = Combined Heat and Power) from gasification. There was talk about a so-called IGCC technology (Integrated Gasification Combined Cycle), where the biomass raw material is gasified at high pressure and temperature and the resulting gas is purified and directed to a CHP plant. A combined power plant consists of a gas and steam turbine in combination with a waste heat boiler (Kurkela, 2006). In Finland, there were two commercial-scale biomass-IGCC demonstration projects planned, but neither of them was put into practice. At the same time the low cost of rival energy production, including oil and natural gas, made solid fuel based plant investments unviable. In addition, it can be said that customers (Forest Industry companies), despite the aid of large public investment, were not willing to take the risk of developing IGCC technology for pulp mills. IGCC technologies were also developed for fossil raw materials (coal, oil).

As we approached 2010 the availability and price uncertainties of fossil crude oil, greenhouse gas emission issues and the forest industry's need to develop alternatives for paper and paperboard products has made biomass gasification-based biorefinery interesting. In practice, all major Finnish forest companies, such as UPM Kymmene Oy, Stora Enso Oy, and Metsäliitto have their own biorefinery project in the commercialisation phase. This also includes Neste Oil Oy and Vapo Oy (Kurkela, 2009). These projects aim to demonstrate the potential of biomass in pressurised gasification, gas purification as well as catalytic processing of synthesis gas to biofuels. The fuel biodiesel is the most interesting, and the most likely, based on the fact that the synthetic production technology of diesel from coal or natural gas has already been demonstrated.

New catalytic processes for conversion of synthesis gas from gasification are already under development. For example in Sweden, the company Chemrec is currently building a DME (dimethyl ether) and a methanol production and distribution plant at Piteå. Supporting this project is the car manufacturer Volvo (Gebart, 2011). Biomass-based gasification demonstration plants for the production of liquid biofuels are being developed across the Nordic countries as well as in Central Europe and North America (Bacovsky, 2009). In Austria, a gasifying plant currently in operation implements the REPOTEC® process. The plant is based on combined heat and power production from woody biomass gasification, but the produced synthesis gas is also demonstrated in advanced production of biodiesel and SNG (synthetic natural gas). SNG can also be used as fuel for transport like natural gas. In Sweden REPOTEC® technology is being introduced in a larger scale in a so-called CoBiGas project (Rauch, 2011).

By 2020, worldwide production of liquid biofuels is expected to increase by 3-6 times (Sohlström, 2010). On an industrial scale, liquid biofuel production is likely to constitute a significant share of the gasified biomass raw material processing, the so-called second-generation technology. The advantage of gasification is the use of raw materials that do not disadvantage food production.

In the so-called decentralized scale gasification of wood biomass and solid waste can bring significant increases in CHP production also on decentralised scale, namely electricity generation from 10 to 1000 kWe. There is also talk about the so-called small- or micro-CHP technology. Gasification-based applications are currently being developed across the Nordic countries and Central Europe, for example based on down-draft-gasifier (Konttinen, 2011). While small scale-CHP is not the solution for the basic power production at a national level, it however can bring new business and jobs to rural municipalities and improve Finland's energy self-sufficiency and security. In addition, it may provide new technological export products. Small scale CHP units can also be combined with other renewable forms of energy production as a hybrid solution, such as biogas, solar and wind power.

In Lahti, Finland, waste fuel is capitalized in a large-scale gasification CHP plant (160 MWth) as a replacement for use of coal fossil fuel. Since 1998, the plant's waste and biomass gasifier has been connected to a pulverized coal boiler (Lahti Energia, 2011). The potential of biomass-based IGCC has not disappeared either (Kurkela, 2006).

In addition to the price trends of competing energy sources, the lack of successful demonstrations has contributed to the slow progress in the commercialisation of gasification technologies. In all the above mentioned technology projects based on gasification, the challenges are still the

demonstration of long term operation as well as providing competitive prices of electricity, heat and liquid biofuel. The most critical technological development for the future is gas purification.

REFERENCES:

- Bacovsky, N.: Overview on Wide Spread Implementation of 2nd Gen Bio-fuel Demonstration Plants in the World. 4th BTLtec, Graz, Austria, September 2009.
- Gebart, R.: Swedish Research on Forest Biomass Gasification and Syngas Conversion into Second Generation Motor Fuels. Swedish-Finnish Flame Days, 2011, Piteå, Sweden, January 2011. http://www.ffrc.fi/Flame-Days_2011/Session_4_Gasification/27gebart.pdf
- Konttinen, J.: Onko jo pien-CHP:n aika? Motiva bioenergy days, Varkaus, December 2010. http://www.motiva.fi/files/3765/Varkaus_Konttinen.pdf
- Kurkela, E.: Biomassan ja jätteen kaasutus. Liekkipäivä 2006, Turku, January 2006. http://www.tut.fi/units/me/ener/IFRF/Liekkipaiva2006_BiomassaJateKaasutus_KURKELA.pdf
- Kurkela, E. : Gasification R&D Activities in Finland. Finnish-Swedish Flame Days 2009, Naantali, January 2009. <http://www.tut.fi/units/me/ener/IFRF/FinSweFlameDays09/Kurkela.pdf>
- Lahti Energia, www.roskatenergiaksi.fi. 4.4.2011
- Rauch, R.: Development of the biomass CHP Güssing to a biosyngas platform; Kraftwerk Güssing GmbH & Co KG; Austria. GREENSYNGAS workshop, Güssing, Austria February 2011.
- Salo, K. (Carbona Oy): Private conversation, 2009.
- Sohlström, H.: Biorefineries – UPM and Biofuels. FOREST BIOENERGY conference, Tampere, September 2009.

GASIFICATION TECHNOLOGY FROM A USER'S PERSPECTIVE

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Thermal energy enterprises and cooperatives typically operate in the 0.3–2.0 MW plant size category. So far, they have focused almost exclusively on the production of heat for their customers. In cost-effective solutions customer groups are large, relative to the plant size, and very close to the heat units. Larger plants usually have more customers, as such the heat transfer canal is wider and heat production is in the form of district heating. Customers are mainly municipalities, cities, churches and other businesses. Heat production has led to contract agreements with users that already have an existing water circulating heating system, for example schools, industry, apartments, retirement homes, etc. Wood chips are the main source of fuel, but peat is often used in peat parishes whilst a mixture of the two can also be used during high heat consumption. However, a number of the energy cooperatives are committed to using only wood as their raw material. Energy Cooperatives were established from the early 1990s up to the early 2000s but in recent years, hardly any co-operatives have been set up. It is clear now that plants, only producing heat, will continue with its life cycle with existing machines until a point when a new solution will be needed. The EU and Finland's energy policy for renewable energy targets will lead to an increase in new investment in downstream energy. In this development CHP plants are one solution.

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- 1 The Forest Owners Union of Central Ostrobothnia
 - 2 Forest Marketing Company of Central Ostrobothnia Ltd
 - 3 Lohtaja Energy Cooperative

The expectations of CHP plants by thermal energy enterprises and cooperatives are high. Technical solutions should be functional, be made as simple as possible, and easily administered in the control system. If necessary, modularity should be an asset when adding and removing components. The base size should match the current 0.3 - 2.0 MW heat production of electric power, whilst heat production and electric power/gas output should be approximately 50 % more than this. The plant's equipment is expected to reach their full potential after 3000-4000 hours of use, e.g. the plant, size 0.3 MW, should produce annually about 600 MWh of heat and about 300 MWh of electricity / gas as its minimum output. The introduction of new technology should be flexible whilst equipment suppliers could guarantee the security of supply solutions such as leasing, or an extensive service network. The investment recovery charge should be closer to five years rather than ten years.

When it comes to the generation of electricity and related energy, it can be assumed that there will always be potential customers, who are probably all using more than 100 000 kWh combined with heating or cooling recovery. This threshold will decrease further when electricity becomes more expensive and incentives favouring small plants are offered by the Central European model. The competitiveness of heat production is improved when competing forms of energy such as light fuel oil becomes more expensive. Beyond incentives, alternatively, there is also investment aid and soft loans for financing. Local Energy is mentioned in a number of organisations strategies including i.e. MTK. Small plants have undeniable advantages when it comes to transportation and employment for rural areas.

Wood gasification process allows the manufacturing and implementation of a number of higher refined energy products locally. Gas can be utilised in a wide range of technologies for engines and generators. Renewable electricity and gas are easy to move and sell in a local area. In comparison, the heat transfer is less favourable due to expensive thermal canal and investment losses.

In traditional heat production, small plants possess an annual efficiency of 75-85 %. This value is dependent on the plant's design (peak load), heat transmission length, average quality of fuel, boiler cleaning and the combustion process itself. During the summer (as expected) efficiency is much lower than during the winter. Furthermore, it was also found that two boilers connected in series provide better fuel efficiency as one large boiler. For example, a 1 MW plant has an improved efficiency with two 0.5 MW boiler, one of which is cold for most of the year. Thermal plants own electricity consumption is about 1-2 % of the heat energy, so the electricity

generated in the CHP energy production from cooperatives / self-heating would largely go on sale.

The fuel efficiency of wood chips can also be improved when the moisture content of raw material is reduced. This decreases the total cost due to lower chip consumption, chipping / transportation expense and fewer failures. Wood chips with a moisture content of 30–35 % are good material for the production of heat. Energy co-operatives members have been trained to achieve the objective of this quality for many years. Finally, as I understand it, the chip quality requirements (humidity) in the CHP generation should be in the same category.

The Finnish government has drawn up a number of obligations, one of which is to increase renewable energy usage at a specific rate until 2020. To achieve these goals the government has decided to increase energy taxes on fossil fuels, including peat. Unfortunately, actual incentives, including feed-in tariffs, bonuses paid for certain heat production, emission trade-tied support for power generation, energy support for small wood production and for investments and support for changes in thermal systems, have yet not been finally approved. New and existing small plants have been mistreated due to size limits and minimum production quantities. Furthermore, the Central European model of the differential feed-in tariff is not being implemented. The quarterly review also predicts speculative solutions if the situation remains this way.

It is desirable that versatile related energy production is encouraged by reasonable elements. This would achieve positive effects in terms of employment, technological development, bio-processing, forestry, a risk-free energy production and lower environmental loading.

BIOFUELS AND UTILISATION OF SYNTHESIS GAS

BIOFUELS OF THE FUTURE

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INTRODUCTION

Energy demand is estimated to grow more than 50 % by 2025 if growth continues at its current rate. Growth in energy consumption is largely due to the emerging economies of countries that possess growing consumption demands. Reduction of fossil fuels and their life expectancy in the world market has forced enterprises, research institutes and policy makers to seek alternative solutions to use alongside transportation fossil fuels.

The EU Directive (Directive 2003/30/EU) outlines targets that will increase the use of biofuels in the European Union. In accordance with the objectives of the directive, the share of biofuels in transport fuels should be 2 % by the end of 2005 and 5.75 % by the end of 2010. Many countries, including Finland, have so far not been able to meet these objectives.

The biofuel debate, research and its production has so far focused mainly on bio-ethanol and diesel (ethers) production. However, the energy density of ethanol compared to existing fossil-fuels (gasoline, diesel) is significantly lower. Because of this, it is also important to consider other possible transportation fuels, such as alcohols, butanol, pentanol, as well as furfural and furans.

The benefits of butanol compared to ethanol are significant. It is estimated that about 0.7 litres of butanol is equivalent to the energy density in one litre of ethanol. In addition, butanol has a better air-fuel ratio and is suitable for use in the existing fuel engines. The main problem with the manufacturing of butanol so far has been the low yields, especially in the production of butanol from bio-based raw materials.

5-hydroxymethylfurfural has previously only been produced efficiently from fructose, but the use of ionic solvents and catalysts for its preparation from glucose has also been found to be effective. For example, 2,5-dimethylfuran has a 40 % higher energy density than ethanol. Therefore, furfural production is an interesting alternative for the production of biofuels, bringing a new perspective for biomass recovery.

TRANSPORT FUELS

The most common used transportation fuels are fossil fuels, such as gasoline and diesel – of which almost five trillion litres are consumed worldwide each year. 97 % of the world's cars use fossil fuels as their energy source with alternative fuels accounting for remaining 3 %, of which 1-2 % is produced from renewable energy sources.

By developing alternative and renewable fuels the dependence on fuel oil can be reduced, or by developing vehicles and engines that can exploit a more diverse range of energy sources. The alternative transportation fuels currently used and those that are designed for use in the future include the following; biodiesel, natural gas and biogas, liquefied petroleum gas, alcohols such as methanol, ethanol and butanol, furfural derivatives, as well as hydrogen.

Amongst liquid and gaseous fuels, other sources have also been examined such as lithium-ion batteries for cars. The first of these applications are already on the market and almost every vehicle manufacturer possesses an existing concept of a hybrid vehicle. Electric cars reduce the dependence on liquid fuels; however, it is worth remembering that the energy of electric cars will also need to be produced.

The physical and chemical properties of transport fuels

Table 2 contains the chemical and physical properties of gasoline, diesel and alcohol fuels. The most commonly used ethanol has a considerably lower energy density than, for example butanol, and 2,5-dimethylfuran (DMF). The total energy of ethanol-gasoline-mixture does not reduce significantly compared to other fuel mixtures, because the maximum allowed ethanol concentration is currently set at 10 vol-%.

TABLE 1. The chemical and physical properties of gasoline, diesel and alcohol fuels. (Gautam et al., 2000)

Fuel	Energy density (MJ/l)	RON	MON	Solubility (%)	Air-fuel ratio	Viscosity, (20°C)
Gasoline	32	91–99	81–89	Insignificant	14.6	0.4–0.8
Diesel	35.5	-	-	Insignificant	(60–100) 14.7	4 (40°C)
n-Pentanol	27.8	Low	Low	0	11.68	-
n-Butanol	29.2	96	78	7	11.12	3.64
Ethanol	19.6	130	96	100	8.94	1.52
Methanol	16	136	104	100	6.43	0.64
2,5-dimethyl furan	30	119		2.3	-	-

EU legislation on fuels

The European Union has regulated the properties of traffic biofuels and their concentrations of different substances. The directive of the European fuels (2007) and European standard EN 228 - quality standard (2008) allow oxygen content up to 3.7 m-% for biofuels, so alcohols and furans are not suitable for transport biofuels, but these biofuels are often mixtures containing different substances. Also, E85 - fuel with higher ethanol content, is recommended specifically for fuel referred cars. In Table 2 the European fuel directive defined by various parameters and the maximum values is presented.

TABLE 2. European fuel directive with different parameters and their maximum values. (Directive of the European fuels, 2007)

Parameter	Unit	Maximum limit
Vapour pressure, summer season *	kPa	60.0**
Olefines	vol- %	18.0
Aromatics	vol- %	35.0
Benzene	vol- %	1.0
Oxygen	mass- %	3.7
Methanol	vol- %	3.0
Ethanol	vol- %	10.0
Ether (e.g. DMF)	vol- %	22.0
Other oxygenates	vol- %	15.0

*) Begin at the latest 1.5. and ends at the earliest 30.9. Member States with arctic or severe winter conditions, will start at the latest 1.6. and ends at the earliest 31.8.

***) Countries with severe winter conditions during the summer period of up to 70 kPa.

In the production of biofuels other factors must also be considered. For example, an oxidation resistance of the fuel mixture, since the maintenance of fuels may come into contact with oxygen in air. Oxygenation can result in precipitated particles that can block car engine filters. For security reasons, the flashpoint of biofuels must not be less than 55 ° C. (Motiva, 2006)

In December 2008, the European Parliament adopted a directive for renewable energy use (COM 2008/19) in which it was stated that renewable energy should make up 20 % of total energy consumption by 2020. Biofuel feedstock's should favour organic waste materials, non-food biomass and lignocellulosic materials, such as pulp liquors. If the biofuel raw material can be produced from soil, which is unsuitable for food production, a bonus for carbon emissions can be awarded. The directive on the use of renewable energy has also set national objectives for each Member State.

Utilisation of biomass in fuel production

Biomass suitable for food has traditionally been used in biofuel production and food production has been reduced globally because of this fact. Such a policy, fortunately, has started to be less popular. As a result of the policy, poverty has increased, and food prices have risen. Furthermore, a change in the cost of biofuels production has reversed the direction of research to residue bioenergy and municipal waste materials. In Finland, the production of biofuel can be based on forest industry residues, which normally have a high cellulose content and energy, as well in the food industry waste masses.

The use of residue biomasses in biofuel production is problematic, since they often contain a lot of different fragments and unused chemicals from processing. These factors will have a negative impact on the manufacturing process. The residual materials should be handled in an environmentally favourable manner, so that their use would be ecological. Residue biomass possesses high energy content and is well suited, for example, to gasification (Sricharoenchaikul et al., 2002). Gasification of biomass reduces the required pretreatment, but gas cleaning is important.

ALCOHOLS AS TRANSPORT FUELS

Alcohol-based fuels can be used to replace fossil fuels to combustion engines and -cells. Alcohols used as fuels, or their components, are methanol, ethanol, propanol and butanol. A number of long-chain alcohols could be used as fuel given their chemical and physical properties, but the manufacturing of alcohols for this purpose is not yet commercially profitable. The use of ethanol has been extensively researched mostly thanks to its low toxicity and well-known manufacturing methods. (Minteer, 2006)

Ethanol as a transport fuel

Bioethanol is the most commonly used alcohol-based transportation biofuel. It is generally used in mixtures with gasoline and despite it having been criticized for its poor efficiency, the use of ethanol and its manufacturing as fuel are well known. Ethanol production has caused considerable environmental damage in countries such as those in South America, where valuable rain forests have been destroyed to make way for biofuel plantations.

Butanol as a transport fuel

n-Butanol is a monovalent alcohol. It is suitable for use either directly or with a small engine adjustment, in existing gasoline car engines as fuel, either alone or alongside fossil fuels. Due to the high manufacturing costs of butanol, the only commercial markets that are viable, for now, are in industrial chemicals and solvents. Butanol has the advantage of low solubility in water, which reduces the side effects if it comes into contact with groundwater. Furthermore, due to the low vapour pressure of butanol, filling up can be achieved in existing distribution fuel networks. (Ramey et al., 2000)

Other Alcohols

Alternatives to ethanol include the use of heavier alcohols as transport fuel due to their higher energy density and low water solubility. Branched-chain alcohols have higher octane numbers compared with the same amount of carbon-containing straight-chain alcohols. Branched-chain alcohols currently cannot be synthesised enough economically by using natural micro-organisms. Methanol has not been studied as a transportation fuel as much as ethanol. Research on methanol has mainly focused on gas-phase methanol synthesis and the use of fuel cell applications. Methanol is currently used with other fuels, mainly as raw materials and additives. (Minteer, 2006)

Furfurals and furans as a transport fuels

Furfural and furans have recently been identified as biofuel alternatives due to their reasonable successes in being manufactured from sugars via existing methods. Moreover, they possess good qualities as fuel. For example, 2,5-dimethyl furan (DMF) energy density is about 40 % higher than ethanol's. 2,5-DMF production has been performed, mainly from fructose, but a new method also allows the use of glucose as a raw material. This enables for example the utilisation of cellulose containing residues from forest industry. (Román-Leshkov et al, 2007)

PREPARATION OF ALCOHOLS

Alcohols are generally produced by fermentation of sugars by enzyme catalysts. Catalytic methods, where the biomass is first gasified to synthesis gas, are developed in large amounts and the first commercial producers are already found within the Americas.

Preparation of Alcohols using Enzyme Catalysts

The preparation of alcohols by an enzyme catalyst is well known. For example, fermentable sugars have been utilised in the production of various alcoholic beverages for many years. The best known method is to produce ethanol from sugar-based raw materials by *Saccharomyces cerevisiae* - an enzyme of yeast. (Glazer et al., 1995; Helle et al., 2004; Lawford et al., 2002)

Preparation of Ethanol

Yeast uses sugar as an energy source (carbon source), for example in this case, occurring through anaerobic (oxygen-free) fermentation. Chemically it is a redox reaction, where there is no net oxidation or reduction. The fermented end product results in final compounds which cells secrete to their surroundings. Ethanol is separated from the aqueous solution by distillation, however not all water is removed and it may be necessary to use various drying chemicals.

Preparation of butanol

Butanol is manufactured using a particular family of bacteria, *Clostridium*. Preparation of butanol occurs in three stages. The first step is the so-called acidogenic phase, where the pH is neutral and the products are acetic and butyric acid. The second step is the solventogenic phase, carried out at low pH (about 4.3 to 4.4). The products of the second step are acetone, butanol and ethanol. The third step is known as the algogenic stage, where products butanol, acetone and ethanol are separated.

Catalytic preparation of biofuels

Catalytic methods are quite common in the processing of crude oil. In this case, reaction temperatures may be several hundred degrees and the reactions take place in the gas-solid interface. Biomasses' thermal stability is significantly lower than crude oil. Therefore, biomass processing should take place in the liquid phase or very carefully in the gas phase if the decomposition of biomass into synthesis gas is to be prevented. In this case, the processes are slower and require larger reactor volumes. (Klass, 2004)

The world's the first commercial technologies have already been developed for the production of biofuels from biomass by gasification and the converting of gas catalytically. These companies, for example: Choren, Coscata and Range Fuels, mainly produce ethanol and alkanes. The gasification process is currently not selective enough for long chain alcohols and alkanes production (Lin et al., 2009). The best known processes are methanol synthesis and Fischer-Tropsch synthesis. Converting biomass into synthesis gas requires several steps, which include biomass gasification, gas cleaning, (in most cases, a water-gas-shift unit) and synthesis gas conversion. (Klass, 2004)

CONCLUSIONS

The conversion of sugars into transportation biofuels still requires much research and development. Fermentation of ethanol is well known, but alternative biofuels and new preparation methods are required. Physical and chemical properties of butanol and some furans compared to ethanol are significant, but preparation methods are not currently economical.

REFERENCES

- Directive 2003/30/EU. Official journal of the European Union, L123/42, 17.5.2003, DIRECTIVE 2003/30/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, “on the promotion of the use of biofuels or other renewable fuels for transport”, Available at: http://ec.europa.eu/energy/res/legislation/doc/biofuels/en_final.pdf 26.4.2011
- Directive of the European fuels (2007). Commission of the European Communities. COM (2007) 18 final. Available also: http://eur-lex.europa.eu/LexUriServ/site/en/com/2007/com2007_0018en01.pdf, 26.4.2011.
- Directive for renewable energy use (COM(2008)19), 24.8.2009, <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0019:FIN:FI:PDF>
- European standard, En 228:2008, *Automobile fuels – Unleaded petrol – Requirements and test methods*
- Gautam, M., Martin II, D.W., Proc. Inst. Mech. Engrs, **2000**, 214 A, 497
- Glazer, A.N. ja Nikaido, H.; *Microbial Biotechnology: Fundamentals of Applied Microbiology*, W.H. Freeman and Company. USA, **1995**, 327–358
- Hadlington S. Chemistry World, news, 2007
- Helle, S.S., Murray, A., Lam, J., Cameron, D.R., Duff, S.J.B, Bioresour. Technol. **2004**, 92, 163
- Klass, D.L, in *Encyclopedia of Energy*, ed. C.J. Cleveland, Elsevier, London, **2004**, 193-212
- Lawford, H.G., Rosseau, J.D., Appl. Biochem. Biotechnol., **2002**, 98-100, 429
- Lin, Y-C, Huber, G.W., Energy and Environmental Science, **2009**, 2, 68
- Minteer, S., *Alcoholic fuels*, 1st edition, CRC Taylor & Francis Group, Boca Raton, **2006**, 1-3
- Motiva, 2006. *Vaihtoehdoiset polttoaineet ja ajoneuvot –opas*, On internet 29.3.2010: http://www.motiva.fi/files/2131/Vaihtoehdoiset_polttoaineet_ja_ajoneuvot.pdf
- Ramey, D., Yang, S-T, *Production of Buturic Acid from Biomass, Final Report*, for U.S. Department of Energy, Morgantown, WV, **2000**
- Román-Leshkov, Y., Barrett, C.J., Liu, Z.Y., Dumesic, J.A. Nature, **2007**, 447, 982
- Sricharoenchaikul, V., Agrawal, P., Frederick, W.J., Jr., Ind. Eng. Chem. Res. **2002**, 41, 5640
- Zhao, H., Holladay, J.E., Brown, H., Zhang, Z.C. Sciencemag., **2007**, 316, 1597

SYNGAS INTO NEW CHEMICAL PRODUCTS AND NEW APPLICATIONS

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BIO-BASED VEHICLE FUELS

Biomass is a renewable resource that has great potential for conversion to bio-based fuels. By thermal treatment of biomass (gasification) gases are obtained that can be used as precursors for the production of fuels and chemicals. Much intensive research is being undertaken in order to find new, bio-based vehicle fuels to replace the fossil fuels currently in use today. Both globally and within the EU targets have been set in order to increase the share of bio-based fuels. The EU aims to increase the portion of bio-based fuels from 5.75 % in 2010 to 10 % in 2020. In the current climate (2009), the proportion was 1.4 %.

FIRST- AND SECOND-GENERATION BIOFUELS

Biofuels are divided into first- and second-generation fuels depending on the raw materials used in production. Raw materials for first-generation biofuels are wheat, maize and sugar cane, or other materials that could be used to produce food (see Table 1).

TABLE 1. First-generation biofuels.

First-generation biofuels			
Fuel	Name	Ingredient	Process
Bioethanol	Conventional bioethanol	Sugarcane, beet wheat, corn	Hydrolysis + fermentation
Vegetable oil	Pure plant oil	Oilseed rape, turnip rape	Cold-pressing Extraction
Biodiesel	RME (rapeseed-oil-methylester) FAME (fattyacid-methylester)	Oilseed rape, turnip rape	Cold-pressing Extraction Transesterification
Biodiesel	Biodiesel from waste	Waste fats and oils, animal fats	Transesterification
Biogas	Upgraded biogas	(Wet) biomass	Metabolism
Bio-ETBE		Bioethanol	Chemical synthesis

For second-generation biofuels, lignocellulose waste is the prominent raw ingredient mainly found in cutting waste, waste from agriculture, demolition wood and specially grown energy crops such as reed canary grass. To some extent, residues from the food industry, such as starchy waste from the potato industry can also be used as raw materials. The idea behind second-generation fuels is that they do not compete with food production, using waste and residues instead.

Since the material consists of lignocellulose a “harder” treatment is required. Techniques used include enzymatic or acid hydrolysis into free sugars followed by fermentation, or direct gasification of biomass which is converted into hydrogen and carbon monoxide, known as product gas.

TABLE 2. Second-generation biofuels.

Second generation biofuels			
Fuel	Name	Ingredient	Process
Bioethanol	Cellulose based Bioethanol	Lignocellulose	Advanced hydrolysis + fermentation
Synthetic biofuel	Biomass-to-liquid (BTL) Fisher-Tropsch diesel Biomethanol Mixed alcohols Bio-dimethylether (Bio-DME)	Lignocellulose	Gasification + synthesis
Biodiesel	Hydro treated Biodiesel	Plant oils Animal Fat	Hydration
Biogas	SNG (synthetic natural gas)	Lignocellulose	Gasification + synthesis
Biowaste	Biowaste	Lignocellulose	Gasification + Synthesis or Biological processes

WHAT MANUFACTURING PROCESSES WILL BE USED IN THE FUTURE?

For a large-scale production of biofuels the process should be assessed throughout from several points of views as the fuel is introduced into a market dominated by fossil fuels. In particular, four criteria are important, namely: efficiency, economy, effects on environment and end use. Moreover, there are also several other considerations that have to be taken into account:

1. The fuel produced through a gasification process is able to treat various types of biomass, as well as wood-based agricultural and municipal waste
2. The manufacturing process allows flexible production of both bio-based materials as well as fossil-based
3. There is an existing infrastructure for distribution
4. Biofuels are mixable with existing fuels

5. The fuel has a high energy density
 6. The fuel can easily be used in fuel cells
 7. There is a high efficiency throughout from well-to-wheel*
 8. The production and use has little or no impact on the environment
 9. The price is low, lower or just slightly higher than the equivalent fossil fuel
 10. An advanced technology is used during the production
- * Well-to-wheel means that all relevant steps in the fuel chain have been included: namely the cultivation and harvesting of the raw material, transportation to the facility where the fuel is produced, the production of fuel, distribution to the filling stations and consumption in vehicles.

BIOFUELS FROM SYNTHESIS GAS

By gasification of biological material so-called synthesis gas (Bio-SNG) is formed. The synthesis gas contains primarily hydrogen (H_2) and carbon monoxide (CO) but also traces of various sulphur compounds, and tars.

Synthesis gas can be used for several purposes:

- Direct energy production by combustion
- Hydrogen can be used on its own or for the production of various other chemicals
- Catalytic conversion (the so-called Fisher-Tropsch reaction, see below) can produce organic compounds ranging from gasoline and biodiesel to different waxes.

Via the reaction path based upon methanol production of dimethylether (DME), various chemicals based on methanol are possible.

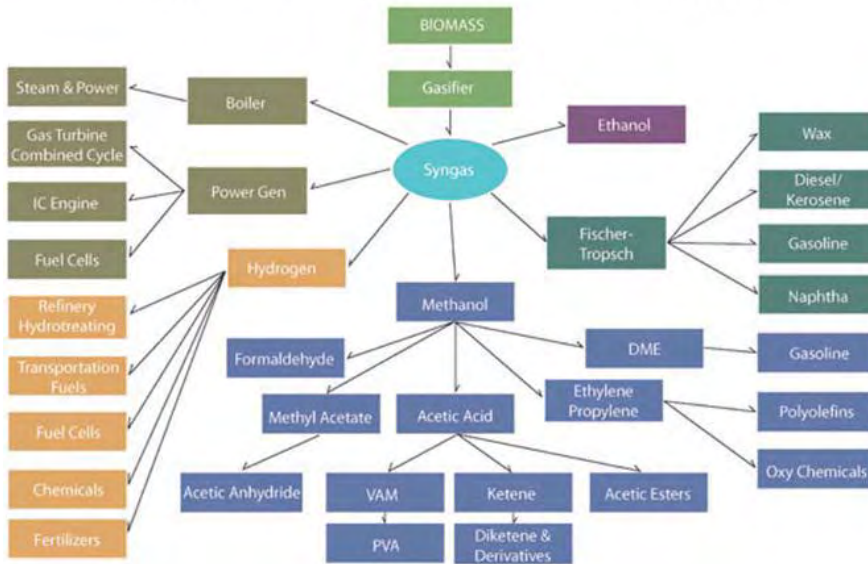


FIGURE 1. Possible applications based on gasified biomass.

PURIFICATION OF THE PRODUCT GAS TO SYNGAS

The gasification of biomass forms in addition to the main components hydrogen and carbon monoxide (H₂ and CO), several other chemical compounds. Most of these compounds are undesirable and will affect the later use of the gas. What compounds are formed and in what amounts they are found in the gas is determined by factors such as feedstock, gasification technology and, crucially, the gasification temperature. A general principle is that the higher the gasification temperature, the lower the levels of polluting components are formed.

If the gas is purified to synthesis gas, which has very strict limitations, the cost of cleaning processes will be very high, according to some estimates, even more than 50 % of total costs.

CATALYSTS AND COMPONENTS OF A CATALYST

A catalyst is a component that speeds up a chemical reaction without participating in the reaction. The use of catalysts makes it possible to carry out chemical reactions under milder conditions and with lower energy consumption.

The active component of a reaction determines the catalyst's chemical activity. The choice of the active component is based primarily on whether the catalyst will be used for oxidation or reduction and the conditions under which the catalyst is used. Other important properties are solubility and reducibility. Normally the catalytic metal is from precursor salts in the form of nitrates, chlorides, etc.

Choice of a supporting substance is affected by how the catalyst will be used and the reaction conditions such as temperature and pH. Key features are to provide a large specific surface of the catalyst as well as good mechanical properties, stability, and to facilitate an even distribution (dispersion) of the active component on the surface. Common support materials are aluminum, silica, activated carbon and carbon nanotubes plus various zeolites. Promoters can be linked to either the supporting substance or to the active component. The support has an effect on the catalyst structure whilst enhancing / suppressing the activity. Coupled to the active component the promoter can affect, for example, the catalyst electrical properties and prevent poisoning of the catalyst.

FISCHER-TROPSCH SYNTHESIS

In 1923, German researchers Franz Fischer and Hans Tropsch developed the so-called Fischer-Tropsch synthesis (FTS), which produces aliphatic hydrocarbons, like diesel, based on syngas. Cobalt (Co), iron (Fe) and ruthenium (Ru) were used as catalysts. By 1925 the new Fischer-Tropsch process was patented and the first commercial FT plant was installed in Germany 10 years later (1935). During World War II the FT process experienced a production peak when Germany needed to produce liquid fuels.

However, from the mid 1950s, the production of FT fuels was no longer profitable because oil from the Middle East was cheap and fossil fuels conquered the world market. During the 1950s, new FT plants were built in South Africa (coal to liquid, CTL) because the country was virtually without any oil due to the embargo caused by apartheid policies. The company Sasol of South Africa produced liquid fuels based on gasified coal by FT synthesis using iron catalyst and made the country independent of oil. During the oil crisis in the 1970s, both the United States and Europe refinanced FT-research.

In Finland, the pulp manufacturer UPM has plans to build a pilot plant to produce FT-biodiesel from waste biomass generated in the production of pulp and paper. VTT (the Technical Research Centre of Finland), Stora-Enso and Neste Oil has a joint project (NSE Biofuels Oy) in which they

have built a pilot plant (12 MW) in Varkaus for the production of second-generation biofuels based on biomass (wood).

The experimental sites mentioned above are in the order of 10 MW, which means that they must be constructed adjacent to existing pulp mills in order to use existing infrastructure. By contrast, Fisher-Tropsch synthesis in decentralised, small scale production has not been implemented in practice.

Fischer-Tropsch synthesis is carried out under conditions of relatively high pressures (20-60 bar) and at high temperatures (200-450 °C). The aggressive reaction conditions in combination with reactive gases; H₂ (hydrogen) is explosive whilst CO (carbon monoxide) is toxic; meaning that the reaction must be conducted under very controlled conditions and with high security demands. By FT reaction a variety of products can be produced. The range of products are determined by a number of factors:

- Synthesis gas composition (varies depending on the raw material used for gasification). The relationship between H₂/CO is especially important since the production of fuels (diesel and petrol) uses a H₂/CO ratio of 2.0 to 2.5. Bio-SNG produced by gasification of wood-based materials has a H₂/CO ratio of about 1 in which the H₂ content must be increased by the addition of water (see reaction 2 below).
- Reaction conditions such as temperature, pressure and reaction time. The reaction is performed at temperatures between 200 and 250 °C and at pressures between 20 and 60 Bar (2-6 MPa).
- Choice of catalyst and catalytic properties. As catalysts for the manufacture of fuels are used Fe- or Co-based catalysts, they are rarely used in pure form but are mixed with a carrier.

Reactions

1. The hydrogen reacts with carbon monoxide producing hydrocarbons and water $(2n + 1) \text{H}_2 + n \text{CO} \rightarrow \text{C}_n \text{H}_{(2n+2)} + n \text{H}_2\text{O}$

this is the real Fischer-Tropsch reaction. The reaction produces a variety of organic compounds and it is virtually impossible that the reaction produces a single pure component.

The relationship of H₂/CO can be regulated by the addition of water:

2. $\text{H}_2\text{O} + \text{CO} \rightarrow \text{H}_2 + \text{CO}_2$

Although the reaction above provides an undesirable formation of CO_2 , the increased amount of H_2 results in benefits that outweigh the negative ones. The reaction is mainly used when using materials that provide syngas with a low H_2/CO relationship, such as wood-based materials.

DEVELOPMENT OF FISCHER-TROPSCH SYNTHESIS IN HIGHBIO

Background

The goal of one of the work packages of the HighBio project is to develop new chemical products based on the gasification products hydrogen (H_2) and carbon monoxide (CO). One of the main project goals is to catalytically convert synthesis gas to traffic fuels through the so-called Fischer-Tropsch process. As mentioned above, the FT reaction is a catalytic reaction in which synthesis gas (hydrogen and carbon monoxide) is converted to hydrocarbons in a pressurised reactor at temperatures between 200 and 300 degrees. At Kokkola University Consortium Chydenius we have, within the HighBio project, produced different catalysts and tested them to optimise the FT reaction.

Within the project the team has focused on some key points concerning the conversion of synthesis gas to chemical compounds. Firstly, the reactor system to test our catalysts, secondly the development of active and stable catalysts for FT reaction and finally the development of the analysis process to measure and identify the chemical components that are formed and also to measure the tar content in the product gas formed during gasification.

The first area of development has been the reactor system and as a result, a functional testing reactor system has been built up from scratch. A schematic diagram of the reactor is presented in Figure 2. The reactor system consists of the following components:

- A reactor mounted in a tubular oven. During the project the furnace has been replaced with a new one in order to achieve more efficient temperature control
- Temperature sensors (Pt 1000, K-type) mounted in the middle of the catalyst bed
- Mass Flow Meters for individual control of gas flows (hydrogen, carbon monoxide and nitrogen)
- Pressure regulator controlled by a pressure sensor
- Collection Devices for the products formed: consisting of a heated one for long carbon chains and waxes and a cooled one for light hydrocarbons

- On-line analysers for analysis of gaseous products formed

The reactor system has been modified several times during the project to fulfill new requirements and needs. For example, recent renovations include adding the ability to test catalysts for the cracking (decomposition) of tar components in the gas. All catalyst testing during the project has been conducted with the above reactor.

The development of catalysts for the conversion of syngas to fuels that can be used in motor vehicles is the most important aspect of the work performed within the work package of the HighBio project. The production and testing of catalysts is a very time consuming process.

Using carriers donated by Sasol in Germany, these were tested together with different catalyst materials in order to find the most suitable active metal. Metal salts were tested to identify the optimal active catalyst whilst studies on the effect of various additives, such as precious and semi-precious metals were also performed. The obtained catalysts were tested with both pure gases and with synthetic syngas however, due to problems with the compression of real gases from the gasifier, these have not been tested.

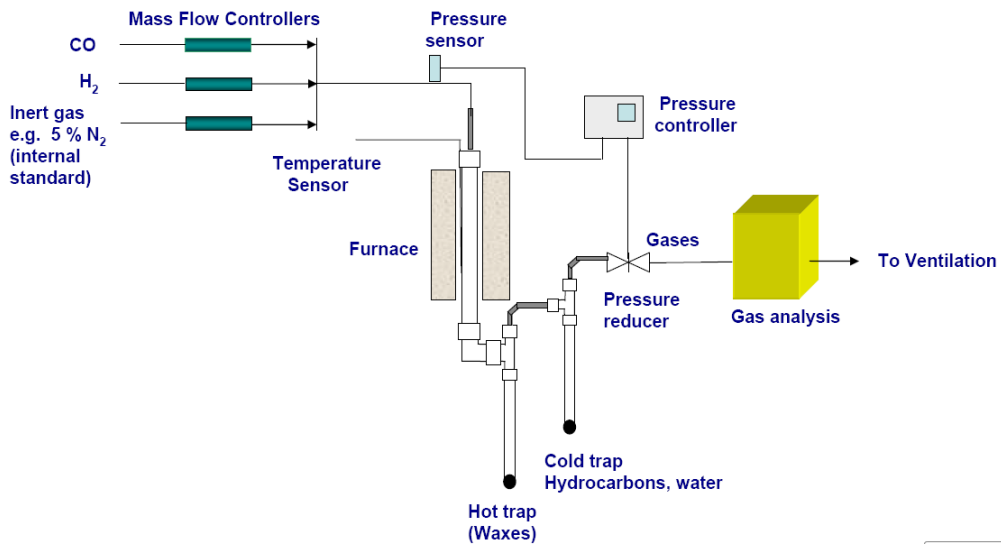


FIGURE 2. A schematic representation of the reactor system built at Chydenius.

Steps in the development of catalysts

- The catalyst (usually a metallic salt) dissolved in water is impregnated on to a porous support
- Drying removes water
- Calcination at 300-600 degrees: the metal salt is converted to a metal oxide
- Reduction of the metal in a hydrogen atmosphere: metal oxide is converted to a pure metal
- Testing of the catalyst in the reactor
- Analysis of reaction products

ANALYTICAL METHODS

In order to assess how the catalysts stated previously work, an analytical development of liquid and gaseous organic compounds is required. For analysis of the organic compounds formed two methods were used:

FT-IR (Fourier-transformed infrared spectrometry), provides information on the chemical bonds that are included in the molecules. GC-MS (gas chromatography mass spectrometer), provides information on which products are formed and the percentage distribution of the formed components.

The first tests for the identification of organic compounds were made with FT-IR. This method provides only information about the types of bonds contained in a sample, and offers limited information about the chemical compounds present. This has led to the development of GC methods, first via GC-FID (gas chromatograph with flame ionization detector) and later through GC-MS. The former provides an adequate separation but it is difficult to identify the individual components. GC-MS, which is the best technique for separation and identification of organic compounds, has, after lengthy method development, proved to provide very detailed information on the composition of the formed compounds.

For the analysis of gaseous, non-condensable compounds from the reactor a gas chromatograph for analysis of so-called permanent gases (hydrogen, carbon monoxide, nitrogen, carbon dioxide and methane) and gaseous hydrocarbons (C1-C6) was obtained. The equipment was mounted on-line to the reactor and the initial experiments have provided new and useful information about the behaviour of our catalysts.

Tar is a very problematic group of organic compounds formed during the gasification of biomass. For the collection of gas samples in the determination of tar components in product gas, collection equipment has

been built and tested during the project. The collected compounds have been analysed via GC-MS as described above.

CONCLUSIONS OF THE DEVELOPMENT

- The reactor systems developed during the project is a good tool for further studies of catalysts and their mechanisms
- With the catalyst tested, we have successfully produced compounds that are similar to diesel produced from crude oil
- Continued testing of the catalysts is necessary: primarily a long-term test and tests with pressurised gas, “real” syngas
- Effective cleaning step in order to convert the product gas obtained by gasification of biomass to synthesis gas is required. Therefore, the cleaning procedures needs further development
- Continued studies of the content tar components in the gas is required to develop the necessary cleaning steps and processes

UTILISATION OF GASIFICATION BY-PRODUCTS

CHEMICAL STUDIES FOR UTILISATION OF BIOASHES

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INTRODUCTION

Bioenergy is increasingly becoming the world's most important alternative to fossil fuels. With electricity prices reaching record highs and increase in the issuing of green electricity certificates, the interest in biomass based heat and power production has never been so great. There are many advantages to the use of wood for energy production. It is renewable, local and creates jobs. Bioash is generated as a by-product of combustion or gasification processes. Gasification is an incomplete combustion process that converts carbonaceous materials such as biomass to biogas. Biomass can be converted at either high temperatures (1200-1400 °C) to biosyngas which contains mainly CO and H₂, or at low temperatures (800-1000 °C) into product gas which contains CO, H₂, CH₄ and other hydrocarbons C_xH_y. Biosyngas and product gas after purification can be used in catalytic processes to synthesise products such as methanol and oils. (Knoef, 2005)

The utilisation of wood ashes from the burning process in forestry and agriculture has been investigated widely. The properties of ashes must first be determined with the requisite methods before they can be utilised. Legislation defines the maximum concentration values of heavy metals allowed in fertilisers and soil conditioning agents. Properties of ashes from biogasification and burning processes can be very varied and thus, it is probable that their potential utilisation applications are different too.

In this study, we have compared the properties of Finnish wood ashes from biogasification and burning processes and the potential utilisation applications. We investigated four ashes: two ashes from the biogasification processes and two ashes from the burning process. All ashes were produced in Northern Finland and the raw material in the ashes 1-3

was Finnish wood. The ash 1 from a biogasification process was obtained from a power plant which has an Entimos gasifier which is a combined updraft and downdraft gasifier. The ash 2 from the biogasification process was obtained from a plant which has a downdraft gasifier. Ash 3 from the burning process was sampled from the thermal power plant. The ash formed in the thermal power plant is largely bottom ash but there is a little fly ash because both ashes are carried along the same ash tank. Ash 4 produced by a burning process was sampled in the form of fly ash from a thermal power plant, which had a bubbling fluidised-bed boiler. The raw material in ash 4 was mostly Finnish wood (75 %) and peat (25 %).

POTENTIAL UTILISATION APPLICATIONS

A number of studies have been carried out investigating the utilisation of wood ashes from the burning process but the utilisation applications developed for ashes from the combustion process cannot be directly applied to the gasification ashes. The utilisation of ashes has to be always case-specific. Properties of ashes differ depending on for example gasification technique, used fuel and temperature.

Traditionally ashes from the combustion process can be utilised as a fertiliser and as a soil conditioning agent. Gasification ashes appear to be less attractive as a fertiliser than combustion ashes. Neutralising value is one of the most important indicators when evaluating the utilisation potential of ash as a liming agent. The neutralising value of commercial limestone produced by SMA Saxo Mineral Ltd. is 38 %. The carbon content of the ash should be under 10 % in order for the utilisation as a fertilizer to be reasonable. Utilisation of carbon-rich ashes as fertiliser is difficult because ashes contain an inert carbon matrix that lowers nutrient content. Carbon is also hydrophobic which means that ash have poor contact with water in nature. (Nurmesniemi et al. 2005, Pels et al. 2005)

The carbon content of gasification ash is typically high and properties could be similar to activated carbon which can be used as an adsorbent. Adsorption properties of activated carbon are typically better than gasification ash but gasification ash properties would be better if it was treated physically or chemically. Ashes are formed as a by-product in gasification or burning processes and their price is quite low. That is the reason why high carbon content ashes could be used in larger loads than activated carbon.

Utilisation as fuel is a viable option for ashes with a significant amount of unburned carbon. Utilisation as a fuel is possible when the carbon content is larger than 35 wt-% or the caloric value is higher than 15 MJ/kg.

Utilisation as a fuel in combustion processes does not completely solve the problem of finding a sustainable way of utilising biomass ashes because combustion creates low-carbon combustion ashes. Those low-carbon content ashes may be utilized e.g. as fertilizer or building material. (Pels et al. 2005)

DETERMINATION OF PROPERTIES FOR ASHES

The physical and chemical properties for ashes have to be known before they can be utilised. The pH and electrical conductivity values of the ash were determined by dissolving ash and distilled water into a liquid to solid ratio L/S 10 (w/w). Determination of dry matter content of the ash was performed in accordance to the European standard SFS-EN 12880 (SFS-EN, 2000a) and the loss on ignition value (LOI) was determined according to the European standard SFS-EN 12879 (SFS-EN, 2000b). Determination of the dissolved organic carbon (DOC) was carried out according to the European standard SFS-EN 1484 (SFS-EN, 1997). Total carbon content (TC) was determined by elementary analysis using a Perkin Elmer CHNS analyser whose method is based on combustion. (Perkin-Elmer, 1991)

Determination of the neutralising value and reactivity value were implemented according to the European standards SFS-EN 12945 (SFS-EN, 2002) and SFS-EN 13971 (SFS-EN, 2003). The specific surface area of the ashes was determined from nitrogen adsorption-desorption isotherms at liquid nitrogen temperature (-196 °C) by using a Micromeritics ASAP 2020. The same equipment was used for the determination of pore size and pore volume.

The total heavy metal concentrations in the samples were determined by acid decomposition (mixture of HCl and HNO₃ in microwave oven) and with ICP-OES. The concentration of Hg was determined with cold-vapour atomic absorption spectrometry.

TABLE 1. The physical and chemical properties of the four investigated bioashes.

Parameter	Unit	Ash 1	Ash 2	Ash 3	Ash 4
pH		10.7	9.0	12.2	12.4
Electrical conductivity	mS cm ⁻¹	1.03	0.455	3.9	7.87
Dry matter content	%	18.7	16.4	43.9	99.8
Loss on ignition	%	94.8	68.4	79.6	8.7
DOC	mg kg ⁻¹	649	565	570	0.84
TC	%	89.4	60.9	72.3	6.5
Neutralising value	% Ca	3.8	8.0	7.9	13.3
Reactivity value	% Ca	1.6	6.6	6.6	10.0
Liming capacity	t t ⁻¹	10	4.8	4.8	2.9
Specific surface area	m ² g ⁻¹	100	15	206	29.8
Pore size	nm	3.91	15.9	2.64	3.18
Pore volume	cm ³ g ⁻¹	0.098	0.0564	0.1374	0.024

Table 1 summarises the physical and chemical properties of the four investigated ashes. The results indicate that all ashes are alkaline. Electrical conductivity value is an index of the total dissolved electrolyte concentration. High electrical conductivity value indicates that part of the dissolved metals may occur as dissolved basic metal salts, e.g. oxides, sulphates and hydroxides. Electrical conductivity values are higher for burning ash comparing to gasification ashes. Gasification ashes contain a lot of moisture because dry matter content is very low. High loss-on-ignition value indicate that the ash contains organic matter. Neutralising and reactivity values are varied between gasification and burning ashes. The neutralising value is one of the most important indicators when evaluating the utilisation potential of ash as a liming agent in acidic soil. Reactivity is the determination of the speed and effectiveness of the neutralising potential of ash. Liming capacity for burning ash 4 is good, requiring 2.9 tons to replace 1 ton of commercial limestone.

Specific surface area, pore size and pore volume are important physical properties that determine the quality and utilisation potential of ashes, for example as an adsorbent. The adsorption properties of ashes would be better suited if the specific surface area is larger. Pore size affects the type of molecules which ash can adsorbed.

TABLE 2.

Total heavy metal concentrations (mg kg⁻¹; d.w.) for the four investigated ashes and the current Finnish maximum limit values (mg kg⁻¹; d.w.) for biomass-derived ashes used in forest fertiliser or agricultural use. (Ministry of Agriculture and Forestry Decree on Fertiliser Products Dec 07)

Element	Unit	Limit value (forest fertiliser)	Limit value (agricultural use)	Ash 1	Ash 2	Ash 3	Ash 4
Cd	mg kg ⁻¹ (d.w.)	15	1.5	< 0.3	6.3	1.6	5
Cu	mg kg ⁻¹ (d.w.)	700	600	15	130	21	83
Pb	mg kg ⁻¹ (d.w.)	150	100	< 3	25	10	27
Cr	mg kg ⁻¹ (d.w.)	300	300	7	210	9	82
Mo	mg kg ⁻¹ (d.w.)			< 1	15	< 1	6
Zn	mg kg ⁻¹ (d.w.)	4500	1500	85	7950	130	380
As	mg kg ⁻¹ (d.w.)	30	25	< 3	< 3	< 3	19
Co	mg kg ⁻¹ (d.w.)			< 1	8	1	8
V	mg kg ⁻¹ (d.w.)			< 2	7	3	210
Ni	mg kg ⁻¹ (d.w.)	150	100	3	110	10	36
Sb	mg kg ⁻¹ (d.w.)			< 4	< 4	< 4	< 4
Ba	mg kg ⁻¹ (d.w.)			120	880	250	860
S	mg kg ⁻¹ (d.w.)			180	3260	830	8420
Ca	mg kg ⁻¹ (d.w.)			12 800	78 400	46 300	96 300
Mg	mg kg ⁻¹ (d.w.)			2650	6670	8020	16 600
K	mg kg ⁻¹ (d.w.)			7110	9340	14 000	18 900
P	mg kg ⁻¹ (d.w.)			1550	9560	4120	12 700
Hg	mg kg ⁻¹ (d.w.)	1.0	1.0	< 0.040	0.040	< 0.040	0.56

Table 2 presents the concentrations of total heavy metals present in the investigated ashes. Concentrations are expressed as dry weight (d.w.). According to table 2, the total heavy metal concentrations in ashes 1, 3 and 4 were lower than the current Finnish maximum limit values allowed in forest fertiliser. As a result, those ashes can be utilised in their own right as a forest fertiliser. In terms of agriculture, results in table 2 shows that the concentration of Cd in ashes 2, 3 and 4 were higher than the current maximum limit value for agricultural use. Also nickel and zinc concentration was too high in ash 2. However, this is not the case for ash 1 which could therefore be utilised entirely as a potential source in agricultural use. Table 2 presents also the concentration of some nutrients. The elevated Ca concentrations in all investigated ashes indicate that the ashes may also be a potential soil conditioning agent.

CONCLUSIONS

This investigation has demonstrated the differences between Finnish wood ashes from burning and gasification processes. The results indicated that the ashes 3 and 4 have a potential to be used as a forest fertiliser because their nutrient content is quite high. From an utilisation point of view, it is notable that the total heavy metal concentrations in those ashes were lower than the Finnish maximum limit values allowed in forest fertiliser. The fact, that ash 4 is strongly alkaline, together with good liming capacity, indicates that the ash has a pH buffering capacity and it could be used as a soil conditioning agent. Wood-based ashes can substitute lime to buffer forest soil acidity.

Ashes from the gasification process and ash 3 from a burning process have high carbon content. Ashes 1 and 3 have fairly high specific surface area which indicates, together with high porosity, that those ashes would be a good adsorbent. Ashes 1-3 could be used as a fuel because the carbon content is higher than the required amount. In this study, the important physical and chemical properties of four ashes were compared and showed that the properties of burning and gasification ashes are very varied and their utilisation application should be therefore different.

REFERENCES

- Knoef, H.A.M., Handbook Biomass Gasification, 2005, BTG biomass technology group BV, The Netherlands, 378 p.
- Ministry of Agriculture and Forestry Decree on Fertiliser Products 12/07, (In Finnish).
- Nurmesniemi, H., Pöykiö, R., Perämäki, P. and Kuokkanen, T., 2005, The use of a sequential leaching procedure for heavy metal fractionation in green liquor dregs from a causticizing process at a pulp mill, *Chemosphere*, 61, 1475-1484.
- Pels, J.R., de Nie, D.S. and Kiel, J.H.A., Utilization of ashes from biomass combustion and gasification, 14th European Biomass Conference & Exhibition, 17-21 October 2005, 17 p.
- Perkin-Elmer, Users Manual PE 2400 Series II CHNS/O Analyzer, 1991, Perkin-Elmer Corp. Norwalk, Connecticut USA, pp. 1-6 (Chapter 1).
- SFS-EN, 1997, The European Standard SFS-EN 1484, Water analysis, Guidelines for the determination of total organic carbon (TOC) and dissolved organic carbon (DOC), Finnish Environment Institute, Helsinki, Finland, 15 p.
- SFS-EN, 2000a, The European Standard SFS-EN 12880, Characterization of Sludge, Determination of Dry Residue and Water Content, Finnish Standards Association SFS, Finnish Environment Institute, Helsinki Finland, 7 p.
- SFS-EN, 2000b, The European Standard SFS-EN 12879, Characterization of Sludge, Determination of Loss on Ignition of Dry Mass, Finnish Standards Association SFS, Finnish Environment Institute, Helsinki Finland, p. 7.
- SFS-EN, 2002, The European Standard SFS-EN 12945, Liming Materials, Determination of Neutralizing Value, Titrimetric Methods, Finnish Standards Association SFS, Chemical Industry Federation of Finland, Helsinki Finland, 10 p.
- SFS-EN, 2003, The European Standard SFS-EN 13971, Carbonate liming materials, Determination of reactivity, Potentiometric titration method with hydrochloric acid, Finnish Standards Association SFS, Chemical Industry Federation of Finland, Helsinki Finland, 12 p.

TECHNO-ECONOMICAL EVALUATION

SMALL-SCALE BIOMASS BASED COMBINED HEAT AND POWER PRODUCTION – ECONOMIC CONDITIONS

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The interest in biomass-based cogeneration in Europe is increasing and will play an important role in the transition to a more sustainable energy supply. An important aspect for the establishment of new power plants is ensuring investment is economically justifiable. Higher electricity prices and the green certificates have improved the conditions for producing combined heat and power even in small scale scenarios. The Nordic countries are very well suited for such plants due to the abundant resources of biomass, amongst other things. Today biomass-based cogeneration is mainly produced in large scale water-steam systems, known as the Rankine cycle. Other techniques such as the Stirling engine and gasification systems (gasifier with gas turbine or gas engine) are still under development and require more research and development. The current development status of some selected biomass CHP routes are shown in Table 1.

TABLE 1. Development status of some selected biomass CHP routes. The first three techniques are based on gasification.

Technology	10-500 kW _{th}	0.5-5 MW _{th}	5-10 MW _{th}	>10 MW _{th}
Fixed bed gasification Gas engine	Commercial	Commercial	Pilot	Not feasible
Fluidised bed gasification Gas engine	Not feasible	Pilot	Commercial	Commercial
Gas turbine, producer gas driven	Pilot	Pilot	Pilot	Demonstration
Organic Rankine Cycle (ORC)	Pilot	Commercial	Pilot	Not feasible
Steam cycle (Rankine)	Not feasible	Not feasible	Commercial	Commercial
Stirling engine (pellets)	Demonstration	Not feasible	Not feasible	Not feasible



HOW MUCH IS SMALL-SCALE BIOMASS-BASED ELECTRICITY PRODUCTION ALLOWED TO COST?

The electricity market is based on marginal pricing, which means that the price is determined by the marginal cost of producing the last unit needed to meet demand. Today, this is based on large-scale electricity generation from coal-and oil-fired power plants. However, small-scale electricity generation, regardless of fuel, also competes with this production. The price of large-scale power production currently amounts to a figure in the range of 350-550 SEK per MWh_{el} (approx. 39–61 €/MWh_{el}) which includes the cost of electricity distribution. For fossil fuel-based electricity, costs for carbon dioxide emissions will be added, corresponding to a major cost for a coal power plant. The price of carbon emissions is determined by a market and fluctuates over time. In recent years, the emissions cost has varied from near 0 SEK up to about 280 SEK per MWh_{el} (approx. 0–31 €/MWh_{el}). For this reason, it is difficult to estimate exactly how much small-scale biomass-based electricity generation may be allowed to cost. But if we assume

that the emission costs will be in the range of 160 and 450 SEK per MWh_{el} (approx. 1850 €/ MWh_{el}) during the next few years and that the production and distribution costs for large scale production remains the same, it would mean that a small-scale biomass based electricity production costing in the range of 500-1000 SEK per MWh_{el} (approx. 56–112 €/ MWh_{el}) could be justified. In some countries, like Sweden, it is difficult to reach profitability. The HighBio project is working to develop more efficient and more reliable installations, which means that the economic conditions may become more favourable in the near future. Amongst other things, the annual operating time is of great importance for the power generation cost and is directly linked to the quality of synthesis gas. Figure 1 show the electricity production cost of a number of technologies and plant sizes as a function of the annual operating time. The red field indicates the cost range in which small-scale electricity generation could be justified according to the above reasoning.

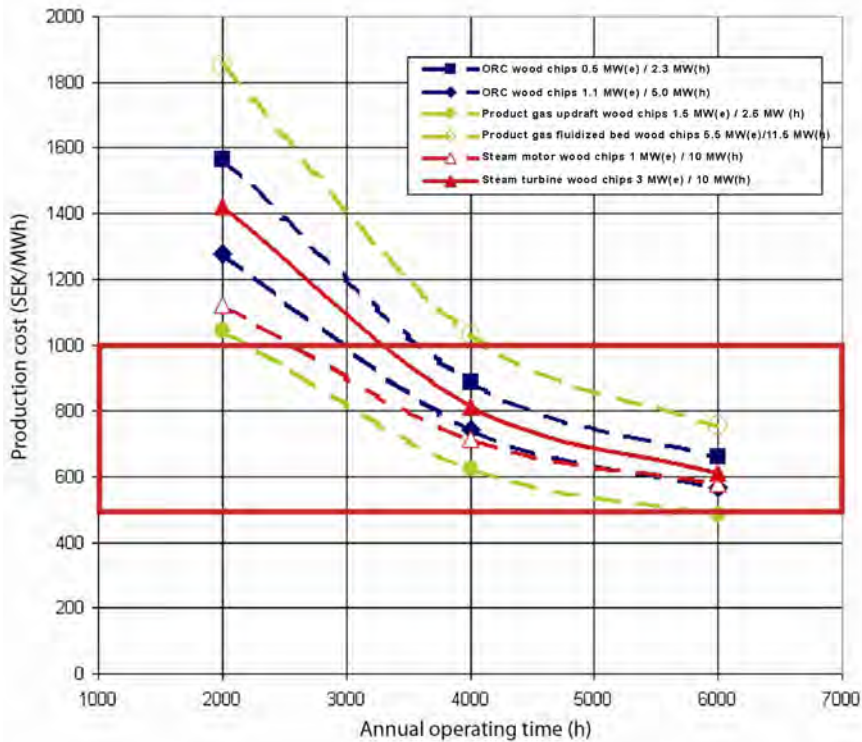


FIGURE 1. Electricity production costs as a function of the annual operating time for various biomass-based technologies for cogeneration over 500 kW_{el} .

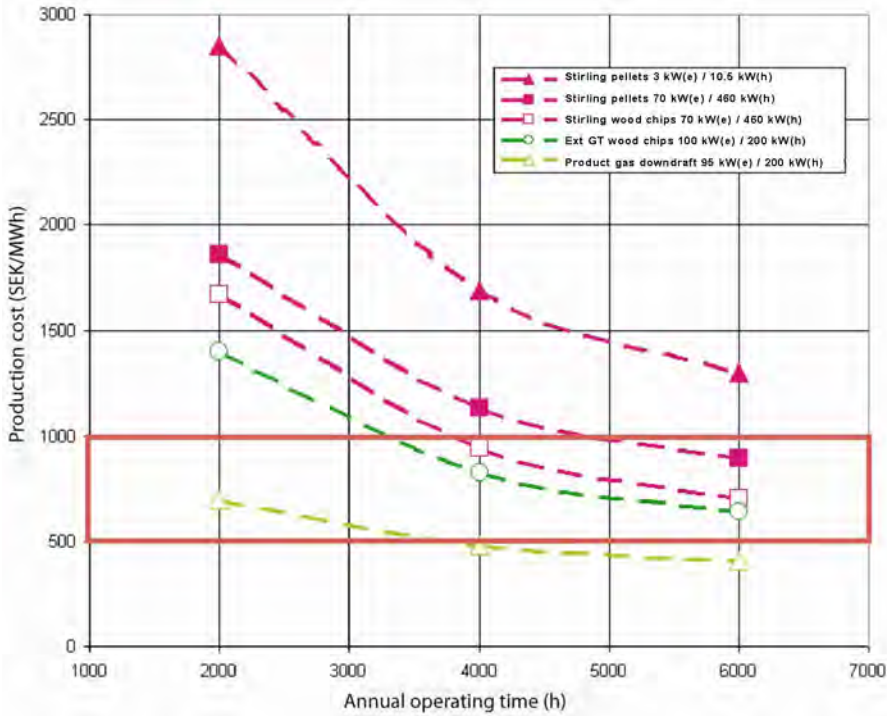


FIGURE 2. Electricity production costs as a function of the annual operating time for different biomass-based technologies for cogeneration below $100 \text{ kW}_{\text{el}}$.

As the figures suggests it is very important that the plant operates continually without disruption for large parts of the year. For most of the techniques, the electricity costs end up within the acceptable cost range if the annual operational time exceeds 4000 hours per year. Estimates for electricity production costs for the gasification concepts developed in the HighBio project are currently underway and will be presented in the final report.

A very promising concept for biomass-based cogeneration on a smaller scale is that of externally fired gas turbines (GT in figure 2.). A combustible gas is produced by gasification and after a gas cleaning step the gas is fired into a separate combustion chamber. The hot gases are used to heat compressed air via a high temperature heat exchanger to about $800\text{-}1000^\circ\text{C}$. The hot air is then expanded in a turbine to generate electricity. A major operational problem is the coating formation on heat exchange surfaces. The coating causes poor heat transfer between gas and air with a lower electrical efficiency and higher electricity costs as a direct consequence. It is therefore probable that the plant would become economically unviable,

especially since expensive gas cleaning equipment must be installed to avoid unnecessary disruption. The coating is caused by high concentrations of alkali (mainly sodium, potassium) in biofuel ashes. It would therefore be desirable to generate a much cleaner gas, which can be achieved with a cleaner fuel.

Within the HighBio project, the integration of a so-called hot water extraction process into an externally fired gas turbine plant has been studied. The extraction process “washes” wood chips (in this case, birch wood) in water pressurised to about 8 bar. Some of the hemicellulose in the wood chips is extracted, resulting in a fermentable sugar stream that can be used for the production of bio-ethanol or green chemicals, for example. As a result, the cogeneration plant would be converted into a small biorefinery, which not only produces heat and electricity, but also chemicals. The “washed” fuel has been shown to contain significantly lower levels of alkali metals as well as having a higher calorific value. Figure 3 shows a photograph of birch wood-chips before and after the extraction.



FIGURE 3. Photograph of birch wood-chips before (left) and after extraction (right)

Figure 4 shows the energy and material flows of the considered process. There is also a possibility to include a separation process after the hydrolysis to produce acetic acid.

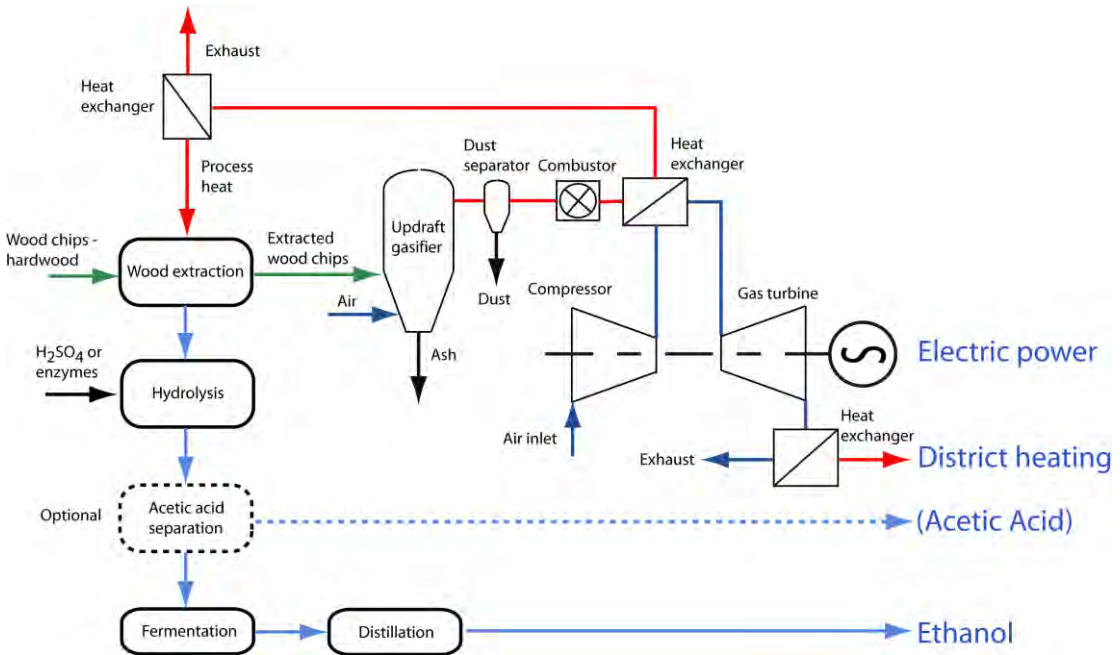


FIGURE 4. Hot water extraction process integrated into an externally fired gas turbine plant

The plant size and the annual operating time have a major impact on the electricity production costs. An economic evaluation of this type of integrated plant is shown in Figure 5.

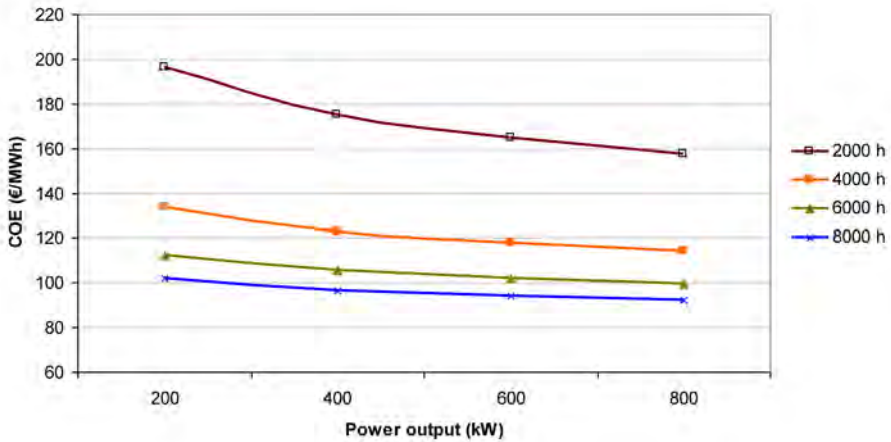


FIGURE 5. Electricity production cost (COE) as a function of plant power output and operational hours.

The results show that electricity can be produced at a cost in the range of € 85 to € 195 per MWh_{el} (corresponding to about 770–1800 SEK per MWh) in the size range 200–800 kW_{el} . The overall plant economy can be further improved by the generation of a fermentable sugar stream. The cost of generating power with 65 g of xylose per litre has been estimated between € 0.4 and 4.2 per kg of xylose. The concept is interesting but requires further investigation.

INFO SHEETS FROM THE HIGHBIO PROJECT

Available in both Finnish and Swedish

* Available in English

- INFO 1 Uusi projekti alkaa, HighBio - Interreg Pohjoinen (2008)
- INFO 2 Jyväskylän yliopisto, Kokkolan yliopistokeskus Chydenius, U-P Granö (2008)
- INFO 3 HighBio - Interreg Pohjoinen-projekti, U-P Granö (2008)
- INFO 4 Bioenergiaraaka-aineiden jalostus, U-P Granö (2008)
- INFO 5 Pienempiä CHP-yksiköitä, U-P Granö (2008)
- INFO 6 Joitakin käytettyjä lyhenteitä sekä termejä, U-P Granö (2008)
- INFO 7 Uusiutuva energia - Vihreä energia, U-P Granö (2008)
- INFO 8 Fossiilinen kaasu sekä biomassasta saatava kaasu, U-P Granö (2008)
- *INFO 9 Katalyyysi ja katalyytit, U Lassi (2008)
Catalysts and catalysis, U Lassi (2008)
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PUBLICATIONS AND REPORTS RELATED TO THE HIGHBIO PROJECT

- Eriksson, D., Weiland, F., Hedman, H., Stenberg, M., Öhrman, O., Lestander, T.A., Bergsten, U. and Öhman, M. (2011) Scots pine stump-root biomass: A possible large scale feed-stock for gasification. To be submitted to Bioresource Technology.
- Haapasaari, S. (2009), research project (Stora Enso Oulu), on the subject " Use of flocculation chemicals made out of ash in removal of phosphor from municipal waste water" ("Tuhkasta valmistetun flokkauskemikaalin käyttö yhdyskuntavesien fosforinpoistossa").
- Heponiemi, A., Rahikka, L., Lassi, U. and Kuokkanen T. (2009) Catalytic oxidation of industrial wastewaters - a comparison study using different analyzing methods, Chemical Engineering Transactions Volume 17.
- HIGHBIO –project (2009) EnePro konferenssi, Advancing Research in the Energy Field at the University of Oulu, 3.6.2009, Oulu
- Hägström, C., Öhrman, O., Gebart, R., Hedlund, J., Catalytic synthesis of methanol from black liquor derived synthesis gas. 4th International DME Conference, Stockholm, 6-9 Sep. 2010.
- Jercku, I. (2010), research project. "Testing the new bomb calorimeter at the Chemical department of Oulu university" ("Pommikalorimetrisia tutkimuksia Oulun kemian laitoksen uutta kalorimetriä testaten ja käyttäen").
- Jokinen, H. (2009), research project on the subject "Use of humid and poor quality wood biomass" ("Heikkolaatuisen ja koston puubiomassan hyödyntäminen").
- Karhu, H. (2009) research project (EVO Kuusamo), on the subject " Use of flocculation chemicals made out of ash in removal of phosphor from municipal waste water" ("Tuhkasta valmistetun flokkauskemikaalin käyttö yhdyskuntavesien fosforinpoistossa").
- Karhu, H. Dissertation for Bachelors Degree (2010) Kuitusavi – hyödynnettäväksi soveltuva paperiteollisuuden jätemateriaali, 31 p.

- Karvonen, L. (2009) research project (Kokkolan Voima), on the subject " Use of flocculation chemicals made out of ash in removal of phosphor from municipal waste water" ("Tuhkasta valmistetun flokkauskemikaalin käyttö yhdyskuntavesien fosforinpoistossa").
- Karvonen, L., Dissertation for Bachelors Degree (2009) Oulun alueen puu- ja turvepohjaiset tuhkat ja niiden hyötykäyttö, 34 p.
- Kilpimaa, S., Kuokkanen T. and Lassi U. (2009) Bio-ethanol production from waste potatoes, In: Proceedings of the EnePro Conference, 3.6.2009, Oulu, p. 21-23
- Kilpimaa, S., Kuokkanen, T. and Lassi, U. Bio-ethanol production from waste potatoes (2009) EnePro konferenssi, Advancing Research in the Energy Field at the University of Oulu, 3.6.2009, Oulu
- Kilpimaa, S., Kuokkanen, T. and Lassi, U. (2011) Physical and chemical properties of wood ash from burning and gasification processes. The Journal of Solid Waste technology and Management, 879-887.
- Kilpimaa, S., Kuokkanen, T. and Lassi, U. (2011) Chemical and leaching properties of wood ash from burning and gasification processes, submitted for publication in Chemical Speciation and Bioavailability.
- Kuokkanen, M. ja Kuokkanen, T. (2009) Puu- ja turvepellettien sekä hakkeen lämpökeskus- ja pienpoltossa syntyvien tuhkien hyötykäyttöön liittyvä tutkimusraportti, Oulun yliopisto, Report Series in Chemistry No. 74. 45 pages.
- Kuokkanen, M., Kuokkanen, T., Nurmesniemi, H. and Pöykiö, R. (2009) Wood pellet ash – a potential forest fertilizer and soil conditioning agent (a case study), The Journal of Solid Waste Technology and Management, p. 659-667.
- Kuokkanen, M., Kuokkanen, T., Stoor, T., Niinimäki, J. and Pohjonen, V. (2009) Chemical Methods in the Development of Eco-Efficient Wood-based Pellet Production and Technology, Waste Management & Research, Volume 27, p.561-571
- Kuokkanen, M., Pöykiö, R., Kuokkanen, T. and Nurmesniemi, H. (2009) Wood ash – a potential forest fertilizer, In: Proceedings of the EnePro Conference, 3.6.2009, Oulu, p. 89-93.
- Kuokkanen, M., Prokkola, H., Larkomaa, J., Stoor, T., Siltaloppi L. and Kuokkanen T.: Specific Staining and Optical Microscopy – a New Method for Characterization of Starch-containing Wood Pellets. - Special Issue of Research Journal of Chemistry and Environment, Proceedings of ICCE-2009, 2010, 311-317.
- Kuokkanen, T., Kaakinen, J., Kuokkanen, M., Prokkola, H. and Lassi, U. (2009) Jättemateriaalien hyödyntämiseen liittyviä kemiallisia tutkimuksia, EnePro Conference, Advancing Research in the Energy Field at the University of Oulu, 3.6.2009, Oulu
- Kuokkanen, V. (2010) research project "Research report regarding the chemical properties of some granulated ashes and trials to use these as adsorbent materials in the cleaning of waste water" ("Tutkimusraportti eräiden rakeistettujen tuhkien kemiallisista ominaisuuksista ja kokeiluista adsorbenttimateriaalina jätevesien puhdistuksessa").
- Lahti, R. Synteesikaasun katalyyttinen konvertointi Fischer-Tropsch synteesin avulla liikennepolttoaineiksi, Master's thesis (2010).

- Lassi, U., Granö, U-P., Tynjälä, P., Kuokkanen, T. and Muilu, Y. (2009) Refining of new products and raw materials by gasification of biomass, In: Proceedings of the EnePro Conference, 3.6.2009, Oulu, p. 32-35.
- Marklund, M. and Engström F. (2010) Water spray characterization of a coaxial air-assisted swirling atomizer at sonic conditions. *Atomization and Sprays* 20(11):955–963.
- Marklund, M., Hedman, H., Weiland, F. And Gebart, R. (2011) Pilot gasification plant for syngas generation from forest residues. Proc. Nordic Wood Bio refinery Conference, March 22-24 2011, Stockholm, Sweden.
- Muilu, Y., Pieniniemi, K., Granö, U-P. and Lassi, U. (2010) A novel approach to biomass gasification in a downdraft gasifier. In: 18th European Biomass Conference and Exhibition, 3-7 May, 2010, Lyon, France, p. 688-692.
- Partanen, K., Tiainen, M. and Lassi, U. (2011) Catalysts used in conversion of 5-hydroxymethylfurfural into 2,5-dimethylfuran. Submitted to 10th Europa-Cat conference, Glasgow, 2011.
- Pieniniemi, K. and Lassi, U. (2010) Gas emission measurements with a FTIR gas analyzer – verification of the analysis method. . In: Proceedings of SkyPro Conference, Clean air research at the University of Oulu, 3.6.2010, Oulu, Finland, p. 117-121.
- Romar, H. Lahti, R. Tynjälä, P. and Lassi, U. (2010) Co and Fe catalysed Fischer-Tropsch synthesis in biofuel production, submitted Topics in Catalysis.
- Romar, H., Lahti, R, Tynjälä, P. and Lassi, U. (2010) Co and Fe catalysed Fischer-Tropsch synthesis in biofuel production, In: Proceedings of 13th Nordic Symposium on Catalysis, Extended abstracts, Helsingör, Denmark, August 29-31, 2010.
- Romar, H., Pieniniemi, K., Tynjälä, P. and Lassi, U. (2010) Sampling and determination of tars in biomass-derived product gas. In: Proceedings of SkyPro Conference, Clean air research at the University of Oulu, 3.6.2010, Oulu, Finland, p. 122-125.
- Romar, H., Tynjälä, P. and Lassi, U. (2011) Effects of early reactions on the Fischer-Tropsch activity and stability over Ru- and Re-enhanced cobalt catalysts, submitted to 10th EuropaCat conference, Glasgow, 2011.
- Runtti, H. (2009), research project on the subject " The use of industrial by-products in the treatment of water" (in the project ash sludge was used as a type of adsorbent) . ("Teollisten sivutuotteiden hyödyntäminen vedenkäsittelyssä" (projektissa mukana tuhkaliete eräänä adsorbenttina).
- Shu, T. (2009), Co catalysts in Fischer-Tropsch synthesis. Thesis.
- Takkinen, T. Esitutkimus jakeistuksen vaikutuksesta Oulun biotuhkien ominaisuuksiin, Master's thesis, to be concluded 2011.
- Tolonen, E. (2010), research project "Sequential extraction in five steps of ash from Kokkola Power plant" ("Viisivaiheinen sekventiaalinen uutto Kokkolan Voiman tuhkalle").
- Tuuttila, T. Biomassan kaasutuksessa muodostuvan synteetikaasun katalyyttinen konvertointi kevyiksi olefiineiksi ja edelleen muoveiksi, raportti (2010). ("Catalytic conversion of synthesis gas formed in gasification of biomass into light olefins and further to plastics", in Finnish).

Öhrman, O., Häggström, C., Wiinikka, H., Hedlund, J., Gebart, R. Analysis of trace components in synthesis gas generated by black liquor gasification. Submitted to Fuel, 2010.

Öhrman, O., Johansson, A-C., Lindblom, M., H₂S removal with short time contactors in a pressurized black liquor gasification plant. International Chemical Recovery Conference, Williamsburg, USA, March 29-April 1, 2010.

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Biomass Gasification to Heat, Electricity and Biofuels

HighBio Project Publication

The aim of the HighBio project was to produce new information on biomass gasification and the utilisation opportunities of product gas in biofuel and biochemicals production. The project was also aimed at studying utilisation properties of biogasification ashes in distributed energy production. Small-scaled CHP plants can be used for simultaneous heat and power production by gasifying wood chips and by burning energy intensive product gas. Compared with thermal combustion, particulate emissions from gasification are lower, which also contributes to the EU's ever tightening emission legislation. Several small and middle scale companies in the Northern part of Finland and Sweden have worked with biomass gasification, and during the project, the birth of new ones has been seen. In this development stage, researchers of the HighBio project have also been strongly involved.

The Finnish partners in the project are University of Jyväskylä, Kokkola University Consortium Chydenius (Lead Partner), University of Oulu and Central Ostrobothnia University of Applied Sciences, Centria, Ylivieska. Swedish participants are Luleå University of Technology and Energy Technology Center, Piteå. The main financier of the project is European Regional Development Fund, Interreg IV A Nord.

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