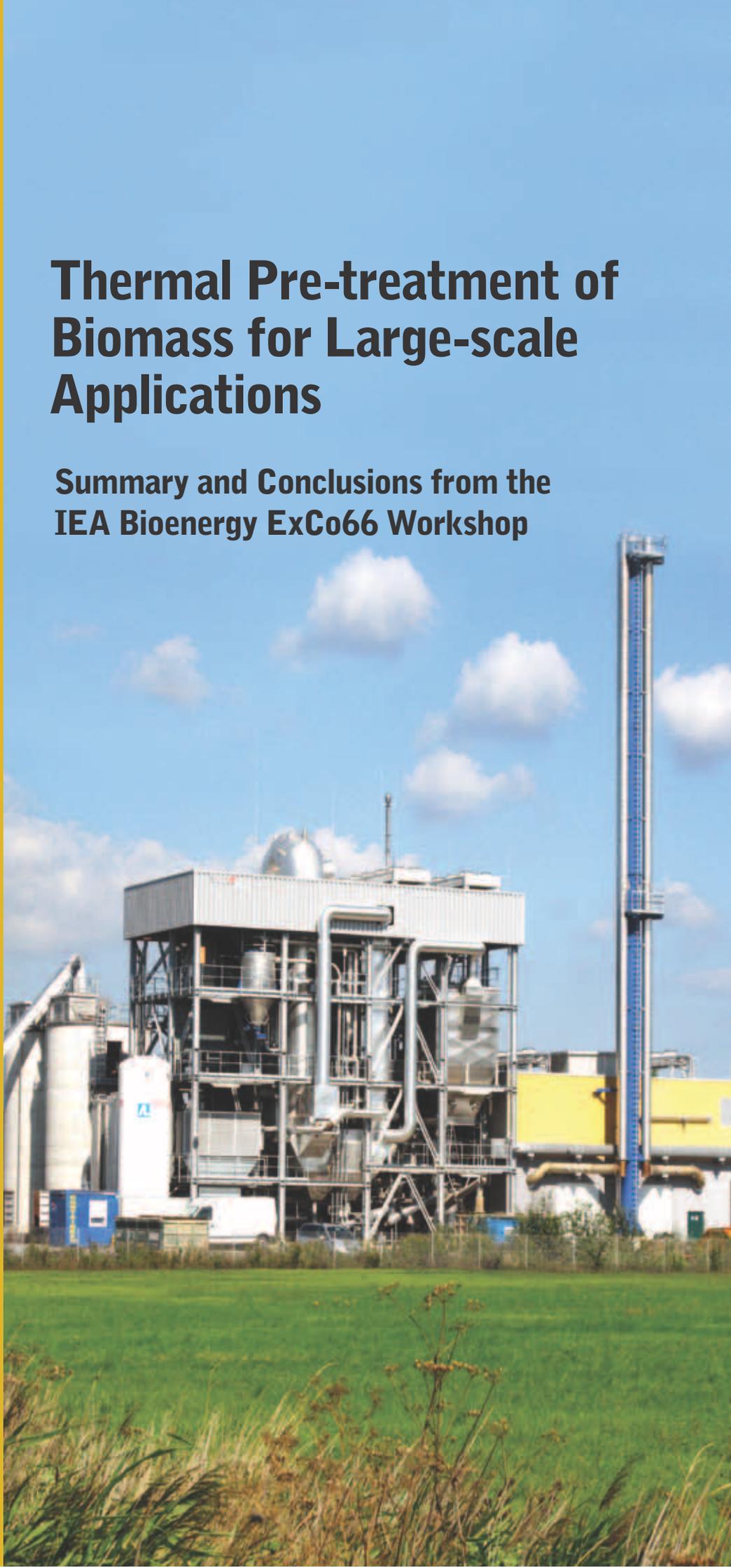


# Thermal Pre-treatment of Biomass for Large-scale Applications

## Summary and Conclusions from the IEA Bioenergy ExCo66 Workshop

This publication provides the summary and conclusions from the workshop 'Thermal Pre-treatment of Biomass for Large-scale Applications' held in conjunction with the meeting of the Executive Committee of IEA Bioenergy in York, United Kingdom, on 12 October 2010.

The purpose of the workshop was to provide the Executive Committee with perspectives on how to integrate large-scale bioenergy deployment with existing fuel logistics. The aim was to stimulate discussion between the Executive Committee, Task Leaders, and invited experts and thereby enhance the policy-oriented work within IEA Bioenergy.



## INTRODUCTION

One of the major goals of IEA Bioenergy is to facilitate commercialisation and market deployment of environmentally sound, sustainable, and cost-competitive bioenergy technologies.

Sustainable growth of biomass for energy production is possible in large areas of the world. Despite debate over 'food versus fuel', there are actually no major limitations to increasing energy crop cultivation. Only a little more than 2% of worldwide agricultural production is used for energy plantations. Unfortunately, large biomass growing areas are not usually located in the vicinity of the urban and industrial areas with the highest energy consumption. Hence, transport is an intrinsic factor in any application of bioenergy. Pre-treatment of biomass to increase its energy density is therefore an indispensable requirement to allow sustainable, long distance transport.

Another handicap of bioenergy is its often low homogeneity. The diversity of compounds that make up plant cells means the production of fuel with a consistent heating value is seldom achievable by purely mechanical means.

Thermal pre-treatment can substantially help to overcome both hurdles by reducing volume, increasing energy density, and equalising energetic homogeneity. However, most of these upgrading technologies are still in a pre-industrial development state, in either R&D or in P&D scale. In some cases it could be at least ten years before full-scale application is mature.

The workshop organised in York discussed technical opportunities and the current state of development. In his welcome speech the Chairman of IEA Bioenergy, Josef Spitzer, identified five key questions that the workshop was expected to answer:

- Which technologies for thermal treatment have a proven extended operation time at a technical-scale?
- Which of the many design options currently in pilot scale will make it to industrial application in pyrolysis, gasification or torrefaction?
- Are there significant barriers holding back market introduction and deployment (costs, logistics, other)?
- Are there major differences in thermal treatment sustainability?
- What additional input is needed by IEA Bioenergy to stimulate market introduction and deployment of the technologies discussed?

He expected that the discussions and conclusions from the workshop would stimulate the work of the Executive Committee and invited everyone to contribute and share the know-how.

The five sessions in the workshop addressed the following topics (session facilitators in parentheses):

**Session 1** – Overview of Processes (Jeremy Tomkinson, UK)

**Session 2** – Pyrolysis (Jeremy Tomkinson, UK)

**Session 3** – Gasification (Pat Howes, UK)

**Session 4** – Torrefaction (Paul Grabowski, USA)

**Session 5** – Environmental Best Option  
(Peter-Paul Schouwenberg, the Netherlands)

The main points and questions raised during discussions are summarised below. The contributions from the speakers can be downloaded from IEA Bioenergy's website [www.ieabioenergy.com](http://www.ieabioenergy.com).

## SESSION 1 – OVERVIEW OF PROCESSES

### Overview of Thermal Pre-treatment Processes for Large-scale Biomass Application – Jaap Kiel, ECN, the Netherlands

Biomass is a difficult energy source to manage logistically, including handling of the raw biomass, transport and storage and feeding the material to pre-treatment or upgrading plants. The most challenging properties are the low energy density, with a lower heating value (LHV) of only 10-17 MJ/kg, and hydrophilic characteristics that make biomass vulnerable to biodegradation. Furthermore, the tenacious fibrous structure makes grinding and substrate flow difficult. Finally, the heterogeneous composition of biomass makes producing a consistent product by conventional thermal treatment challenging.

Any pre-treatment process applied must:

- convert the biomass into a homogeneous, high-energy density bioenergy carrier with favourable logistical characteristics and end-use properties;
- deal with the difficult biomass properties at the source;
- allow the de-coupling of availability and end-use in scale, time and place;
- relate to existing logistic infrastructures (coal, oil, gas); and
- allow conventional trading schemes as with other commodity fuels.

Depending on the water content of the biomass there are two basic pre-treatment options – one for dry biomass (<50% moisture content) and the other for wet biomass (>50% moisture).

**Wet biomass:** There are two basic technologies to treat wet biomass: anaerobic digestion and hydrothermal processing. Anaerobic digestion is a biological process that is well developed and applied in a large number of biogas plants all over the world. Both highly engineered industrial plants and very basic designs in developing countries are in operation. The products of the degradation process are biogas, composed of carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>), and a wet organic fraction called digestate with a high fertiliser quality.

Hydrothermal treatment is still in a very preliminary state of development. Four different processes are under evaluation: TORWASH (producing biocoal), hydrothermal carbonisation (producing a charcoal-like product), hydrothermal upgrading – HTU (producing a bio-oil), and hydrothermal gasification (producing BioSNG). SNG stands for substitute natural gas or synthetic natural gas.

Hydrothermal carbonisation occurs under high pressure (>20 bar) and at relatively low temperatures (around 200°C). Reaction time is between two and 12 hours. The process

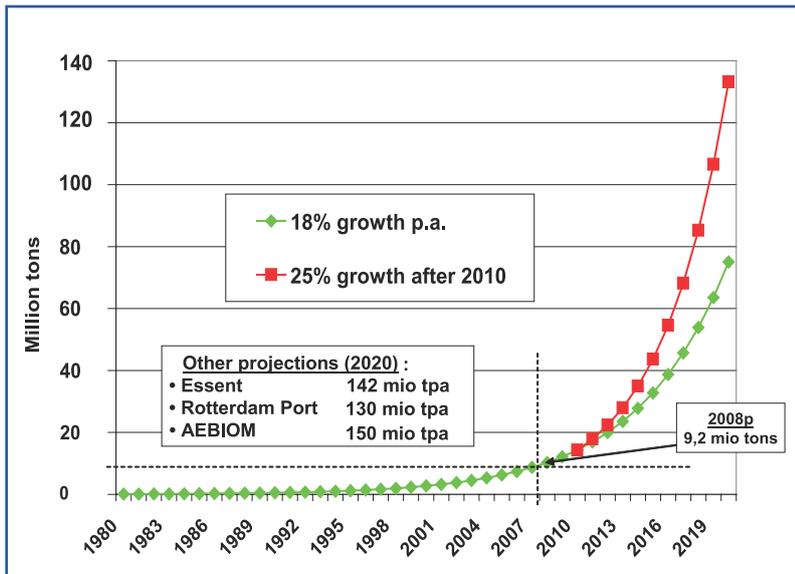


Figure 1. Scenarios of European pellet consumption.<sup>2</sup>

can be combined with biogas production. In a first step the easily degradable substances are biologically converted into methane and carbon dioxide and the remaining organic fraction is then hydrolysed to bio-coal.

**Dry biomass:** The simplest form of dry biomass processing is densification, i.e. briquette or pellet formation from sawdust or milled fresh wood. The growth of the pellet market over the last 10 years is a real success story. Since 2000 pellet consumption in Europe has increased from less than 1 million tons to 9.2 million tons per year in 2008. Different scenarios, e.g. from Essent, AEBIOM and ECN, predict a continued annual growth rate of 25% or more on average, expecting to reach 140 million tons and upwards by 2020 (Figure 1).

Worldwide a growing commodity market in pellets has been established, as was shown by André Faaij during the last ExCo workshop in Nara, Japan<sup>1</sup>.

Another option for dry biomass treatment is pyrolysis to bio-oil. The emphasis of existing technologies is on fast pyrolysis where the maximum liquid fraction can be produced. A large number of different reactor concepts have already been considered, such as fixed bed, fluidised bed, circulating cones, etc., that is described in more detail in 'Session 2: Pyrolysis'. Most of the designs are still in a pilot or demonstration scale. The choice will certainly be reduced once the development approaches industrial scale.

Bio-oil can either be used directly in burners or as a substrate for a secondary conversion step. Crude bio-oil is not an ideal bioenergy carrier. It contains lots of water and oxygen and is characterised by a low pH and an upper heating value of typically only 17 MJ per kg, which corresponds to about 40% of mineral oil's energy content (Table 1). In addition, it does not mix well with hydrocarbons. For proper application an upgrading step is needed, such as co-refining in standard refineries (drop-in fuels).

A third option for pre-treating dry biomass is torrefaction followed by pulverisation and densification to bio-coal pellets or briquettes. Torrefaction is a low temperature thermal treatment in the absence of oxygen that is operated at temperatures between 200-300°C near atmospheric pressure. At these low temperatures mainly hemicelluloses are degraded. The residence time in the reactor is typically between 10-30 minutes. The biomass has to be milled to a particle size of <4 cm. Approximately 90% of the biomass remains in the coal – only 10% is gasified. Importantly, densification of the energy content occurs by a factor of 1.3 to 1.5. The process is slightly exothermic. For economic reasons it is important to use the heat produced during the process.

Besides the bio-coal, a small fraction of undesirable liquids is formed. Torrefaction is an old technology that has been used for years for coffee roasting. However, treating 100,000 tons per year of biomass is not quite the same as treating a few hundred kilos per year of coffee. Process control becomes extremely important at large throughputs.

After pulverisation the fuel is a hydrophobic powder of a homogeneous, friable structure that is easily stored. The lower heating value has increased to 19-22 MJ/kg. After pelletisation, the product becomes a convenient commodity

Table 1: Typical properties and characteristics of wood derived crude bio-oil.<sup>3</sup>

Physical property	Typical Value
Moisture content	20-30%
pH	2.5
Specific gravity	1.20
Elemental analysis	
C	55-58%
H	5.5-7.0%
O	35-40%
N	0-0.2%
Ash	0-0.2%
HHV as produced	16-19 MJ/kg
Viscosity (40°C and 25% water)	40-100 cp
Solids (char)	0.1-0.5%
Vacuum distillation residue	Up to 50%
Characteristics	
Liquid fuel	
Ready substitution for conventional fuels in many stationary application	
Heating value of 17 MJ/kg at 25% wt. water, is about 40% that of fuel oil/diesel	
Does not mix with hydrocarbon fuels	
Not as stable as fossil fuels	
Quality needs definition for each application	

<sup>1</sup>IEA Bioenergy ExCo65 Workshop: Developing Sustainable Trade in Bioenergy <http://www.ieabioenergy.com/DocSet.aspx?id=6568>

<sup>2</sup>Source: ProPellets analysis 2008 plus presentations by Essent, Rotterdam Port & AEBIOM

<sup>3</sup>Source: [www.pyne.co.uk](http://www.pyne.co.uk)

**Table 2:** Quality of torrefaction pellets as compared to corresponding raw material.

Properties (willow, typical values)	Unit	Wood	Torrefied Wood	Wood Pellets	Torrefaction Pellets
Moisture Content	wt. %	35	0	10	3
Calorific value (LHV)					
Dry	MJ/kg	17.7	20.4	17.7	20.4
As received	MJ/kg	10.5	20.4	15.6	19.9
Mass density (bulk)	kg/m <sup>3</sup>	475	230	650	750
Energy density (bulk)	GJ/m <sup>3</sup>	5.0	4.7	10.1	14.9
Pellet strength				Good	Very good
Hygroscopic nature		Hydrophilic	Hydrophobic	Hydrophilic	Hydrophobic
Biological degradation		Fast	Slow	Fast	Slow
Handling properties		Normal	Normal	Good	Good

with excellent properties including high energy content (13-17 GJ/m<sup>3</sup>) and a bulk density of 650-750 kg/m<sup>3</sup> (Table 2).

ECN pellet tests have shown that good quality pellets can be produced without additional binder. However, good control of torrefaction conditions is essential for a proper pelletisation performance.

There are a number of torrefaction technologies. Most are derived from drying or pyrolysis technology. The major bottlenecks are limited process control (e.g. temperature, residence time, and distribution), limited efficiency and fuel flexibility (robustness). Scale-up of pilot systems is often a barrier as well.

ECN has developed a process (ECN BO<sub>2</sub>) with compact dedicated moving bed technology with direct heating (no moving parts) and conventional drying and pelletisation. Heat recovery and recycling allows high energy efficiency (>90%) and makes the process cost effective.

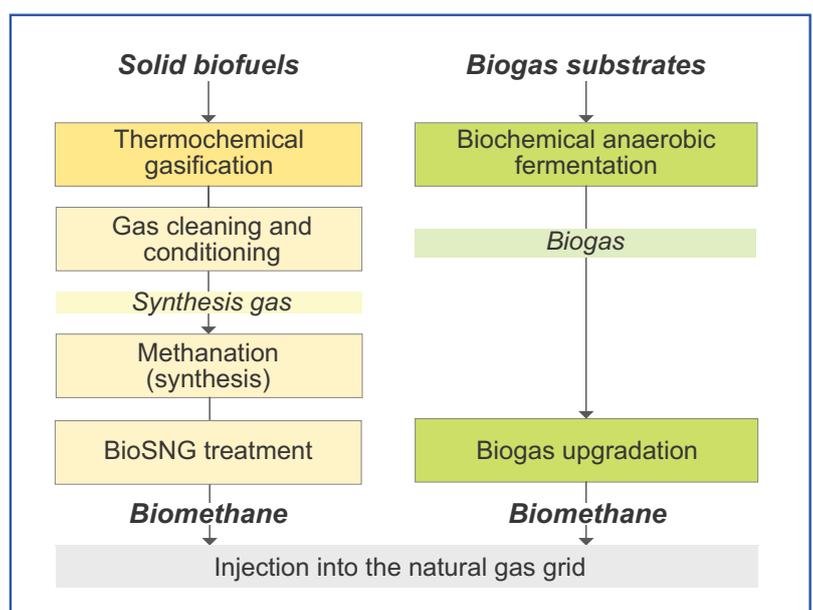
Looking at the different torrefaction companies on the market gives the impression that the technology is a Dutch invention. ECN, who built a first demonstration plant together with Vattenfall, had a leading role in the development of the basic processes, as did KEMA, another private Dutch research institute. The major industrial stakeholders are Netherlands-based companies such as Stramproy Green, Foxcoal, Torrcoal and Topell. The latter has signed a 49.5% joint-venture with RWE Innogy – a 100% owned subsidiary of RWE, Germany's largest electricity and gas company – to build a first full-scale torrefaction plant in the Dutch town of Duiven near Arnhem. The €15 million plant, which will be operational in 2011, will have an initial production capacity of 60,000 tons<sup>4</sup>.

Electricity producers are keen to replace coal with bio-coal in their power plants to reduce CO<sub>2</sub> emissions instead of investing in expensive CCS or even algae plants<sup>5</sup>. Recently Stramproy transported the first load of bio-coal to a power station and successfully tested the substitution of coal at production scale.

The last option to pre-treat dry biomass is the production of SNG via gasification and methanation. SNG is increasingly called biomethane because it has the same chemical composition as biomethane from anaerobic digestion and can replace natural gas when it is fed into the gas grid (Figure 2). For transport of the energy carrier gas injection is one of the best options because the infrastructure exists and transport energy is marginal.

There are different technical options for gasification:

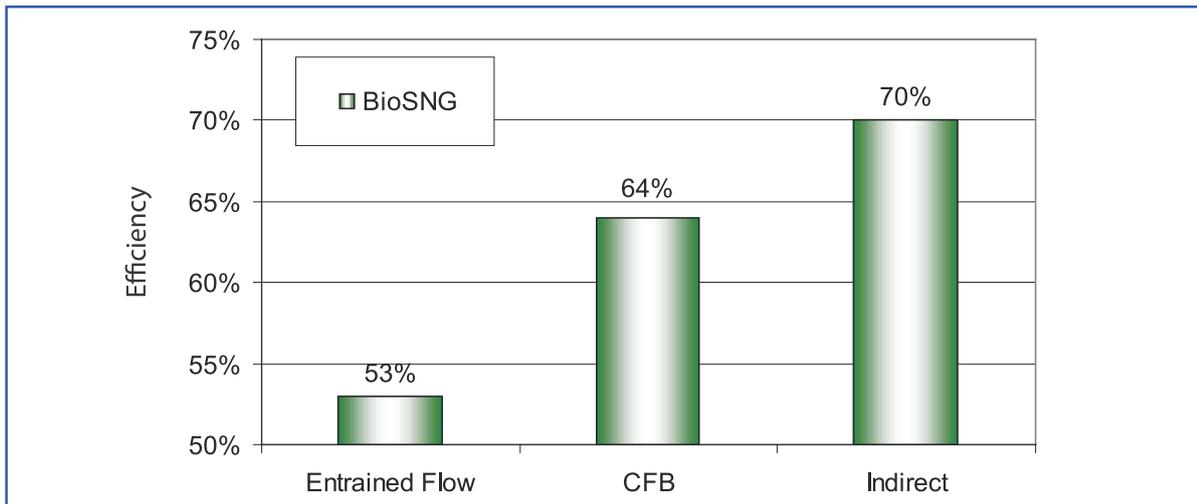
- Oxygen-blown entrained flow is operated at elevated pressures. It has the advantage that there is no tar in the product gas but at the same time no methane either.



**Figure 2.** The basic principles of BioSNG and biogas upgrading to biomethane.

<sup>4</sup>European Energy Review; 1 June 2010: A breakthrough for second-generation biofuels

<sup>5</sup>IEA Bioenergy ExCo64 Workshop: Algae – the Future for Bioenergy <http://www.ieabioenergy.com/DocSet.aspx?id=6436>



**Figure 3.** Overall conversion efficiency of the different gasification processes.<sup>6</sup>

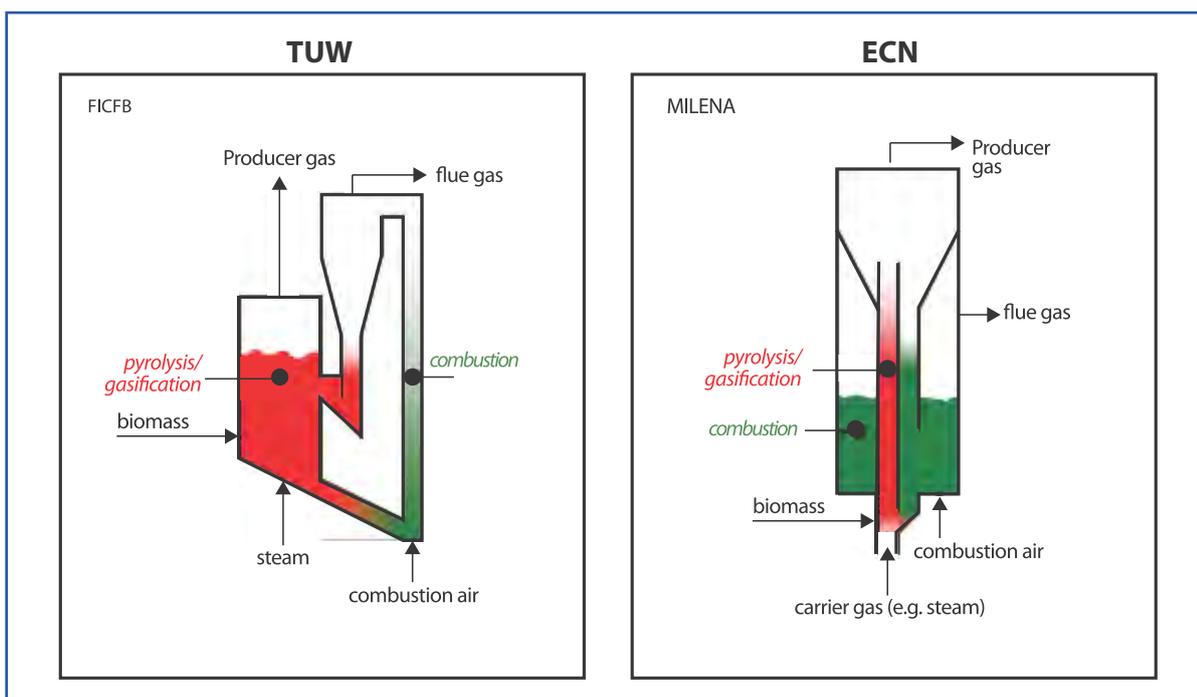
- Oxygen-blown Circulating Fluidised Bed (CFB) is operated at only slightly increased pressure. The product gas contains methane but also tar and organic sulphur. There is only limited tar conversion.
- Indirect/allothermal gasification produces methane but also tars and organic sulphur. The process does not require oxygen production, i.e. process energy is reduced.

In fact indirect gasification demonstrates by far the highest efficiency (Figure 3).

There are two major indirect gasification technologies, one developed by the Technical University in Vienna, the other by ECN (Figure 4). In both pyrolysis/gasification is locally separated from combustion. The Güssing plant in Lower Austria is the longest running using the TU Vienna system, with a thermal capacity of 10 MW.

SNG production is not a new technology; it has been applied in the USA and South Africa for many years, albeit with mineral coal. The behaviour of biomass is quite different and creates quite a challenge. Even more difficult is the gas cleaning because the gas from mineral coal is free of unsaturated hydrocarbons. In the two concepts of indirect gasification different gas cleaning processes have been applied. ECN's concept is based on an improved tar remover from France (OLGA) whereas in Güssing catalytic conversion developed by TU Vienna and PSI from Switzerland has been applied.

As it stands now, there is still a long way to go to increase the size of a methanation/gas upgrading process from the reality of 1 MW in Güssing to 20 MW or even 100 MW capacity. However, in Göteborg, Sweden the planning stage of a 20 MW SNG plant has been completed and construction will start soon.



**Figure 4.** Basic outline of the TU Vienna and the ECN indirect gasification process.

<sup>6</sup>van der Meijden, C.M. *et al.* (2010); B&B 34: 304 – 311.

## SESSION 2 – PYROLYSIS

### Biomass Pyrolysis – Tony Bridgwater, Aston University, UK

Pyrolysis is a process where biomass is heated in the absence of air or oxygen to decompose or devolatilise into a mixture of three products: solid char, liquid as bio-oil, tar or pyrolygneous liquor and gas. Three products are always produced, but the yields depend on the biomass composition, the vapour and solids residence time, and the reaction temperature. The temperature is in between that of torrefaction and gasification (Table 3).

**Table 3:** Modes of pyrolysis.

Mode	Conditions	Wt % products	Liquid	Char	Gas
Fast	~ 500°C; very short hot vapour residence time (RT) ~1 s; short solids RT		75%	12%	13%
Intermediate	~ 500°C; short HVRT ~10-30 s; moderate solids RT		50% in 2 phases	25%	25%
Slow	~ 400°C; long HVRT; very long solids RT		35%	35%	30%
Torrefaction	~ 300°C; long HVRT; long solids RT		Vapours	85% solid	15% vapours
Gasification	~ 800-900°C; short HVRT; short solids RT		1-5%	<1% (all burned)	95-99%

Fast pyrolysis aims to maximise liquids. This is achieved with very high heating rates and short retention times of a few seconds, usually requiring very small particle sizes of generally <3 mm in size in order to maximise heat transfer and <10% moisture. Intermediate temperatures should be avoided because they favour coal formation.

Clean wood gives highest liquid yields up to 75% (w/w) on dry biomass feed. The liquid is homogenous i.e. single phase, with a low viscosity. It has a distinctive odour - an acrid smoky smell - which can irritate the eyes if exposed for a prolonged period to the liquids. The cause of this smell is due to the low molecular weight aldehydes and acids. The liquid contains several hundred different chemicals in widely varying proportions, ranging from formaldehyde and acetic acid to complex high molecular weight phenols, anhydro-sugars and other oligosaccharides.

Charcoal forms about 10-15% (w/w) of the products. It retains virtually all the alkali metals which is excellent for the oil quality.

Torrefaction aims to produce the greatest amount of solids possible, and 85% solids production can easily be achieved. Gasification aims at high gas production with 95-99% gas.

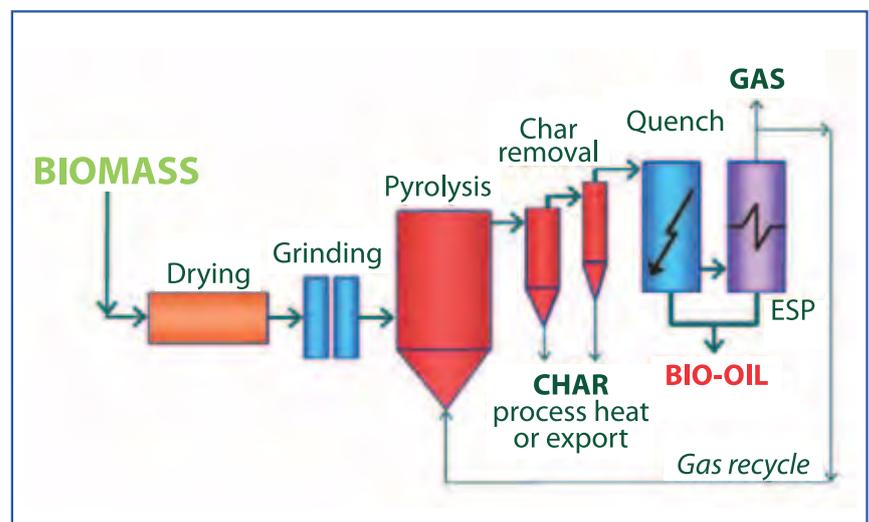
**Quality of bio-oil:** Bio-liquids easily mix with water, i.e. with moist biomass poor products are formed tending to separate into two phases, of water and oil. High ash content will lead to separation of the liquid fractions as well. Generally, bio-oil has a moisture content of 25%. Half of this is produced during the reduction process and is not controllable, unlike the biomass moisture content that can be selected. Bio-oil cannot be distilled in the same way as fossil oil. It forms a type of azeotropic mixture at moisture contents of 15% or higher (up to a maximum of 50%).

The positive effect for intermediate storage and transport of biomass is the approximately tenfold increase in specific gravity (1.2 tons/m<sup>3</sup>) when compared to the original biomass. The resulting higher heating value (HHV) is 17 MJ/kg. The solid char fraction in the liquid is lower than 0.1%. Besides the water, the oxygen content of the bio-oil is also high with 35-40%. For direct utilisation this must be removed.

**Reactor designs:** In the literature around 15 different reactor designs are described, but only five are the subject of commercial activity: Fluid bed, spouted fluid bed, transported bed, rotating cone and ablative reactors have been developed into large-scale application. The largest plants in operation handle between 100-200 tons per day.

Rotary kiln, screw or auger reactors could handle more complex and difficult material in a process called intermediate pyrolysis. The charcoal forms about 25 wt.% of the products. Due to the mechanical and abrasive action of the reactor, the particle size of the charcoal tends to be small.

A typical fast pyrolysis system like the different beds or the rotating cone is composed of various elements (Figure 5).



**Figure 5.** Elements of fast pyrolysis systems.

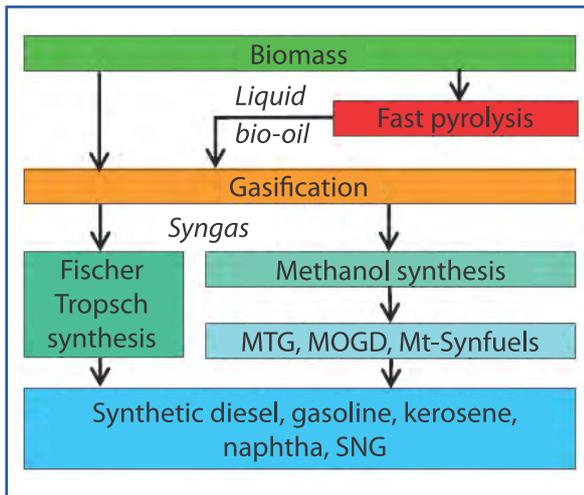


Figure 6. Possible processes from biomass to (liquid) biofuel.

Ablative pyrolysis is substantially different in concept compared to the other methods<sup>7</sup>. In other methods, the rate of reaction is limited by the rate of heat transfer through a biomass particle. Small particles are therefore required. The mode of reaction in ablative pyrolysis is analogous to melting butter in a frying pan, when the rate of melting can be significantly enhanced by pressing down and moving the butter over the heated pan surface. In ablative pyrolysis heat is transferred from the hot reactor wall to 'melt' wood that is in contact with it under pressure. The pyrolysis front thus moves unidirectionally through the biomass particle. As the wood is mechanically moved away, the residual oil film both provides lubrication for successive biomass particles and also rapidly evaporates to give pyrolysis vapours for collection in the same way as other processes. The rate of reaction is strongly influenced by pressure, the relative velocity of wood on the heat exchange

surface and the reactor surface temperature. The key features of ablative pyrolysis are therefore as follows:

- High pressure of particle on hot reactor wall, achieved by either centrifugal force or mechanical action.
- High relative motion between particle and reactor wall.
- Reactor wall temperature less than 600°C.

As reaction rates are not limited by heat transfer through the biomass particle, large particles can be used. In principle there is no upper limit to the size that can be processed. In fact the process is limited by the rate of heat supply to the reactor rather than the rate of heat absorption by the pyrolysing biomass as in other reactors. There is no requirement for inert gas, so the processing equipment is smaller, and the reaction system is thus more intensive. However the process is surface area controlled so scaling is more costly and the mechanically-driven reactor is more complex.

*Indirect use of bio-oil:* Gasification of fresh biomass in a forest-rich area is more cost-efficient than passing via fast pyrolysis. With longer transport distances the formation of pyrolysis oils has its merits thanks to the easy handling of the homogeneous liquid and the higher energy density reducing transport cost (Figure 6). Synthetic diesel from bio-oil (or directly from biomass) or methanol is produced via gasification followed by hydrocarbon or alcohol synthesis. The selectivity and efficiency for methanol production is better than for Fischer Tropsch.

One of the more advanced systems with a combination of pyrolysis and gasification is the one developed by KTI and marketed by the German company Bioliq, with a high pressure entrained flow gasification system. A first demonstration plant is in the commissioning phase in Karlsruhe, Germany (Figure 7).

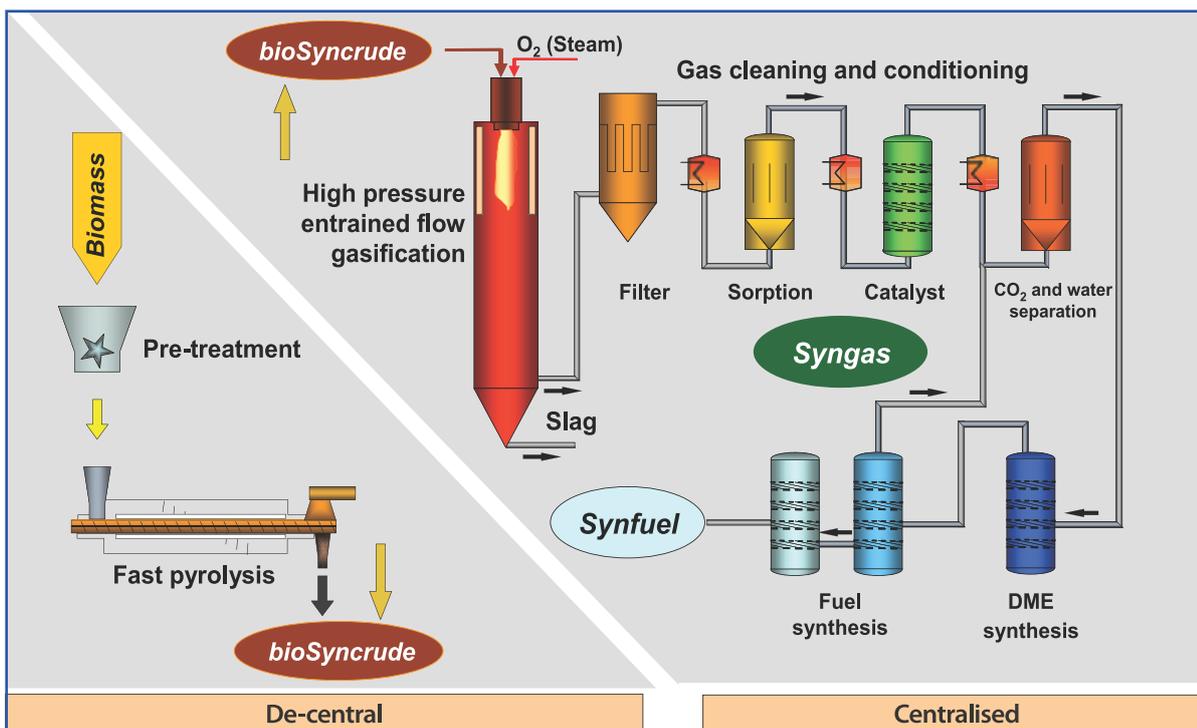


Figure 7. Schematic layout of the Bioliq process.

<sup>7</sup> www.pynet.eu

**Direct fuel production from bio-oil:** Bio-oil contains 35-40% oxygen which has to be removed for the production of hydrocarbons. Using catalytic upgrading of liquid or vapour the bio-oil can be converted into higher quality products that can be integrated into a conventional refinery.

The so called hydrotreatment, i.e. liquid processing with hydrogen at high pressure, rejects oxygen as H<sub>2</sub>O. The projected yield is around 15% of a naphtha-like product for refining to diesel, using co-produced hydrogen.

An alternative method is Zeolite cracking that rejects oxygen as CO<sub>2</sub>. It is a close coupled process for upgrading vapours requiring constant catalyst regeneration. On the other hand no hydrogen is needed and no high pressure. The projected yield is around 18% aromatics for refining to gasoline.

The cost of bio-hydrocarbon production is still considerable at present stage of development (Table 4) with pyrolysis as a pre-treatment step.

**Table 4:** Cost of bio-hydrocarbon production.<sup>8</sup>

	Yield Wt %	€/t Product	HHV, GJ/t	€/GJ Product	€/toe
Wood feed (daf)	100	67	20	3	145
Pyrolysis oil output	70	147	19	8	331
Diesel (EXCL H <sub>2</sub> )*	23	592	44	13	578
Diesel (INCL H <sub>2</sub> from biomass*)	13	880	44	20	860
Gasoline*	22	453	44	10	443
FT diesel#	20	1060	42	25	1030
MTG gasoline#	26	1320	43	31	1320
Crude oil at \$100/bbl	-	560	43	15	560

\* Basis: 100 t/d daf wood feed at €67/dry t, 2006.

# Basis: 1 mt/y product derived by gasification (DENA report), 2006.

**Production of chemicals:** Bio-oil is not only an energy carrier but also a source of a large number of chemicals. Fractionated oil can be used for the production of liquid smoke (commercial), anhydrosugars, asphalt, de-icers, fuel additives, preservatives, resin precursors, slow release fertiliser, and hydrogen.

Hydrogen is produced by catalytic steam reforming of the bio-oil to hydrogen and carbon dioxide. This concept has several advantages over the traditional gasification/water-gas shift technology.

A specific advantage is the potential production and recovery of higher value-added co-products from bio-oil that could significantly impact the economics of the entire process. The lignin-derived fraction would be separated from bio-oil and used as a phenol substitute in phenol-formaldehyde adhesives while the carbohydrate-derived fraction would be catalytically steam reformed to produce hydrogen. Hydrogen can be efficiently produced by catalytic

steam reforming the carbohydrate-derived bio-oil fraction using a commercial nickel-based catalyst in a fixed bed reactor.

The development of most of the processes is still in a P&D stage. The production of only a few specific chemicals is close to or in a full commercial state, such as acetic acid (commercial), furfural, hydroxyacetaldehyde, levoglucosan, levoglucosenone, maltol, and phenol and phenolics.

Besides production of bio-coal using a slow pyrolysis process, Lambiotte is producing chemicals from the liquids. In 2000/2001 they used 100,000 t/a wood and produced as a side product 56 t/a of fine chemicals. Some 4% are acids and alcohols. Total liquids produced are 40,000 t/a, mostly acetals. Acetals belong to a specific chemical family, generally referred to as solvents, but distinct from ethers. Lambiotte's acetals are produced by reactions between alcohols and aldehydes. The acetal molecule can be either linear or cyclic.

Acetals are solvents for a large number of applications such as coatings, pharmaceuticals, veterinary, polyurethanes, agrochemicals, cosmetics, etc.

**Conclusions:** Pyrolysis is very flexible in the process and products. It provides an alkali metal free liquid as an energy carrier. Bio-oil has a high energy density and allows long distance transport. However, there is a cost penalty for using fast pyrolysis for pre-treatment. Bio-oil can be used for fuel, chemicals or biofuel production by upgrading processes.

Fast pyrolysis technology needs to be improved to reduce costs and increase liquid yield and quality. The liquid upgrading needs to be further developed and demonstrated. Biochar is of great interest but has questionable economics at present.

## SESSION 3 – GASIFICATION

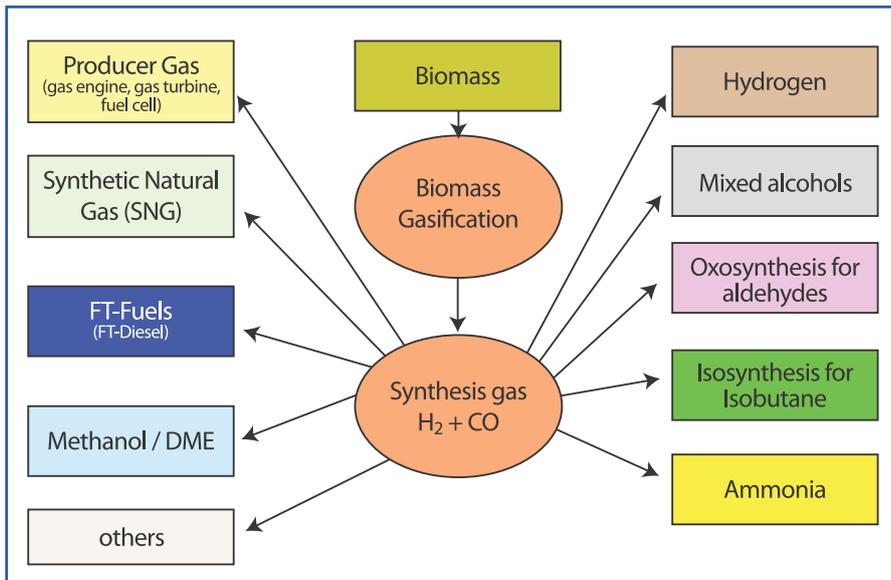
### Overview of Full-scale Gasification Processes – Reinhard Rauch, TU Wien, Austria

Gasification is a process by which either a solid or liquid carbonaceous material from biomass, containing mostly chemically bound carbon, hydrogen, oxygen, and a variety of inorganic and organic constituents, reacts with air, oxygen, and/or steam. The reactions provide sufficient exothermic energy to produce a primary gaseous product containing mostly CO, H<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O(g), and light hydrocarbons loaded with volatile and condensable organic and inorganic compounds. Most of the inorganic constituents in the feedstock are chemically altered and either discharged as bottom ash or entrained with the raw product gas as fly ash.

The major products of the synthesis gas formed are hydrogen and carbon monoxide. Up to 40% H<sub>2</sub> and 20% CO is possible. These two major gases can be used separately or can be used as reactants to produce natural gas (biomethane) or to synthesise a large variety of other hydrocarbons (Figure 8).

Today, the syngas market covers about 6000 PJ/y or 2% of the total energy market. More than 50% is used for

<sup>8</sup> [http://www.dena.de/fileadmin/user\\_upload/Download/Dokumente/Publikationen/mobilitaet/BtL\\_Realisierungsstudie.pdf](http://www.dena.de/fileadmin/user_upload/Download/Dokumente/Publikationen/mobilitaet/BtL_Realisierungsstudie.pdf)



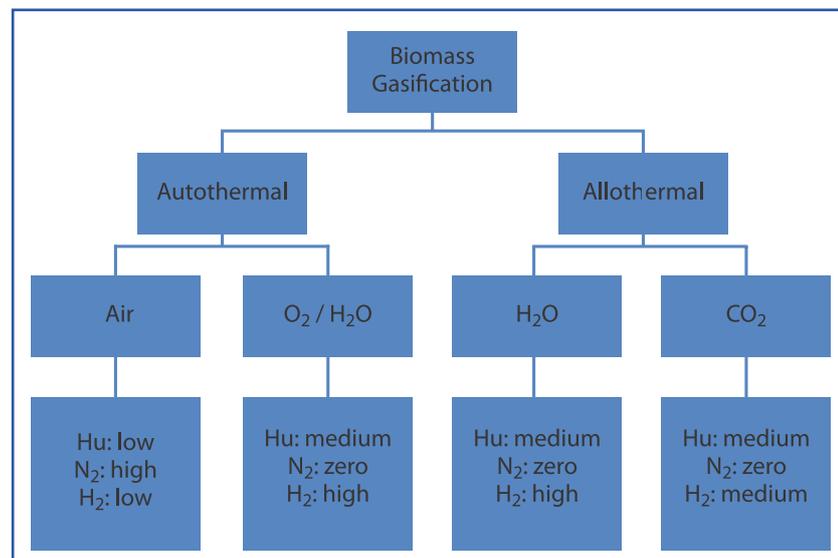
**Figure 8.** Possible product formation from raw synthesis gas.

ammonia production<sup>9</sup> followed by refineries (H<sub>2</sub>-production) with 23% and methanol synthesis with 11%. The same authors predict a share in energy production of 10% or 50,000 PJ per year in 2040. Half of this amount is expected to be used for biomass to liquid (BTL) production.

**Gasification systems:** There are two types of gasifiers: autothermal and allothermal reactors. Gasification is an endothermic process. Therefore, heat supply is necessary to run gasification processes. In the case of an autothermal gasification process the necessary heat is produced directly by partial oxidation in the reactor itself. However, oxygen has to be added. If heat is supplied indirectly by heat exchangers or a circulating heat carrier, other gasification media such as CO<sub>2</sub> or steam can be used. These processes are called allothermal. This type is well suited for medium-scale plants in the range of 20-300 MW input energy. In autothermal processes air or steam/oxygen is injected to burn part of the products produced.

Injection of air instead of oxygen leads to a high concentration of nitrogen in the product gas. In case of synthesis gas production the raw gas should be almost nitrogen free. Also, the calorific value of the gas is low because very little hydrogen is formed. Autothermal production with oxygen and steam leads to a higher heating value of the gas with a high hydrogen concentration (Figure 9).

The same is true for allothermal gasification with steam whereas external heat provision with carbon dioxide leads to a medium hydrogen concentration.



**Figure 9.** The different gasification systems.

**Reactor designs:** There is quite a choice of different reactor designs mainly determined by the reactor power (Figure 10). For smaller-scale production fixed bed gasifiers are frequently used. For larger-scale fluidised bed gasifiers as well as entrained flow gasifiers are employed.

**Fixed bed gasifiers:** In small-scale fixed bed gasifiers the biomass flows from top to the bottom. In updraft reactors the air is fed at the bottom and the producer gas leaves the reactor at the top (Figure 11). The process is characterised by a high

thermal efficiency and a product gas with low carbon content in the ash but with high tar formation.

The producer gases in the down draft reactors contain very little tar, however, they display a lower efficiency and are susceptible to particle size and water content of the biomass.

**Fluidised bed reactors:** The circulating fluidised bed and the entrained flow reactors are autothermal reactors whereas the dual fluidised bed is an allothermal gasifier (Figure 12). The latter demonstrates the longest operational experience, with some 10,000 hours in two full-scale designs. The other designs are only pilot-scale or are demonstration units in the start-up or commissioning phase. This holds true for fluidised or bubbling bed reactors (Chrisgas, Enerkem, Milena or Multi Clean Gas) and entrained flow or staged gasification (Bioliq, CarboV and Chemrec). The major difference between a bubbling and a fluidised gasifier is the velocity of the particles with 1-2 m/sec compared to 4-8 m/sec. Entrained flow gasifiers are used for very small particles of less than a millimetre which can be gasified in seconds at very high temperatures (>1,000°C).

<sup>9</sup>Observations on the current status of biomass gasification (2005). A Task 33 report. [http://128.131.132.12/app/webroot/files/file/publications/58\\_BiomassGasification.pdf](http://128.131.132.12/app/webroot/files/file/publications/58_BiomassGasification.pdf)

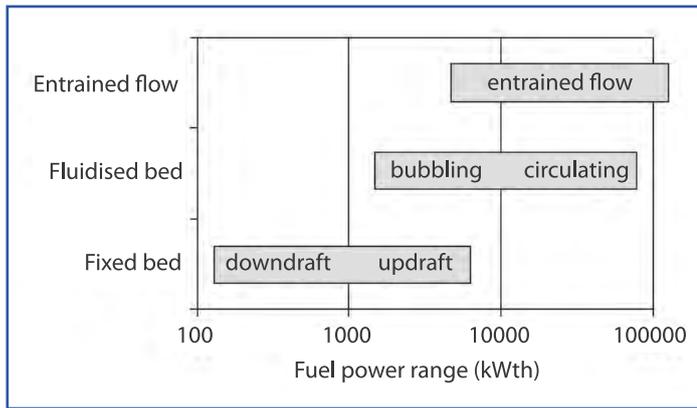


Figure 10. Typical gasifier designs by thermal power function.

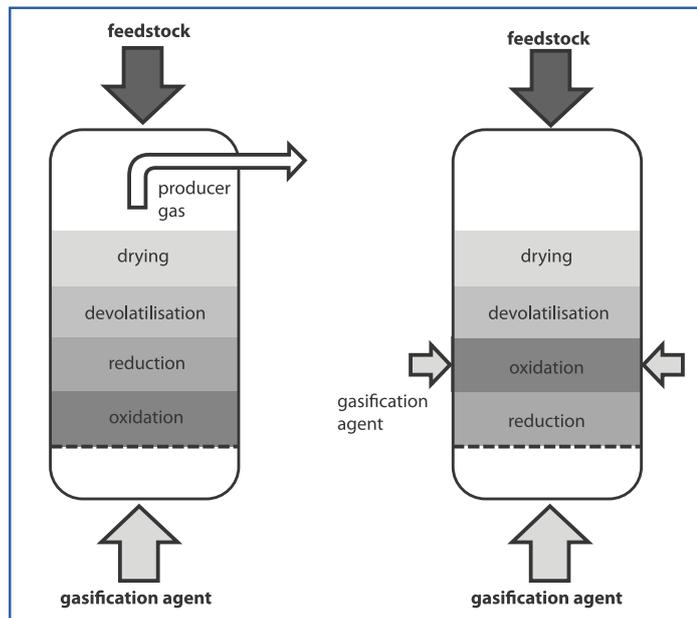


Figure 11. Updraft (counter-flow) and down draft fluidised bed reactors. Source: Hermann Hofbauer; TU Wien.

**Gas upgrading:** Unless the raw gas is combusted immediately, it is cooled, filtered, and scrubbed with water or a process-derived liquid to remove condensables and any carry-over particles. Alternatively, the raw gas can undergo either medium-temperature (350-400°C) or high-temperature (up to gasifier exit temperatures) gas cleaning to provide a fuel gas that can be used in a variety of energy conversion devices, including internal combustion engines, gas turbines, and fuel cells.

Biomass, when gasified with steam and/or oxygen will produce 'synthesis gas', rich in CO and H<sub>2</sub>, which in turn can be catalytically converted to produce methane (biomethane), high-value fuels (BTL or DME) and chemicals (methanol).

**Gas utilisation:** The upgraded producer gas is used for different purposes, such as the production of heat and power, syngas and/or DME (Biolig, Choren, BioDME); the production of methanol (BioMCN); Fischer Tropsch BTL (Choren, Stora Enso and Neste Oil); or biomethane (FICFB Repotec, ECN). Methanol is probably the most interesting starting product because it can serve as a basic substrate for a number of other compounds such as DME, etc. The technology is available. The disadvantage is that the scale has to be very big – 1 GW or more. Because of the cost road transport is not an option and such plants can only be built at harbours such as Rotterdam. The market for DME looks promising. Volvo Trucks Corporation is starting to build up an infrastructure for DME. The company expects that for the whole of Europe about 1,000 filling stations are needed, which, it says, should be easily accomplished.

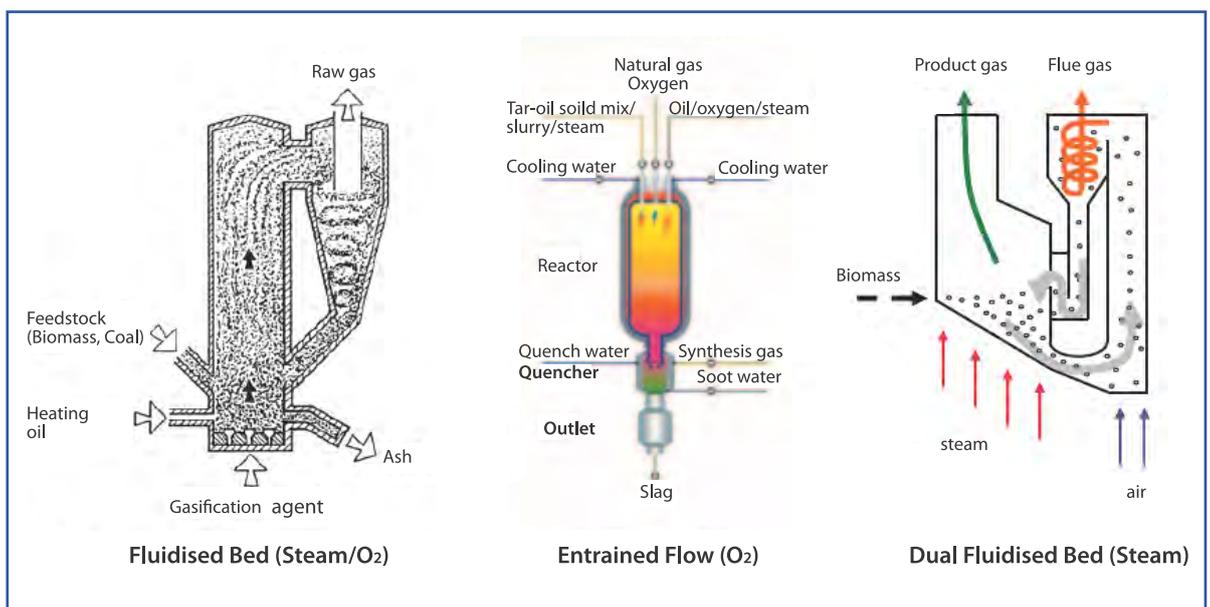


Figure 12. Basic designs of fluidised bed and entrained flow reactors.

For advanced biofuels the production of Fischer Tropsch BTL, SNG and methanol are of special interest. All of these synthesis-reactions are catalytically promoted reactions and have to be carried out at more or less high pressure. Furthermore, the requirements for gas purity are much higher than for utilisation in gas engines or gas turbines. The optimal thermal conditions and the composition of the producer gas of the three processes are different (Table 5).

**Table 5:** Production conditions for different products from bio-syngas. Source: Herrmann Hofbauer, TU Wien.

Synthesis	H <sub>2</sub> /CO	Catalyst	Pressure Bar	Temperature °C
Fischer Tropsch	1.5 – 2	Fe/Co/Mo	25 – 40	250 – 350
Methanol	2	Zn/Cr, Cu/Zn	50 – 300	220 – 450
SNG	3	Ni/Mg	1 – 5	300 – 450

**The GoBiGas Project: Efficient Transfer of Biomass to Biofuels – Ingemar Gunnarsson, Göteborg Energi, Sweden**

The Swedish government wants to increase use of renewable energy to 50% of total energy consumption by 2020. As in all EU countries, 10% of the transport fuel must be provided by renewables. By 2030 the Swedish transport sector wants to be independent of fossil fuels. Sweden does not have feed-in tariffs for electricity. On the other hand biomethane as a transport fuel is promoted through a series of incentives such as the support of production plants and fuelling stations, tax exemption for the fuel, tax reductions on cars, free parking in the major cities, and exemption from congestion charges, etc.

Göteborg Energi, the major energy distributor in the west of Sweden, is investing in biomethane and sees that energy carrier as one of tomorrow's most important energy sources. A major advantage of biogas is that the existing natural gas grid can be used for distribution. Natural gas in this respect acts as a bridge to the renewable biomethane. The big advantage of biomethane is the fact that it can replace natural gas at any ratio without changes in gas appliances or gas engines. The concept promoted by Göteborg Energi is called the 'green gas concept' (Figure 13).

Biomethane can be produced by two completely different processes. Anaerobic digestion (AD) is a microbial degradation of organic material producing biogas, a mixture of carbon dioxide and methane. The degradation process works in a wet environment and is therefore well suited to treat all kinds of water-rich wastes such as sewage sludge, source-separated household waste, and restaurant waste as well as purpose-grown energy crops such as beets or maize. It is equally suitable for the treatment of industrial waste waters. However, anaerobic

bacteria cannot degrade lignin. Biogas is upgraded to biomethane (a gas with the same physical characteristics as natural gas) by a variety of different adsorption or absorption processes. The technology has undergone fast development over the past 10 years and is well-established today.

The second technology to produce biomethane is the gasification process followed by an upgrading and a methanation step using catalysts.

Biogas production in Sweden from AD currently amounts to approximately 1.5 TWh. The estimated potential is 10 times higher at 15 and the estimated potential for biomethane from gasification amounts to 59 TWh. The vision of Göteborg Energi's partner E.ON Sweden is the production of 20 TWh of biomethane by 2020, 10 TWh each through gasification and anaerobic digestion.

Göteborg Biomass Gasification Project (GoBiGas) is Göteborg Energi's largest investment in the production of biomethane through gasification of wood residues from forestry. The project is being developed in cooperation with E.ON.

*Development of the technology:* In spring 2006, Göteborg Energi conducted a feasibility study with Swedish and Dutch expertise in order to compare the technology and economics of two gasification technologies, indirect gasification and pressurised oxygen-blown gasification. In 2007 in-depth studies of various gasification technologies with multiple suppliers were carried out. The choice fell on indirect gasification using a technology from the Austrian company Repotec, which has good operational experience with the Güssing plant.

Over the whole experimental phase Göteborg Energi cooperated with Chalmers University of Technology and has invested in a research facility for the indirect gasification constructed together with an existing biofuel boiler, built with CFB technology.

GoBiGas was granted financial support by the Swedish Energy Agency of SKR220 million (approximately US\$35 million) for the first phase as a demonstration plant in September 2009, which allowed detailed engineering to start. In 2010 the European Commission also approved support.



**Figure 13.** Göteborg's green gas concept.

The gasification plant in Güssing, Austria, which has been in commercial operation since 2002, provides a technical reference. By the end of 2009 this plant had more than 44,000 hours of operation. It is a dual fluidised bed gasifier with a total power of 8 MW. Güssing operates a gas engine of 2 MW<sub>eI</sub> and 4.5 MW<sub>th</sub>. The heat is fed to a district heating system.

On the same site, there is also a pilot methanation plant of 1 MW, based on a technology developed by PSI and marketed by the Swiss company CTU. The project GoBiGas was involved in the operation with staff on site from October 2009 to January 2010 in order to evaluate the technology.

**The full-scale project:** For the full-scale plant an allothermal, indirect gasification technology was chosen in order to achieve high efficiency. The target is to reach an energy conversion of 65% from biomass to biomethane and to achieve overall energy efficiency above 90%. The design includes a gasification unit and a combined gas cleaning/methanation unit (Figure 14).

The GoBiGas project is divided into two phases in which Phase 1 is a demonstration plant and Phase 2 is planned to be a commercial installation. The Phase 1 plant (about 20 MW gas) is planned to be built during 2011-2012 and be operational in late 2012. The second phase is planned after evaluation of Phase 1.

- **Performance goals:**
  - Biomass to biomethane 65-70%
  - Energy efficiency >90%
- **Phase 1:**
  - 20 MW biomethane generating 160 GWh/year in operation 2012
  - Allothermal (indirect) gasification
  - 2000 Nm<sup>3</sup>/hr or 16 m Nm<sup>3</sup>/yr

- **Phase 2:**
  - 80 MW generating 640 GWh/year of biomethane
  - Technology not yet chosen
  - 8000 Nm<sup>3</sup>/hr or 64m Nm<sup>3</sup>/yr

In Phase 1 the following input streams will have to be provided:

- Fuel in the form of wood pellets 32 MW
- Electricity 3 MW
- RME (biodiesel) 0.5 MW

The output will include the following power:

- Biomethane 20 MW
- Direct district heating 5 MW
- Heat to heat pump 6 MW

The plant will be built on the waterfront. Phase 1 will be built on the Rya harbour, on the same site as an existing hot water plant fired with wood pellets. The Phase 2 plant is planned on an adjacent plot of land with access to the quay. The location for the GoBiGas plants has been selected because of its potential for long-term and flexible fuel reception with ship and rail access. It is also close to a hub for Göteborg electricity, gas and district heating. Cooling water for the process can be taken from the adjacent Gota River.

Biomethane is very well accepted by Swedish car drivers. It is an important addition to the choice of environmentally-friendly fuels. Without biomethane there wouldn't be any gas in the east of Sweden because the gas grid covers only the south west of the country. In fact biomethane from AD (as there is no gasification plant yet) covers about 60% of the gas consumption for vehicle fuel and the trend is increasing.

Göteborg Energi expects to deliver biomethane equivalent to 1 TWh in 2020. This represents about 30% of today's deliveries in Göteborg, or fuel for 100,000 cars.

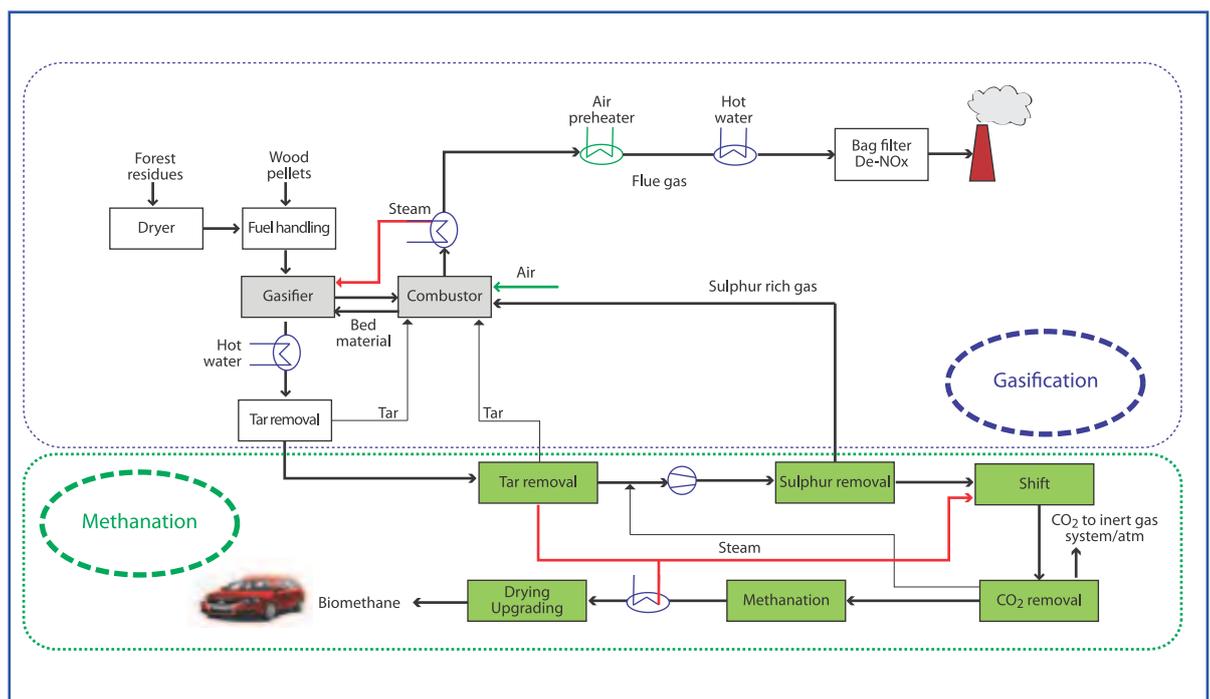


Figure 14. The GoBiGas concept.

## SESSION 4 – TORREFACTION

### Bioenergy Carriers: Integrated Pyrolysis and Torrefaction Concepts – Kai Sipilä, VTT, Finland

The European Commission has high expectations for biomass as an energy carrier. Most of the 10% of renewable transport fuel by 2020 targeted by the Renewable Energy Directive (RED) and even more after that is expected to be provided by biomass. One of the problems is the lack of low priced raw material. The key focus must therefore be directed towards overall chain integration and achieving high efficiencies.

As a consequence, the European Industrial Bioenergy Initiative (EIBI) calls for new solutions alongside seven value chains (Figure 15).

The estimated total budget needed to develop the seven chains to commercial installations is in the order of US\$8.5-11.5 billion. Half of it this should be provided by the industry, the other half by public money. The question is whether there is enough biomass available to produce all the planned energy carriers.

An evaluation by the European Biomass Association (AEBIOM) shows current biomass utilisation in Europe (Figure 16).

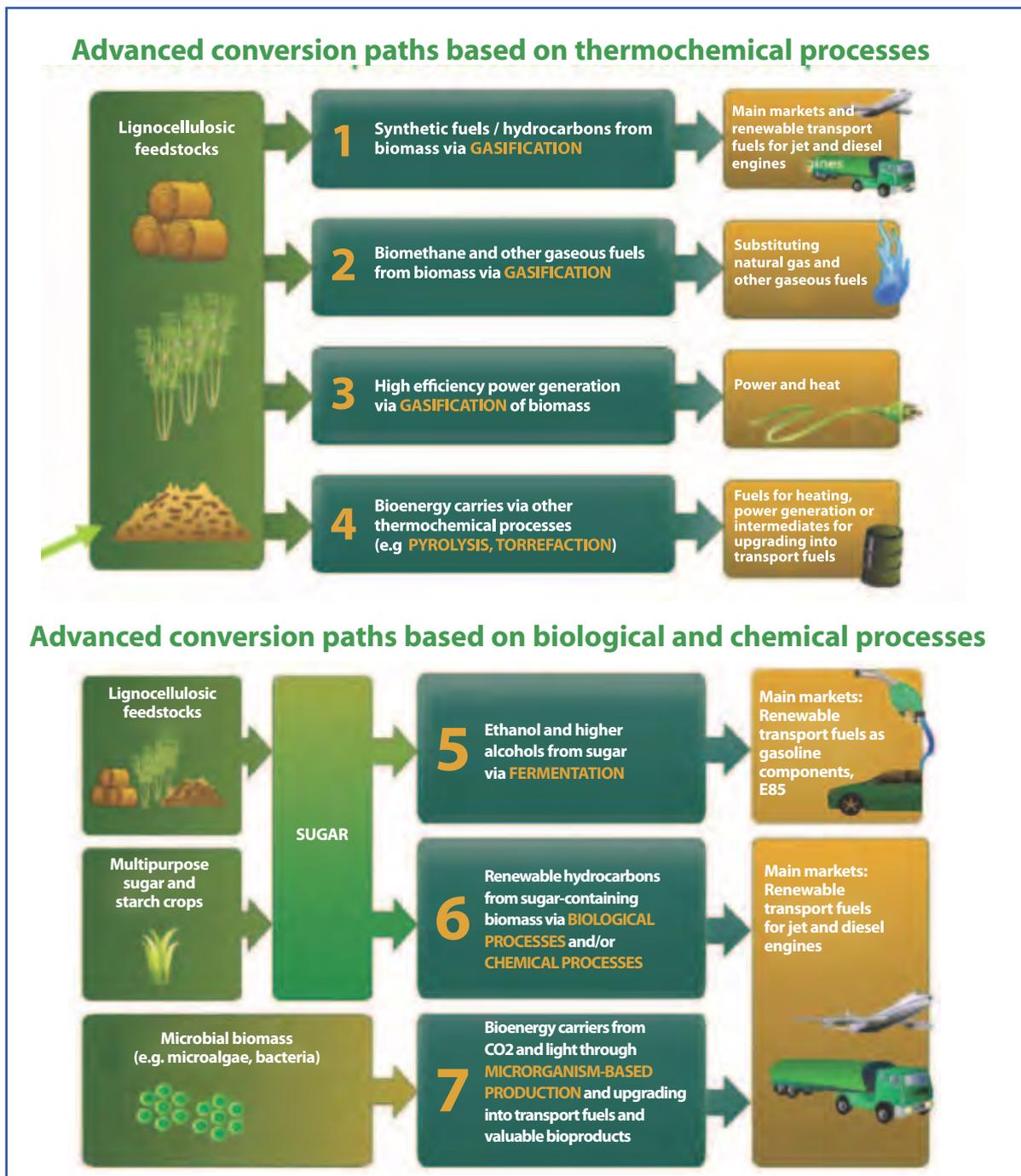


Figure 15. The EIBI's seven thermochemical and biochemical conversion paths.

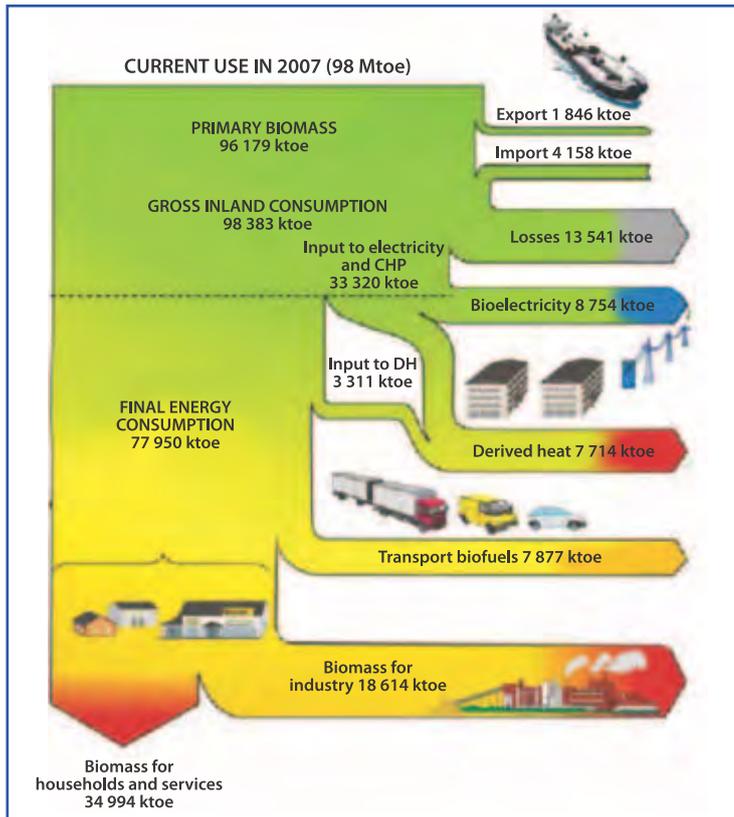


Figure 16. Current biomass utilisation in Europe. Source: J.-M. Jossart, AEBIOM.

In the short-term, until 2020, biomass-based energy carriers will be mainly based on current technologies that have been developed at least to demonstration-scale.

In 2009 VTT in collaboration with Pöyry Forest Industry Consulting has evaluated the biomass potentially available

for energy application either as heat and power or as (liquid) fuel. Their estimates for wood-based heat and power production in Europe are reasonably consistent with the data from AEBIOM (Figure 17).

The questions remain as to how the additional energy can be produced with essentially the same amount of biomass available in the short-term and whether there is enough investment capital available to finance the technology change.

In other words, how can these technologies be integrated into existing industry processes so that the existing 'old' technology can be replaced by a biorefinery concept. The technologies that have been considered are: green electricity, wood fuel oil, FT biodiesel from wood, EtOH from waste fibre, DME, and torrefaction.

An initial economic evaluation showed that bio-oil production via pyrolysis for transport and bio-oil or pellets for 'green' electricity production are the two most promising technologies at present and worthy of further evaluation.

The bulk of industrial wood is used in over 950 pulp and paper mills in Europe. In order to integrate the bio-oil concept, old boilers have to be replaced. Under the assumption that 50% of the boilers older than 25 years and 25% of the boilers older than 15 years are replaced by 2020, the authors estimated a potential of 60 boilers (Figure 18).

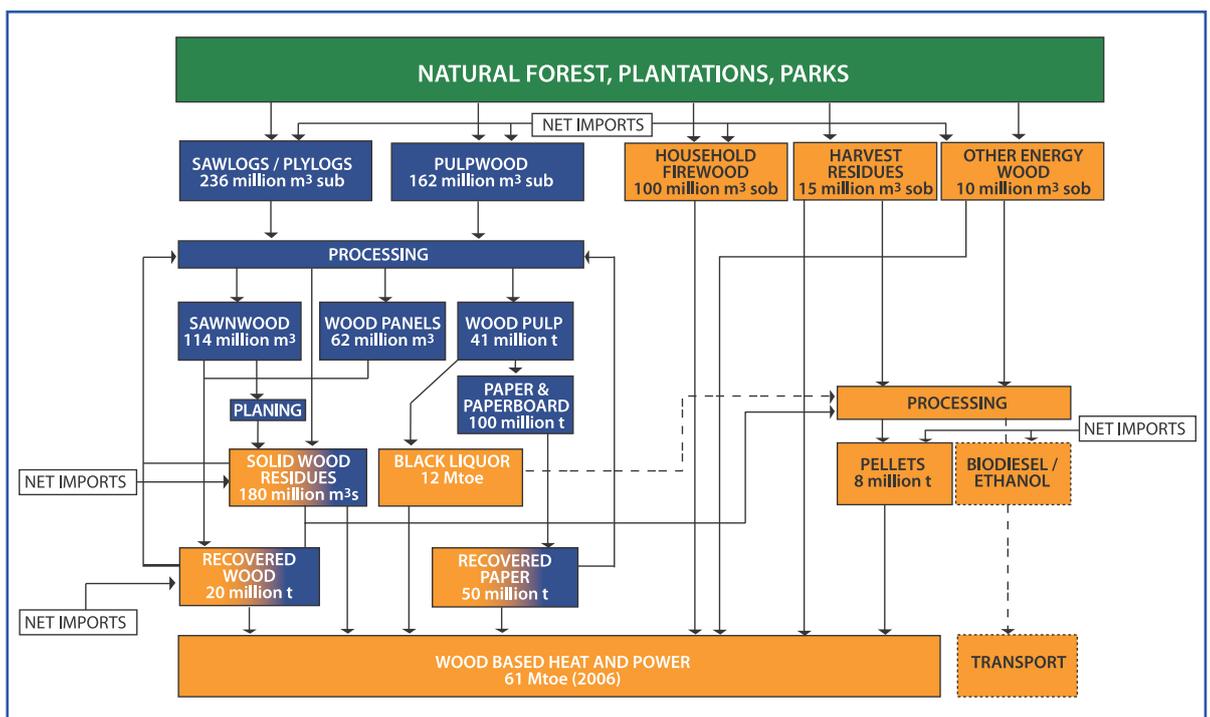
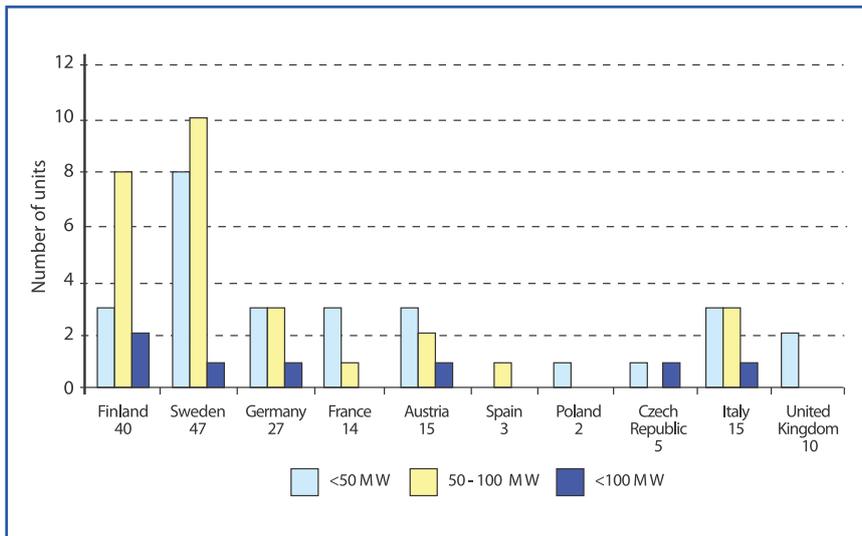


Figure 17. Wood flow by end-uses in EU-27 (2006).



**Figure 18.** Potential of boilers in pulp and paper mills until 2020 in selected countries. (Figures in y-axis indicate the total number of boilers).

**Pyrolysis:** The calculations for bio-oil production were based on data from VTT's ITP pyrolysis concept. (ITP is an acronym for integrated thermal processing technology, developed by VTT). In this concept the pyrolyser is integrated into a traditional fluidised bed boiler where the sand is re-circulated to the pyrolyser in order to optimise energy efficiency. All by-products can be burnt in the existing boiler. Similar concepts can be applied for torrefaction and gasification as well.

The fuel input to the pyrolysers was assumed to be 25 MW in industries with boilers <50 MW, 40 MW in boilers with 50-100 MW and 80 MW in boilers larger than 100 MW. The pyrolysis oil was planned to be processed to transportation fuels in existing oil refineries in Europe.

The resulting total potential pyrolysis oil production is 11,000 GWh/a, corresponding to 0.95 Mtoe. This would be produced in 58 units in the 11 major countries, with Sweden and Finland accounting for more than half of this. The corresponding solid wood fuel demand is 17 TWh/a, which is equivalent to 14% of the European forest residue. As a comparison, this pyrolysis oil potentially covers 130% of fossil fuels used in European lime kilns.

The concept of integrated bio-oil production has been developed to pilot scale by a joint project of Metso, UPM, Fortum and VTT. A 2 MW<sub>th</sub> fast pyrolysis unit has been integrated with a Metso 4 MW<sub>th</sub> circulating fluidised bed boiler, located at Metso's R&D Centre in Tampere.

The concept has been proven to be reliable:

- More than 70 tons of bio-oil have been produced from sawdust and forest residues.
- The process demonstrated a high availability.
- Bio-oil utilisation was demonstrated – more than 20 tons of bio-oil (50 MWh) replaced heavy fuel oil in a district heating boiler in Masala, Finland.

A demonstration plant is planned.

**Pellets:** The demand for wood pellets from the European coal-based industry has grown steadily as co-firing is viewed as a necessity in order to reach CO<sub>2</sub> targets. The same holds true for Japan<sup>10</sup>. In the USA, the Renewable Portfolio Standard (RPS) programme requires electricity utilities to produce a minimum portion of their supply from renewable sources, including biomass.

Replacing 5% of the total European coal consumption of 820 million tonnes per year with pellets translates into a requirement for 45 million tonnes of pellets per year – five times European pellet production in 2008.

However, European forest resources will mainly be utilised by the forest industries and their own bioenergy production. There will hardly be any additional European wood available by 2020 for co-combustion in conventional coal boilers. However, there are woody biomass resources available for import from Russia, and North and South America (Figure 19).

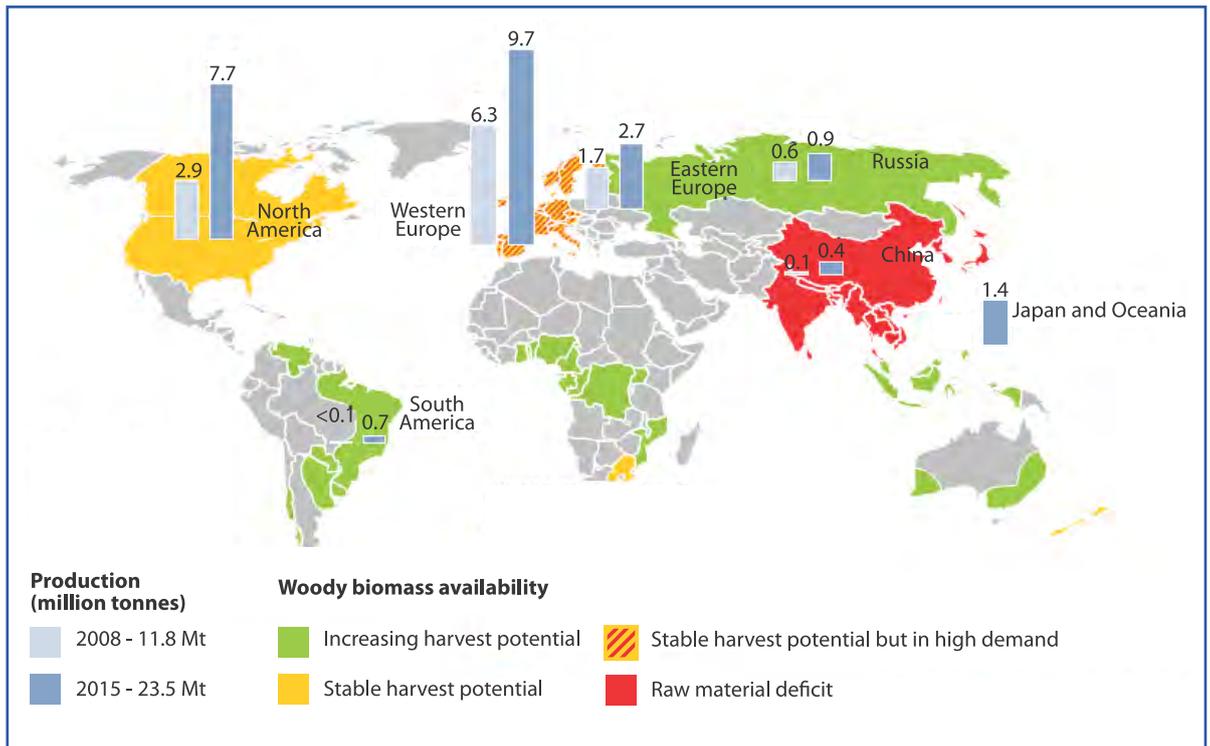
When importing huge amounts of woody biomass for co-combustion, the question of transport cost becomes important. Is it economically more favourable to import pellets or bio-oil? A cost comparison between the two energy carriers produced in Canada and utilised in Holland showed that the resulting electricity prices are about the same, however the investment cost for pellets is far lower.

**Torrefaction:** In order to increase energy density and thus reduce transport costs it might be feasible to torrefy the wood and then make the pellets. This would make sense for existing distant wood supply chains such as from Russia (where all wood residues are required to be removed from the forest). Sawmills utilise only the logs and waste wood is often not utilised. Torrefied pellet production could be integrated to sawmill wood chains.

In North America, especially on the west coast, the major wood flow goes through sawmills. Economic problems in the pulp and paper industry often leave large amounts of wood unutilised. Sawmills could be feasible sites for integrated production of torrefied pellets due to logistics and energy supply. Torrefaction might be particularly interesting in pine beetle affected areas, where more harvesting is required than the market demands. Thermal treatment of pine beetle affected wood is required in any event and this could be achieved by torrefaction or pyrolysis.

The potential for torrefaction or bio-oil production in North America is substantial. The production of sawn wood in softwood sawmills with a capacity of over 50,000 m<sup>3</sup> per year is 73 million m<sup>3</sup> (2008) in the USA and 42 million m<sup>3</sup> in Canada.

<sup>10</sup>IEA Bioenergy ExCo65 Workshop - Wood Pellet Production, K. Kojima. <http://www.ieabioenergy.com/DocSet.aspx?id=6568>



**Figure 19.** Global raw material availability and pellet production, 2008 – 2015.

The same VTT/Pöyry study showed that in North America bio-oil can be produced from 69 sawmills with production based on sawmill chips, bark and sawdust. They have a production potential of 3.9 Mtoe annually. The potential is almost equal in USA and Canada (Table 6). The bio-oil potential in Canada is larger in the wood processing industry than in the pulp and paper industry.

**Table 6:** Bio-oil potential in USA's and Canada's wood industry.

	Number of Units	Capacity GW	Production GWh/a	Production Mtoe/a	Raw material demand GWh/a	Raw material demand 1000 m <sup>3</sup> sub/a
Canada	30	3290	21640	1.9	33300	16700
USA	39	3650	23970	2.1	36870	18400
Total	69	6940	45610	3.9	70170	35100

Even though the study showed that the potential for thermal pre-treated wood is substantial, the supply would not be enough to cover the targeted >5% biomass for co-combustion in coal-fired power plants. In any case, it is questionable whether this is the right way to go in the long run because it simply prolongs the life of coal-fired power plants. New forest industry platforms offer greater benefits for future bioenergy carrier investments in process integration and industrial CHP applications. New green electricity and biofuel production will have the lowest production cost when they are integrated into global forest industry operations at sawmills and pulp and paper mills.

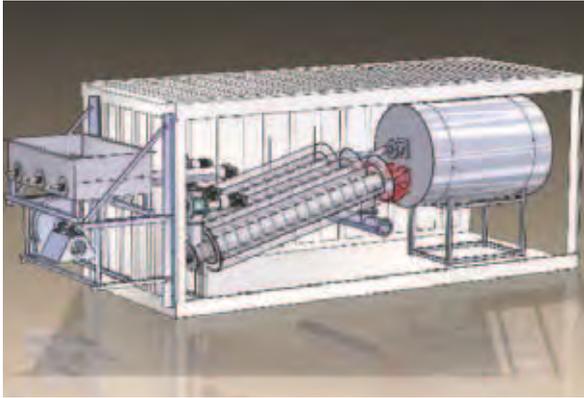
### The Pyrolysis of Biomass to Give us Biochar and Using it as a Soil Improver – Michael Weaver, Pyreg Ltd, Germany

The primary goal of the Pyreg process is the production of a soil improver in the form of charcoal (biochar). The heat produced is a secondary product that is used internally to run the pyrolysis process (indirect heating) and externally e.g. for injection into a small district heating system.

*The process:* The development of the Pyreg process started in 1999 with a conventional down flow gasifier. The actual concept of an inclined gasifier with a double screw was designed in 2005 and first tested in a pilot unit in 2008 on a waste water treatment plant in Germany. The capacity was 40 kg/h of dry matter with a thermal output of 100 kW<sub>th</sub>. A first full-scale plant started operation in November 2009 in Switzerland. The Pyrec 500 plant has been designed for small-scale applications, utilising locally produced biomass and biochar in order to avoid transport costs. The mass flow rate is limited to 1500 t of dry solids per year. The whole plant can be delivered in a 20 feet container with the major components installed at the factory (Figure 20).

Technical specifications are:

- Feedstock - Calorific Power: up to 500 kW per unit
- Feed mass flow: 40-180 kg/h, up to 1200 t/year (dry solids)
- Boundary values: Calorific Value >10 MJ/kg, humidity <100%, particle size <40 mm
- Carbon production (Biochar): up to 350 t/year. (dependent on feedstock)
- Thermal heat capacity: up to 150 kW (dependent on feedstock)
- Electrical power for operation: ca. 3.5 kWel

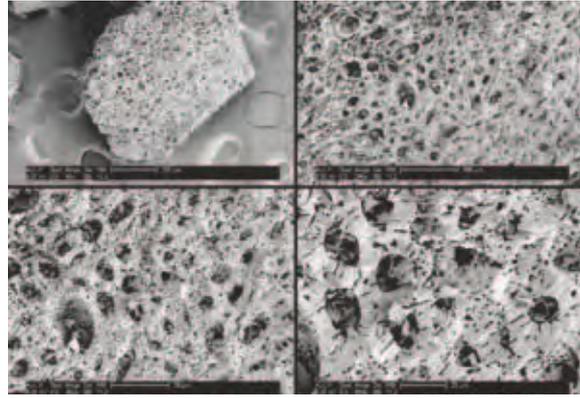


**Figure 20.** Layout of the Pyrec plant.

- Weight ca. 10 t
- Size: 20 feet ISO Container with feeder bin (ca 8m x 2.5m x 2.5m)

The fuel can be made from a variety of materials, for example tree branches, bark, needles, leaves, bio-waste, milling waste, straw, olive stones, nuts, sewage sludge, digestate, *Miscanthus*, etc. However, it must be of reasonably homogeneous character – small sized particles.

The fuel is dosed from the holding tank through a gas tight rotary star valve into the reactor. In the reactor the biomass is transported by two electrically-driven screws and at the same time heated to the reaction temperature of 750°C. It is both indirect heating, using the recovered heat of the flue gases of the boiler, and directly heated by the exothermal reaction of the gasification process. Only a small part (about one-third) of the energy potential of the biomass goes into energy conversion. About two-thirds remain in the carbon (Figure 21 and 22).

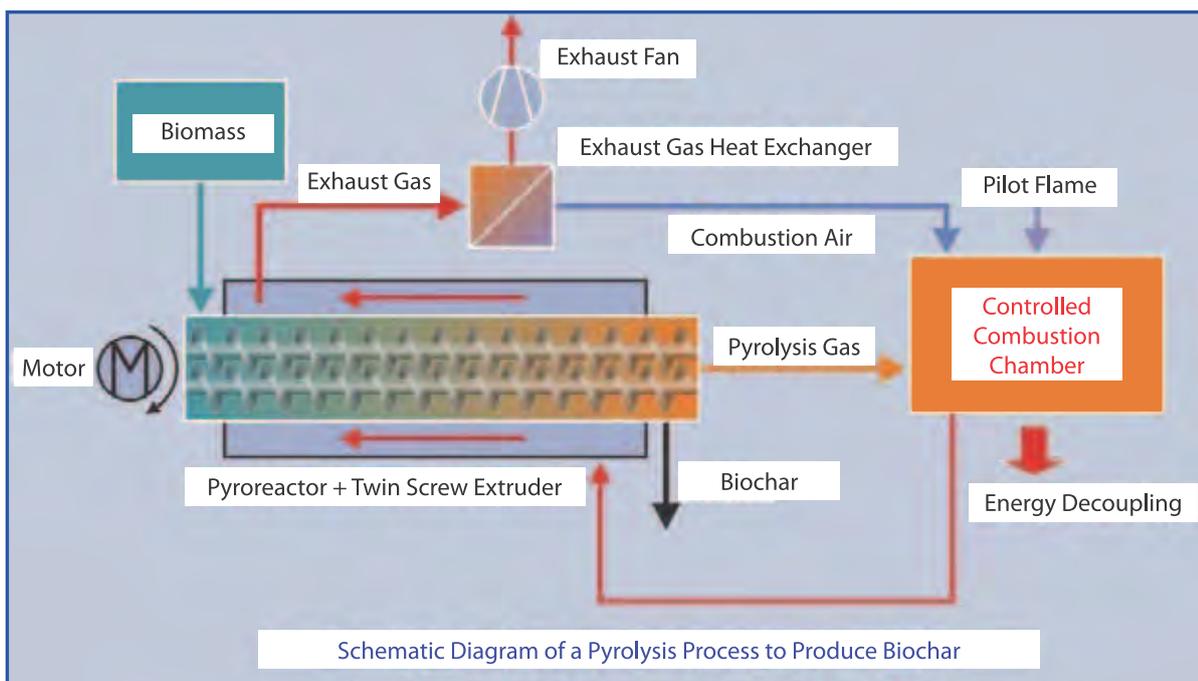


**Photo 1.** Typical molecular sieve structure of a carefully produced biochar.

The pyrolysis gas is used in a burner employing the flameless oxidation process (FLOX®) operated at temperatures between 900-1000°C. The low temperature of the FLOX-process produces extremely low emissions which make further treatment unnecessary.

*Charcoal as a soil improver:* The utilisation of charcoal as a soil improver is not a new development. Its origin dates back some 2000 years when charcoal was used in the Amazonas to improve the soils. The Amazonian black earth gave the name of the product 'Terra Preta'. A similar phenomenon is found in the Ukraine where the dark soil – Chernozem – was formed by the charcoal of numerous prairie fires. The effect of charcoal remains over an extended period of time because it is not degraded and the structure remains intact.

The art of charcoal production is to form particles with a highly porous structure (Photo 1) enabling a high nutrient and water retention capacity. The specific surface of biochar is about 300 m<sup>2</sup> per gram. Best results are achieved with



**Figure 21.** Scheme of a Pyrec 500 plant.

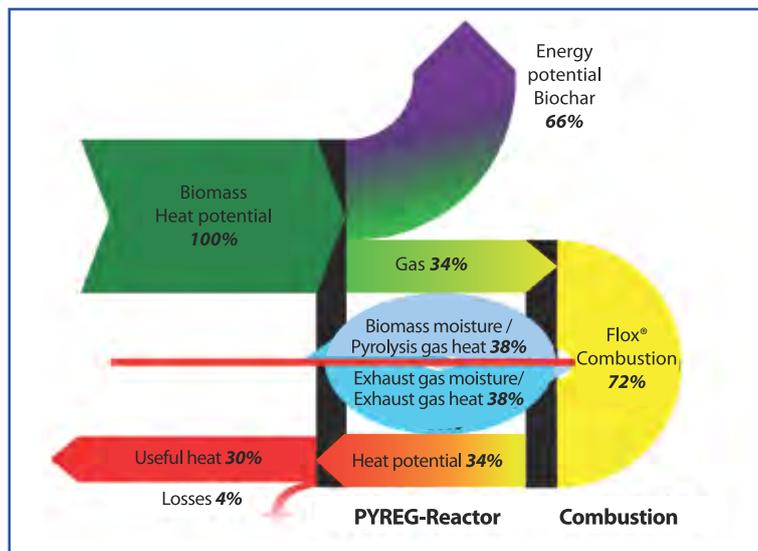
slow pyrolysis at temperatures between 350-500°C. The quality of the char is also dependent on the composition of the biomass. For small-scale units it is recommended to use white pellets in order to avoid emission problems. Lignin-rich woody material produces higher quality char and less ash than cellulose-rich biomass.

The positive effect of charcoal was re-discovered only recently, when experiments were established in Germany. Charcoal has no fertiliser effect by itself, but it has an extremely strong adsorptive power retaining minerals and preventing them from leaching into the ground water. Biochar also demonstrates some buffering capacities against soil acidity. Good charcoal has a fine pore structure allowing plant roots and micro-organisms to penetrate and create equilibrium between mineral production, adsorption, and utilisation.

## SESSION 5: ENVIRONMENTAL BEST OPTIONS

### Life Cycle Assessment of Thermal Processes: Examples for Gasification and Pyrolysis to Transportation Biofuels, Electricity and Heat – Gerfried Jungmeier, Joanneum Research, Austria

Life Cycle Assessment (LCA) is a method of estimating the material and energy flows of a product (e.g. transportation) in order to calculate the environmental effects over the total lifetime of the product from 'cradle-to-grave'. A LCA is always a comparative approach e.g. compare System A to System B providing the same service. A selected (renewable) system – in this case a biomass system – is compared to a reference system (commonly a fossil energy resource) producing the same final energy product.



**Figure 22.** Energy flow in a Pyrec 500 plant of a typical biomass.

Depending on the crop to be planted biochar addition might be in the range of 10-50 tonnes per hectare. Trials with biochar (brand name 'agrchar') demonstrated impressive results on Australian carbon-depleted soils. Crop growth yields doubled and, in one case, tripled when applied at the rate of 10 tonnes per hectare. For wheat, agrchar alone was about as beneficial in terms of yields as using nitrogen fertiliser only<sup>11</sup>. NPK fertilisation was significantly reduced. Mixing with compost materials can further reduce the need for artificial fertiliser.

As well as charcoal, ash is also produced during pyrolysis. Analyses have shown that the quality achieved permits its use as a fertiliser according to German biofertiliser ordinance (Table 7).

**Table 7:** Ash analysis after pyrolysis of sewage sludge.

Polychlorinated Biphenols (PCB)	<0.01 mg/kg (TS)
Halogenated Hydrocarbons (HHC)	<0.01 mg/kg (TS)
Aromats: Benzol, Toluol, Xylol und Ethylbenzol (BTXE)	<0.1 mg/kg (TS)
Polycyclic Aromatic Hydrocarbons (PAH)	0.65 mg/kg (TS)

The LCA methodology has been developed over the last 15-20 years. Today, the method is well established and even standardised (ISO 14040). At the same time large databases have been created containing data on energy use and emissions for a large number of processes. A lack of know-how still exists when it comes to data on direct land use change (dLUC) and indirect land use change (iLUC). Currently there are different assessment approaches for LUC under discussion.

Despite the standardisation, there is still a wide margin to weigh the different variables within a given model (health, environment, plant and animal diversity, land use, etc.)<sup>12</sup>. It

is therefore important, when comparing results calculated with different models, to make sure that comparable weighting factors have been used and the derivation of the result is done within the same limits, i.e. it should start with the resources at their origin and provide the same energy services by using the same allocations of environmental effects to products and by-products (Figure 23). The longer the conversion chain the more complex the LCA. The focus should therefore be on the major contributors to the life cycle effects (sensitivity analysis). A comparison should always include energy and material flows. Key elements of a comparison are the resources used, the pathway to utilisation, and the energy services provided. This sounds trivial but there are a number of questions to be solved on the way, like how to deal with co-products, what to do with residues, or what would happen to the land when it is not used for energy crops (reference scenario).

In the following reference examples the complexity of comparing different energy services within a given process, even when vigorous limitations are applied, is demonstrated.

#### Example 1: SNG from biomass with heat as end product:

In this first example the supply of heat with synthetic natural gas (SNG) from wood or *Miscanthus* is analysed and compared to a fossil fuel boiler (natural gas) and to

<sup>11</sup><http://www.dpi.nsw.gov.au/research/updates/issues/may-2007/soils-offer-new-hope>

<sup>12</sup>IEA Bioenergy ExCo64 Workshop: Algae - the Future for Bioenergy? <http://www.ieabioenergy.com/DocSet.aspx?id=6436>

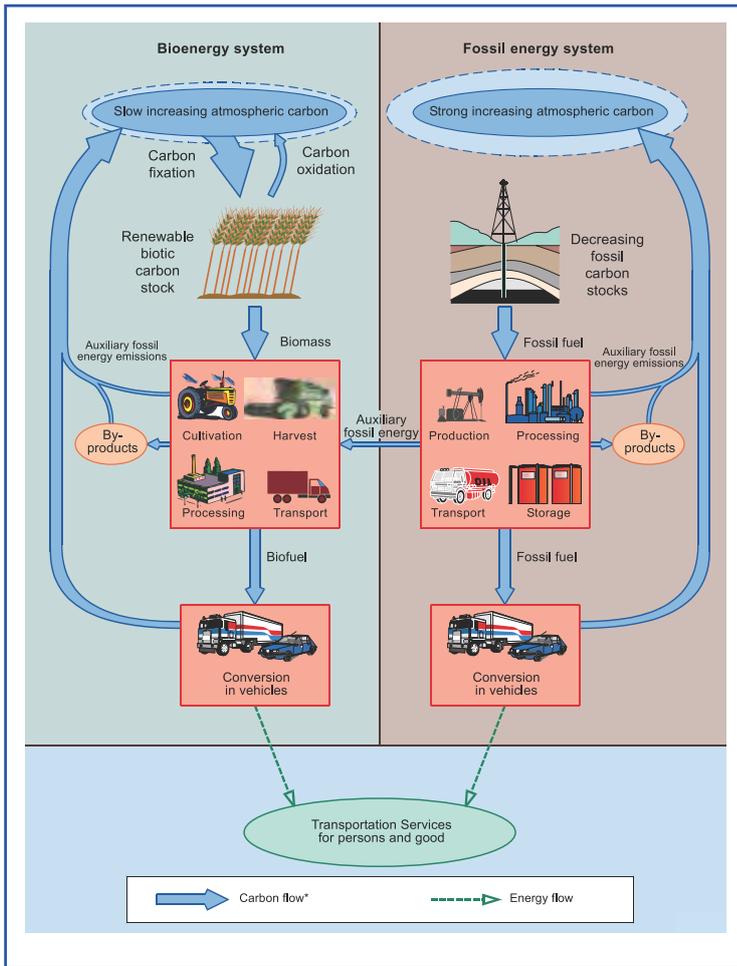


Figure 23. Exemplary development of a LCA.

biomass-fired boilers (forest residues, *Miscanthus* and short rotation forestry).

Three different gasification systems were considered: an oxygen-blown entrained flow system (EF); an oxygen-blown circulating fluidised bed (CFB) or an indirect heated system with air-steam. The latter was considered with and without CCS.

Figure 24 shows the greenhouse gas emissions of all the above mentioned possibilities. The results show that the most important difference in GHG emission expressed as CO<sub>2</sub>-equivalents, including CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O, comes from the feedstock and not from the process. The direct use of wood in a small-scale wood burner in living homes is hardly any different from the various gasification technologies. About 80% of the GHG is emitted during the production of the feedstock. Because the process energy of the considered systems is mainly

derived from renewable energy (only about 10% is of fossil origin) there is no remarkable difference in fossil energy consumption between the technologies. Only when the total primary energy consumption is considered, is the process energy for SNG production up to 30% higher than the direct consumption of wood in a boiler.

**Example 2: SNG for transportation fuels:** In this example the complexity of the comparison is increased because two different renewable systems are compared: 1) fuel produced straight from SNG with some heat (fuel optimised system); and 2) a polygeneration system including fuel, heat and power with a lower efficiency of fuel production but higher production of heat and power. As reference systems natural gas for power and transportation fuel and a pellet boiler for heat production are assumed (Figure 25).

Again, the results show a clear advantage for the renewable systems over the reference system with a reduction of 79% and 89% of GHG for the fuel optimised and the polygeneration systems respectively. The direct comparison of the two renewable systems shows an advantage for the polygeneration system with a 10% higher GHG reduction (Figure 26). The reduction of the cumulated fossil

energy demand is even higher than the GHG reduction with roughly 95%.

**Example 3: Fischer-Tropsch biofuels:** A comparable scenario to the SNG system was calculated for Fischer Tropsch (FT) fuel. A polygeneration system with five smaller production

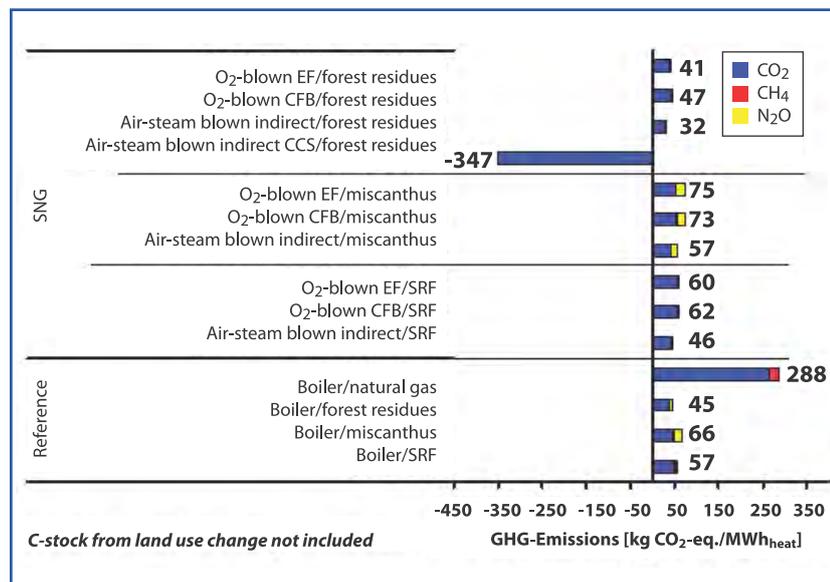


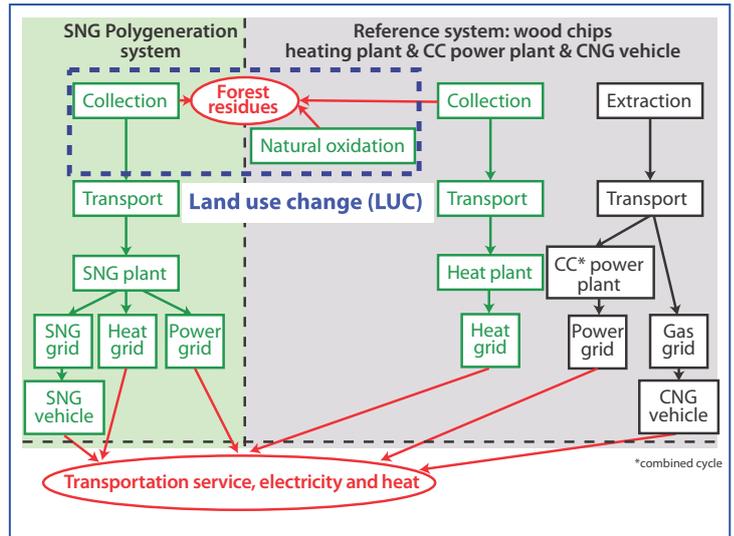
Figure 24. Comparison of GHG emissions by a variety of heat providing technologies.

plants of 100 MW each for FT fuel and heat and a single product plant of 500 MW were compared to a reference system with wood-fired district heating and fossil vehicle fuel. FT fuels included FT diesel and FT gasoline. Two options in the choice of the feedstock were taken into account including forest residues (80%) and wheat straw (20%) and a mixture of wheat, corn and oilseed straw, short rotation forestry and forest residues (Figure 27).

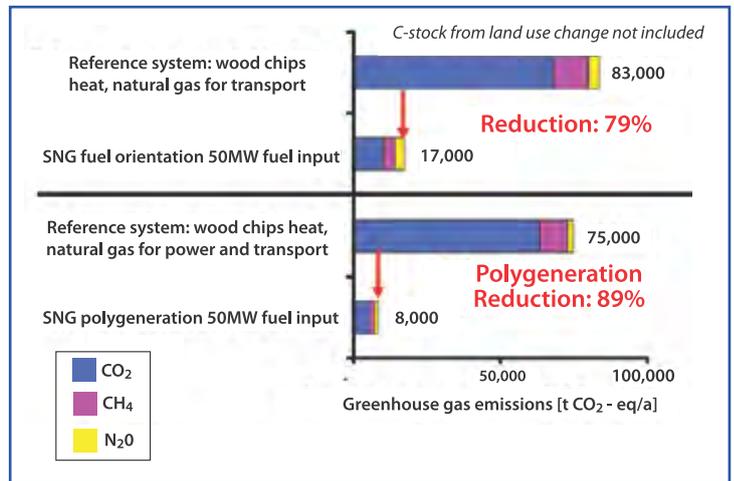
The calculation demonstrates that the differences in GHG emissions between the two FT systems with reduced or extended feedstock composition are marginal. However, the differences with the reference system are significant with an average of 70%. Only particle emissions showed significant differences between all three systems with 90 t/a for the five 100 MW plants, 158 t/a for the single 500 MW FT fuel only plant and 117 t/a for the fossil/wood variant.

**Example 4: Energy systems with bio-oil from pyrolysis:** Two different energy products – heat and electricity – produced with bio-oils were compared with either fossil fuels (natural gas) or different sources of biomass both utilised in a steam and power engine. The biomass was assumed to derive from different sources: forest and industrial residues, short rotation forestry, cereals, stalks and a type of thistle.

The GHG emissions of the bio-oil CHP were more than 90% lower than those of a natural gas powered CHP combined with a boiler for heat. The comparison of the two renewable systems producing heat and power with either pyrolysis oil or more conventionally with a wood-fired power plant demonstrated significantly lower GHG emissions (with the exception of bio-oil from SRF) for the direct



**Figure 25.** Comparison of a polygeneration system and a direct SNG system with natural gas for power and transportation fuel and wood chips for heat.



**Figure 26.** GHG reduction by the SNG systems when compared to conventional production of heat, power and fuel.

**Table 8:** GHG emissions of electricity production with bio-oil compared to emissions of a wood-fired combined power plant (in percentage and absolute values).

	[g CO <sub>2</sub> -eq/kWh]	Bio-oil forest residues	Bio-oil industrial residues	Bio-oil short rotation forests	Bio-oil cereals	Bio-oil stalk	Bio-oil thistle
		75.0	72.8	161.0	190.0	63.3	125.0
Bio-oil forest residues	105	40%	44%	-35%	-45%	66%	-16%
Bio-oil industrial residues	102	36%	40%	-37%	-46%	61%	-18%
Bio-oil short rotation forests	197	163%	171%	22%	4%	211%	58%
Bio-oil cereals	333	344%	357%	107%	75%	426%	166%
Bio-oil stalk	111	48%	52%	-31%	-42%	75%	-11%
Bio-oil thistle	219	192%	201%	36%	15%	246%	75%

use of the solid biomass (Table 8). One of the reasons is that the efficiency loss during pyrolysis cannot be compensated for by higher efficiency of the oil combustion.

**Conclusions:** Calculations of GHG emissions in complex systems of energy production with various types of biomass used in a wide range of thermochemical processes demonstrates that the LCA methodology has matured and is ready to be used. Overall it can be concluded that the GHG emissions of bioenergy systems are lower than the fossil alternatives. The examples given, however, indicate that it is not sufficient to compare a single bioenergy production chain to a single conventional fossil system. It is essential to include other biomass pathways or, even better, combined biomass and fossil pathways.

A few other issues have been highlighted as well, as compiled in Figure 28, e.g. the fact that feedstock production is highly relevant for environmental effects or that the utilisation of by-products is essential for sustainable processes.

## DISCUSSION AND CONCLUSIONS

The workshop gave an excellent overview of the variety of thermal pre-treatment options that are currently available and applied with dry biomass. Wet biomass was not dealt with by the workshop and was only mentioned in Jaap Kiel's introductory overview.

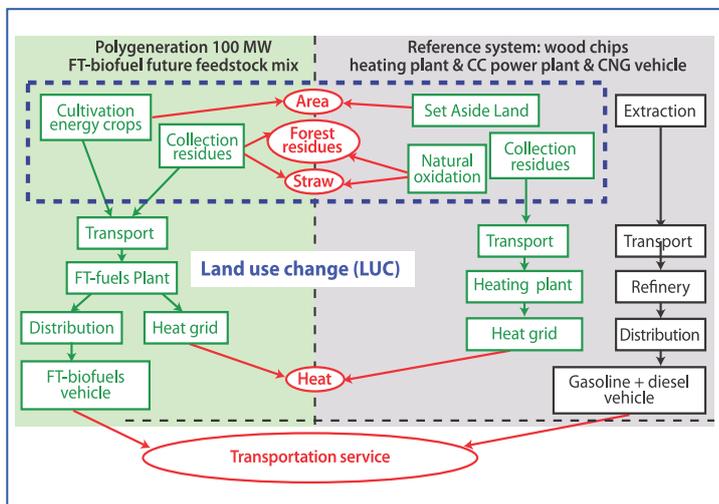
The expectations expressed by some of the speakers were fully supported by the audience, namely that thermal pre-treatment of biomass will become a key step in the chain of formation of energy products. It is not only the volume reduction and energy densification of the intermediate product that is of crucial importance for long distance transport of biomass, it is also the homogenisation of the consistency of raw biomass. Unfortunately, there is no single best pre-treatment for all sources and all products of biomass. The speakers made it clear during discussion that one of the most important decisions for a successful pre-treatment step is to choose the right technology for the biomass source available, in order to achieve a high quality

intermediate or final product that fits the final upgrading or application. However, due to lack of experience with full-scale plants, the speakers were not yet able to indicate which technology best fitted each type of biomass.

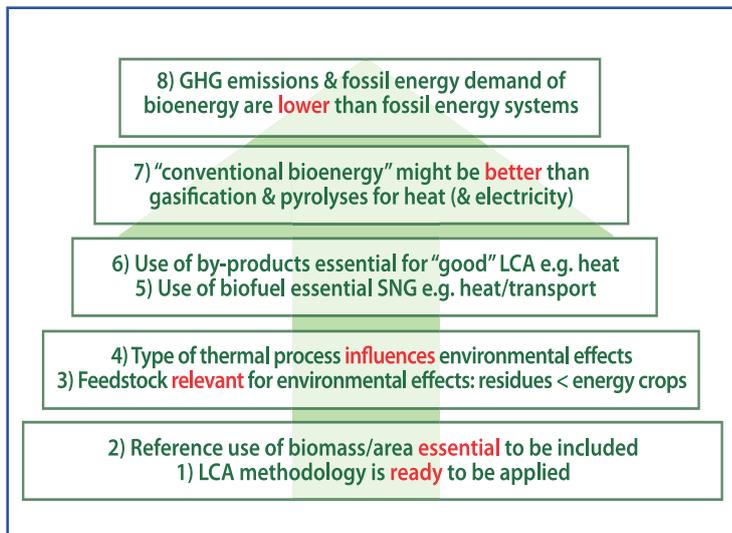
The speakers presented the three basic concepts of torrefaction, pyrolysis and gasification. Within these technologies there is a multitude of applications able to produce gaseous, liquid or solid products. The essential pre-condition for formation of a given product is the need for a well-controlled process. The discussion showed that the decision as to which products should be favoured depends on a number of parameters such as the reason for and goal of the pre-treatment, the market value(s) of the product(s) and the political incentives available. The choice of the governing parameter also dictates the configuration of a plant.

Evidently, not all the processes are at the same level of development. Most of the processes that were discussed are still in a pilot scale, some have made it to demonstration size and only a few are at initial commercial scale. Moreover, as indicated by the speakers, some of the processes will never make it to full application.

Opinion was unanimous that biomass as a feedstock is not the simplest material to deal with. It is difficult to handle because it has low bulk and energy density, high moisture content and has a heterogeneous and complex chemistry.



**Figure 27.** Layout of a 100 MW FT-fuel plant in comparison to wood-fired district heating and conventional petrol and diesel vehicle fuel.



**Figure 28.** Conclusions drawn from model LCAs with bioenergy sources

## Comparison of the Different Technologies

While discussing the different options of pre-treatment the audience continually came back to the question of which technology might be the best at the end of the day with respect to robustness, efficiency and cost. Not surprisingly, none of the speakers were really able to give a definite answer.

The presentations gave the impression that gasification, followed by torrefaction, are currently the two most developed processes, demonstrating some of the first but still small industrial scale installations, followed by a few specific industrial applications of pyrolysis.

## Stages of Development

In gasification technology the development of indirect gasification was cited as the most advanced system, with the Güssing model in Oberwart, Austria with a regular operation time of 8000-plus hours per year. A comparable system will be applied in larger-scale (20 MW) in the Goteborg harbour by Göteborg Energi and E.ON. Another system is the ECN MILENA model which will be first applied in the Netherlands at 50 MW-plus scale. Beside the indirect processes there is also ongoing development of entrained flow gasifiers e.g. by Bioliq (pilot plant) and staged gasification by CarboV that will soon be demonstrated in Germany.

Torrefaction followed by pelletising does not only lead to a densification of the biomass by a factor of about 1.5 but also renders the material hydrophobic which is an important advantage when it comes to stability during transport and storage. ECN, in collaboration with Vattenfall, is one of the leading producers with its  $\text{BO}_2$ -system moving bed plant in pilot operation in the Netherlands. A large-scale co-incineration plant of biochar with black coal in Berlin is in the planning stage. In small-scale torrefaction (500 kW) for the production of biochar as soil conditioner, Pyrec has advanced experience with its first full-scale plants.

Fast pyrolysis is the most promising among about two dozen pyrolysis methods capable of achieving industrial scale. The liquid formed (about 75% of total input in the form of wood) has a high potential for densification by a factor of about 100. According to Tony Bridgwater, there is a limited number of pilot plants in operation e.g. in the USA, Canada and Malaysia with capacities of approximately 100 tpd. The only large-scale pyrolysers in operation are slow processes (Lurgi, Lambiotte). Usine Lambiotte (100,000 t/y of wood) is making most of its income by producing fine chemicals, alcohols and acids while the bulk of products in the form of charcoal have comparatively little value.

Historically, one of the major advantages claimed for pyrolysis processes has been the utilisation of waste material (MSW, tires, plastic, etc.), resulting in reduced costs thanks to the avoidance of gate fees and avoiding the issue of LUC. However, with numerous problems with clean biomass still to be addressed, it was considered that waste was not the first choice of feed stock. In addition, plastic is not a renewable energy, although it could be discounted from the organic waste fraction by  $\text{C}^{14}$  determinations. There is an algorithm developed in the UK which can be used to calculate the share of plastics.

## Efficiency

The question raised by the audience as to which of the technologies would be the most efficient could not be answered per se. The major reason is the lack of practical data from large-scale installations. Most data derive from lab or pilot scale plants without the full pre-treatment chain including energy recovery and final product preparation (pelletising of biochar, etc.). Usually process energy is extrapolated.

For the production of raw pyrolysis oil the data from R&D plants look promising, as indicated by Tony Bridgwater. According to his data only 4% of the mass yield or 10% of the energy yield needs to be re-invested as process energy in a plant that is so-called self-sufficient in heat and power.

The corresponding results for SNG production can be based on a wider set of data including demonstration size installations. A publication of van der Meijd – as cited by Kiel – indicates that in the best case of an indirect gasification operation the production of SNG requires no more than 30% process energy in contrast to circulating fluidised bed and entrained flow gasifiers where 36% and 47% respectively of the biomass energy need to be re-invested as process energy.

However, the quality of the product is another decisive element when process energy is considered. The data given above for pyrolysis and SNG production cannot be compared because the raw oil is the result of the primary pre-treatment whereas SNG can be considered a final product.

## Cost

As with the other parameters there are only rough estimations for production costs available as long as there is no industrial-scale experience to draw on. However, initial figures show that, as with all industrial technologies, there is a strong dependence on economy of scale.

Extrapolations by Tony Bridgwater for pyrolysis plants indicated that only sizes above 200,000 t/y of product seem to have reasonably low specific capex costs. Resulting production costs of FT fuels would be in the order of €80/GJ for a 100,000 t/a FT plant assuming that pre-treatment would be done in decentralised pyrolysis plants followed transport and central gasification and FT transformation. This cost can be reduced to at least €30/t at sizes of 1 million t/a. Centralised pyrolysis would allow a reduction in production costs by an additional 25%.

The joint Metso, UPM, Fortum and VTT project has successfully demonstrated the integration of a fast pyrolysis unit into a fluidised bed boiler in pulp and paper mills to replace fossil fuel. Because of limited resource availability they assumed that the biomass would be imported either from North-Western Russia or from Eastern Canada in the form of wood pellets or pyrolysis oil. It was interesting to realise that there is hardly any price difference between wood pellet and pyrolysis oil utilisation. However, the transport distance makes a big difference. Both pellets and bio-oil were at around €20/MWh from Russia and €95/MWh from Canada hence at least in the same order of magnitude as oil at the spot market.

However, the price for the two processes, FT and co-incineration will be higher if the cost for the woody biomass feed has to be taken into account. In fact this amounts to close to €70 per metric ton of product.

There was also the question of whether a process such as gasification followed by methanation and injection into the grid or co-incineration of pyrolysis oil would be preferable over FT production because of reduced cost. The speakers accepted that the FT technology was expensive but nevertheless considered it as a valuable option. For initial cost reductions they opted rather to narrow down the sources of biomass for a given process in order to avoid multiple feeding and treatment chains leading to complex process designs.

### Size of Plants

The argument that FT plants would have to be bigger than other systems was not accepted. MeOH and DME plants are being built in the same sizes. In any case, no one really defined what large means. Even a 300 MW plant referred to in Finland might be considered small when compared to economically interesting pyrolysis plants of 1 million tons of product per year, corresponding to more than 600 MW or even a conventional refinery of some 10 GW. But it is big when compared to the planned GoBiGas plant of only 20 MW.

### Specification of Substrates

There was some debate over the quality of biomass needed for the different technologies. According to the experts it is particularly important for gasification processes to specify the quality and the moisture content of the biomass. The less variation, the lower the investment and operational cost.

However, even for co-combustion the quality of the wood pellets seems to be important. The technology for white pellets is considered as mature whereas the utilisation of black pellets with higher ash contents still needs development. The ash content is also important for torrefaction. Small-scale units such as Pyrec's are entirely operated with white pellets. Ash might not only disturb the process but with its high mineral content should also be recycled to land, to close the cycle.

There was some discussion whether torrefaction is an endothermic or exothermic process. The classic theory claims that torrefaction is an endothermic process, however more recent results seem to indicate that it might be slightly exothermic. There appear to be two phases. At first energy has to be invested up to a temperature of about 250°C, above that, up to 450°C the reaction is clearly exothermic. However, in any event, careful heat recovery is needed.

There were some doubts about the need for a soil improver instead of energy production. With the current state of research in Germany, Austria and Australia, a definitive answer is not yet possible. Initial results indicate that biochar has a positive effect, especially when combined with compost. Whether it could also help to remediate soils or even be used as a carbon sink (sequestration) still has to be verified.

The possibility of using waste material was considered to be one of the big advantages of pyrolysis. The waste might yield some gate fees and it does not create LUC. Most experts warned of too much optimism because there is no proven long-term experience. While waste can be processed, it needs to be separated and pre-treated carefully. Intermediate pyrolysis as a pre-treatment step is not so much dependent on particle size but is very susceptible to glass remaining in the waste fraction. There has been some research and development experience on the subject at the University of Hamburg, Germany, and also a company focusing on pyrolysis of plastic from a MURPH plant. But plastic does not seem to be the first choice for the process. PVC has to be completely avoided. Above all, plastic is not renewable. However, if used together with biomass from waste the renewable part can be defined by C<sup>14</sup> determinations in the stack gas.

In conclusion, the development of thermal pre-treatment was considered an important pre-requisite for the transport, and therefore for the whole development, of biomass applications. It is of particular interest to importing regions like Europe. It is therefore no surprise that industry in European countries is pushing development and starting to build the first industrial sized plants.

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Arthur Wellinger prepared the draft text. John Tustin, the Secretary, and Danielle Rickard facilitated the editorial process and arranged the final design and production.

## IEA Bioenergy

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