# Review of Technologies for Gasification of Biomass and Wastes

## Final report

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## Glossary

**Main terms:**

| | |
|---|---|
| BTL | Biomass-To-Liquids |
| FT | Fischer-Tropsch |
| HAS | Higher Alcohol Synthesis |
| WGS | Water Gas Shift |
| MSW | Municipal Solid Waste |
| WTE | Waste To Energy |
| RDF | Refuse Derived Fuel |
| CHP | Combined Heat and Power |
| IGCC | Integrated Gasification Combined Cycle |
| BIG-GT | Biomass Integrated Gasifier-Gas Turbine |

**Gasifier types:**

| | |
|---|---|
| EF | Entrained Flow |
| BFB | Bubbling Fluidised Bed |
| CFB | Circulating Fluidised Bed |
| Dual | Dual Fluidised Bed |

**Units:**

| | |
|---|---|
| ppm | parts per million, by mass |
| ppmv | parts per million, by volume |
| ppb | parts per billion, by volume |
| odt | oven dried tonnes |
| t | wet tonnes |
| kW | kilowatt |
| MW | megawatt |
| $MW_{th}$ | megawatts thermal |
| $MW_e$ | megawatts electric |
| LHV | Lower Heating Value |
| HHV | Higher Heating Value |

**Chemical key:**

| | |
|---|---|
| $H_2$ | hydrogen |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| $H_2O$ | water |
| $CH_4$ | methane |
| $C_2H_2$ | acetylene |
| $C_{2+}$ | higher hydrocarbons |
| $CH_3OH$ | methanol |
| $N_2$ | nitrogen |
| HCN | hydrogen cyanide |
| $NH_3$ | ammonia |
| $NO_x$ | nitrous oxides |
| COS | carbonyl sulphide |
| $H_2S$ | hydrogen sulphide |
| $CS_2$ | carbon bisulphide |
| HCl | hydrogen chloride |
| Br | bromine |
| F | fluorine |
| Na | sodium |
| K | potassium |
| $SiO_2$ | silica |
| Co | cobalt |
| Cu | copper |
| Fe | iron |
| Ni | nickel |
| As | arsenic |
| P | phosphorous |
| Pb | lead |
| Zn | zinc |
| ZnO | zinc oxide |
| $Al_2O_3$ | aluminium oxide |
| Cr | chromium |
| $Cr_2O_3$ | chromium oxide |
| $MoS_2$ | molybdenum sulphide |

# 1 Introduction

## 1.1 Background

Recognising the limitations of many current biofuel production technologies, in terms of resource potential, greenhouse gas savings and economic viability, there is considerable interest in second generation routes. These offer the potential for a wider range of feedstocks to be used, lower greenhouse gas impacts, and lower costs. Gasification is an important component of several of the proposed second generation routes, such as catalytic routes to diesel, gasoline, naphtha, methanol, ethanol and other alcohols, and syngas fermentation routes to ethanol. Many of the component technologies for some of these routes, such as feedstock preparation, gasification, and Fischer-Tropsch or methanol synthesis are commercially viable or technically mature for other applications. However, the systems as a whole are at the early demonstration stage worldwide, with further development and learning needed to achieve commercially viable fuel production. In biomass gasification itself, there is greater experience with gasifiers for heat and power applications than for fuels production.

As a result, NNFCC commissioned E4tech to provide a review of current and emerging gasifier technologies that are suitable for liquid fuel production from syngas, including their type, characteristics, status, prospects and costs, together with their suitability for the UK, in terms of suitable feedstocks and scales.

## 1.2 Approach

This project aims to provide a consistent comparison of gasification technologies suitable for liquid fuels production in the UK. This is achieved through:

- **Assessing the needs of syngas using technologies (Section 2).** In order to establish which gasifiers could be suitable for liquid fuels production, we first established the requirements of the different technologies that will use the syngas produced. This analysis is then used to narrow down the generic gasifier types covered in the rest of the report
- **Providing a review of current and emerging specific gasifier technologies (Section 3).** In this section, we review gasifier technologies that are currently commercially available, or planned to be available in the short-medium term, for biomass feedstocks relevant to the UK. Further details on each gasifier are given in the annex
- **Comparing generic types of gasifier (Section 4)** to assess their status, feedstock requirements, scale and costs
- **Drawing conclusions (Section 5)** on which generic types might be most suitable for fuel production in the UK

## 1.3 Introduction to gasification and fuel production

Gasification is a process in which a solid material containing carbon, such as coal or biomass, is converted into a gas. It is a thermochemical process, meaning that the feedstock is heated to high temperatures, producing gases which can undergo chemical reactions to form a synthesis gas. This 'syngas' mainly contains hydrogen and carbon monoxide, and can then be used to produce energy or a range of chemicals, including liquid and gaseous transport fuels. The gasification process follows several steps[1], explained below - for the full set of reaction equations, see[2]:

- Pyrolysis vaporises the volatile component of the feedstock (devolatilisation) as it is heated. The volatile vapours are mainly hydrogen, carbon monoxide, carbon dioxide, methane, hydrocarbon gases, tar, and water vapour. Since biomass feedstocks tend to have more volatile components (70-86% on a dry basis) than coal (around 30%), pyrolysis plays a larger role in biomass gasification than in coal gasification. Solid char and ash are also produced
- Gasification further breaks down the pyrolysis products with the provision of additional heat:
    - Some of the tars and hydrocarbons in the vapours are thermally cracked to give smaller molecules, with higher temperatures resulting in fewer remaining tars and hydrocarbons
    - Steam gasification - this reaction converts the char into gas through various reactions with carbon dioxide and steam to produce carbon monoxide and hydrogen
    - Higher temperatures favour hydrogen and carbon monoxide production, and higher pressures favour hydrogen and carbon dioxide production over carbon monoxide[3]
- The heat needed for all the above reactions to occur is usually provided by the partial combustion of a portion of the feedstock in the reactor with a controlled amount of air, oxygen, or oxygen enriched air[4]. Heat can also be provided from external sources using superheated steam, heated bed materials, and by burning some of the chars or gases separately. This choice depends on the gasifier technology
- There are then further reactions of the gases formed, with the reversible water-gas shift reaction changing the concentrations of carbon monoxide, steam, carbon dioxide and hydrogen within the gasifier. The result of the gasification process is a mixture of gases

There is considerable interest in routes to liquid biofuels involving gasification, often called thermochemical routes or biomass-to-liquids (BTL), as a result of:

- The potential for thermochemical routes to have **low costs, high efficiency, and high well-to-wheel greenhouse gas savings**. Use of a range of low cost and potentially low greenhouse gas impact feedstocks, coupled with an efficient conversion process, can give low cost and low greenhouse gas emissions for the whole fuel production chain
- The potential ability of gasifiers to accept a **wider range of biomass feedstocks** than biological routes. Thermochemical routes can use lignocellulosic (woody) feedstocks, and wastes, which cannot be converted by current biofuel production technologies. The resource availability of these feedstocks is very large compared with potential resource for current biofuels feedstocks. Many of these feedstocks are also lower cost than current biofuel feedstocks, with some even having negative costs (gate fees) for their use

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[1] Boerrigter, H. & R. Rauch (2006) "Review of applications of gases from biomass gasification", ECN Research
[2] Opdal, O.A. (2006) "Production of synthetic biodiesel via Fischer-Tropsch synthesis: Biomass-To-Liquids in Namdalen, Norway", Norwegian University of Science and Technology thesis
[3] Haryanto et al. (2009) "Upgrading of syngas derived from biomass gasification: A thermodynamic analysis" Biomass & Bioenergy 33, 882-889
[4] Juniper (2007) "Commercial Assessment: Advanced Conversion Technology (Gasification) For Biomass Projects", report for Renewables East

- The production of fuels with **improved fuel characteristics** compared with today's biofuels. Whilst some thermochemical routes produce the same fuel types as current biofuels routes, such as ethanol, others can produce fuels with characteristics more similar to current fuels, including higher energy density
- The potential ability of gasifiers to accept **mixed and variable feedstocks**: mixtures of feedstock types, and feedstocks that vary in composition over time. Biological routes to fuels using lignocellulosic feedstocks, such as hydrolysis and fermentation to ethanol, involve pre-treatment steps and subsequent biological processes that are optimised for particular biomass types. As a result, many of these routes have a limited ability to accept mixed or variable feedstocks such as wastes, at least in the near term. The ability to use mixed and variable feedstocks may be an advantage of thermochemical routes, through the potential for use of low cost feedstocks, and the ability to change feedstocks over time

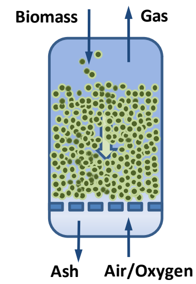
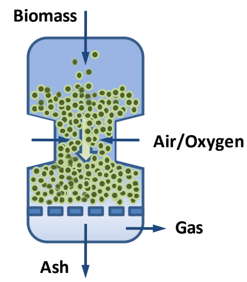
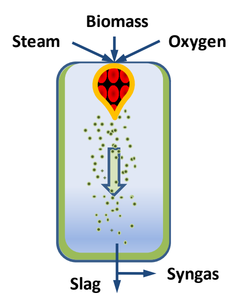
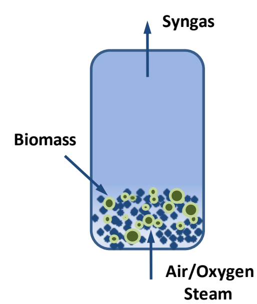
### 1.4 Introduction to gasifier types

There are several different generic types of gasification technology that have been demonstrated or developed for conversion of biomass feedstocks. Most of these have been developed and commercialised for the production of heat and power from the syngas, rather than liquid fuel production. The principal types are shown in the figures below, with the main differences being:

- How the biomass is fed into the gasifier and is moved around within it – biomass is either fed into the top of the gasifier, or into the side, and then is moved around either by gravity or air flows
- Whether oxygen, air or steam is used as an oxidant – using air dilutes the syngas with nitrogen, which adds to the cost of downstream processing. Using oxygen avoids this, but is expensive, and so oxygen enriched air can also be used
- The temperature range in which the gasifier is operated
- Whether the heat for the gasifier is provided by partially combusting some of the biomass in the gasifier (directly heated), or from an external source (indirectly heated), such as circulation of an inert material or steam
- Whether or not the gasifier is operated at above atmospheric pressure – pressurised gasification provides higher throughputs, with larger maximum capacities, promotes hydrogen production and leads to smaller, cheaper downstream cleanup equipment. Furthermore, since no additional compression is required, the syngas temperature can be kept high for downstream operations and liquid fuels catalysis. However, at pressures above 25 – 30bar, costs quickly increase, since gasifiers need to be more robustly engineered, and the required feeding mechanisms involve complex pressurising steps

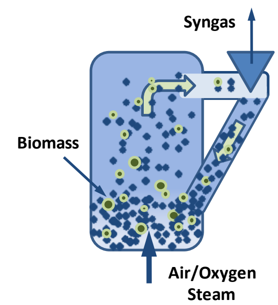
**Table 1: Gasifier types**

Note that biomass particles are shown in green, and bed material in blue

| | |
|---|---|
| **Updraft fixed bed**<br>• The biomass is fed in at the top of the gasifier, and the air, oxygen or steam intake is at the bottom, hence the biomass and gases move in opposite directions<br>• Some of the resulting char falls and burns to provide heat<br>• The methane and tar-rich gas leaves at the top of the gasifier, and the ash falls from the grate for collection at the bottom of the gasifier |   |
| **Downdraft fixed bed**<br>• The biomass is fed in at the top of the gasifier and the air, and oxygen or steam intake is also at the top or from the sides, hence the biomass and gases move in the same direction<br>• Some of the biomass is burnt, falling through the gasifier throat to form a bed of hot charcoal which the gases have to pass through (a reaction zone)<br>• This ensures a fairly high quality syngas, which leaves at the base of the gasifier, with ash collected under the grate |   |
| **Entrained flow (EF)**<br>• Powdered biomass is fed into a gasifier with pressurised oxygen and/or steam<br>• A turbulent flame at the top of the gasifier burns some of the biomass, providing large amounts of heat, at high temperature (1200-1500°C), for fast conversion of biomass into very high quality syngas<br>• The ash melts onto the gasifier walls, and is discharged as molten slag |   |
| **Bubbling fluidised bed (BFB)**<br>• A bed of fine inert material sits at the gasifier bottom, with air, oxygen or steam being blown upwards through the bed just fast enough (1-3m/s) to agitate the material<br>• Biomass is fed in from the side, mixes, and combusts or forms syngas which leaves upwards<br>• Operates at temperatures below 900°C to avoid ash melting and sticking. Can be pressurised |   |

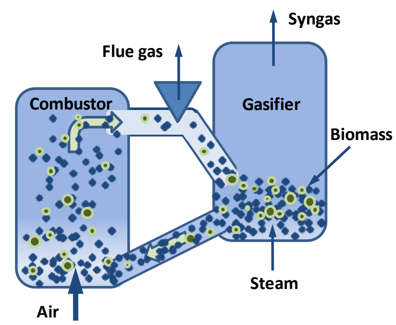
**Circulating fluidised bed (CFB)**

- A bed of fine inert material has air, oxygen or steam blown upwards through it fast enough (5-10m/s) to suspend material throughout the gasifier
- Biomass is fed in from the side, is suspended, and combusts providing heat, or reacts to form syngas
- The mixture of syngas and particles are separated using a cyclone, with material returned into the base of the gasifier
- Operates at temperatures below 900°C to avoid ash melting and sticking. Can be pressurised



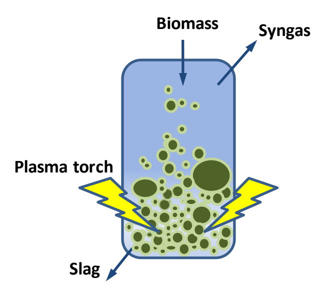

**Dual fluidised bed (Dual FB)**

- This system has two chambers – a gasifier and a combustor
- Biomass is fed into the CFB / BFB gasification chamber, and converted to nitrogen-free syngas and char using steam
- The char is burnt in air in the CFB / BFB combustion chamber, heating the accompanying bed particles
- This hot bed material is then fed back into the gasification chamber, providing the indirect reaction heat
- Cyclones remove any CFB chamber syngas or flue gas
- Operates at temperatures below 900°C to avoid ash melting and sticking. Could be pressurised




**Plasma**

- Untreated biomass is dropped into the gasifier, coming into contact with an electrically generated plasma, usually at atmospheric pressure and temperatures of 1,500-5,000°C
- Organic matter is converted into very high quality syngas, and inorganic matter is vitrified into inert slag
- Note that plasma gasification uses plasma torches. It is also possible to use plasma arcs in a subsequent process step for syngas clean-up




**Note on units and assumptions used in this report**

Throughout the report, oven dried tonnes (odt) of biomass input are used as the principal unit for comparison. Therefore, for some plants we have had to make assumptions about the feedstock moisture content in order to make direct comparisons, such as in Figure 3. The manufacturer's original units are given alongside the odt conversion in the annexes. Inputs (in odt) can be converted to energy units by using the energy content of the biomass. For example, wood contains around 18 GJ/odt, hence a gasifier that takes in 48odt/day of wood has a 10$MW_{th}$ input

Throughout the report, unless specified, gasification plants are assumed to operate at 90% availability

# 2 Syngas conversion to liquid fuels

## 2.1 Introduction

There are four principal uses of syngas that are currently being explored for production of liquid fuels:

- Fischer-Tropsch synthesis, a chemical catalytic process that has been used since the 1920s to produce liquid fuels from coal-derived syngas and natural gas
- Methanol synthesis, also a chemical catalytic process currently used to produce methanol from syngas derived from steam reformed natural gas or syngas from coal
- Mixed alcohols synthesis, a chemical catalytic process that produces a mixture of methanol, ethanol, propanol, butanol and smaller amounts of heavier alcohols
- Syngas fermentation, a biological process that uses anaerobic microorganisms to ferment the syngas to produce ethanol or other chemicals

Each process has different requirements in terms of the composition of syngas input to the process, and the scale of syngas throughput needed to allow the process to be commercially viable. In this section, we describe each of these processes' requirements, and establish which types of gasifier might be able to meet them. A summary of the requirements and their implications is given at the end of the section. Note that all the data in the text is given in the summary table, with references provided in Section 7.

## 2.2 Fischer-Tropsch synthesis

In Fischer-Tropsch (FT) synthesis, the hydrogen ($H_2$) and carbon monoxide (CO) in the syngas are reacted over a catalyst to form a wide range of hydrocarbon chains of various lengths. The catalysts used are generally iron or cobalt based. The reaction is performed at a pressure of 20–40 bar and a temperature range of either 200-250˚C or 300-350˚C. Iron catalysts are generally used at the higher temperature range to produce olefins for a lighter gasoline product. Cobalt catalysts are used at the lower temperature range to produce waxy, long-chained products that can be cracked to diesel. Both of these catalysts can be used in a range of different reactor types (fixed bed, slurry reactor etc)[5] – for example, CHOREN use a cobalt catalyst in a fixed bed reactor, developed by Shell, to produce FT diesel.

The main requirements for syngas for FT synthesis are:

- The correct ratio between $H_2$ and CO. When using cobalt catalysts, the molar ratio of $H_2$ to CO must be just above 2. If the syngas produced by the gasifier has a lower ratio, an additional water-gas shift (WGS) reaction is the standard method of adjusting the ratio, through reacting part of the CO with steam to form more $H_2$. Iron catalysts have intrinsic WGS activity, and so the $H_2$ to CO ratio need not be as high. The required ratio can be between 0.6 and 1.7 depending on the presence of catalyst promoters, gas recycling and the reactor design
- Very low sulphur content (of the order of 10-100 ppb). Sulphur causes permanent loss of catalyst activity, and so reduces catalyst lifetimes. There is a trade-off here between the additional costs of gas cleaning, and the catalyst lifetime. In general, S, Cl, and N compounds are detrimental to

[5] P.L. Spath and D.C. Dayton (2003) "Preliminary Screening — Technical and Economic Assessment of Synthesis Gas to Fuels and Chemicals with Emphasis on the Potential for Biomass-Derived Syngas" NREL

catalytic conversion; hence it is desirable to employ wet scrubbing to completely remove these contaminants. Cobalt catalysts have higher activities than iron catalysts, but are more expensive and have lower contaminant tolerances

- Removal, to concentrations of less than 10's of ppb, of tars with dewpoints below the catalyst operating temperature. These heavier tars would condense onto surfaces, reducing the catalyst surface area and lifetimes. While this is a serious problem with fixed bed catalysts, slurry bed reactors can tolerate traces of aromatics without any serious problems
- Low proportion of non-reactive gases, such as nitrogen and methane, which increase the size and cost of equipment needed

CHOREN, one of the leading developers of biomass to liquids via the FT route, estimate that the minimum economic scale for an FT plant would be around half of the scale of their Sigma plant, which corresponds to 100,000 t/yr BTL fuel output, or around 1,520 odt/day biomass input[6]. However, there are also newer process technologies in development that could reduce this minimum economic scale. For example, the Velocys technology recently acquired by Oxford Catalysts has been estimated to allow FT catalysts to be viable at outputs of 500 to 2000 barrels/day[7], which would correspond to biomass inputs of 300 – 1220 odt/day.

### 2.3 Methanol synthesis

Methanol production from syngas involves reacting CO, $H_2$ and a small amount of $CO_2$ over a copper-zinc oxide catalyst. The reaction proceeds via the water gas shift reaction, followed by hydrogenation of $CO_2$. The process is carried out at 220˚C-300˚C and 50-100bar, with the raw products fed into a distillation plant to recycle unused syngas, volatiles, water and higher alcohols back to the reactor.

Methanol synthesis has a very high catalyst specificity, and since the syngas C–O bond remains intact, only involves a few simple chemical reactions compared to the complex reactions in an FT or mixed alcohols process. The main requirements for syngas for methanol synthesis are:

- The relative quantities of $H_2$, CO and $CO_2$. The stoichiometric ratio of ($H_2$-$CO_2$) to (CO+$CO_2$) should be greater than 2 for gas reactions using alumina supported catalysts, and around 0.68 for slurry based reactors. As an example, 11 molecules of $H_2$ and 4 molecules of CO to 1 molecule of $CO_2$ gives a stoichiometric ratio of 2
- Removal, to concentrations of less than 10's of ppb, of tars with dewpoints below the catalyst operating temperature
- Avoidance of alkalis and trace metals, which can promote other reactions, such as FT and mixed alcohols synthesis

Methanol synthesis has similar syngas cleanup requirements to FT synthesis, and overall biomass to methanol plant efficiencies are generally similar to FT plants[8]. The minimum economic scale is also of

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[6] Pers. comm. CHOREN. Sigma plant scale taken from Kiener, C. (2008) "Start up of the first commercial BTL production facility ", Valencia, with biomass input of 1 Modt/yr at 90% plant availability, producing 200,000 t/yr of BTL fuel output, equivalent to 5000 barrels/day

[7] Tonkovich et al (2008) "Improved FT economics", Velocys. Converted from barrels/day output to odt/day biomass input by comparison with CHOREN's Sigma plant 5,000 barrels/day output, and 3,044odt/day input

[8] Brown, R. (2006) "Renewable Fuels From Biomass and More", Engineers for a Sustainable World Conference

the order of a few hundred tons/day output[9], i.e. around 100,000 t/year methanol output, equating to a biomass input of 1,520 odt/day. The new process technologies in development for FT would also be applicable to methanol catalysts.

### 2.4 Mixed alcohols synthesis

Mixed alcohols synthesis, also known as Higher Alcohol Synthesis (HAS) is very similar to both FT and methanol synthesis. It often uses catalysts modified from those processes, with added alkali metals to promote the mixed alcohols reaction. The process produces a mixture of alcohols such as methanol, ethanol, propanol, butanols and some heavier alcohols. We have considered four processes here; two based on methanol catalysts, and two based on FT catalysts (one as an alkali-doped sulphide catalyst[10]). The requirements for syngas are very similar to the parent processes, except that the $H_2$ to CO ratio must be 1-1.2; hence the need for a water-gas shift reaction during syngas conditioning is reduced. Also, for the sulphide catalyst, some sulphur (between 50-100ppmv) is actually required in the syngas, rather than needing to be removed[11].

Since the catalysts and reactors are based on FT or methanol technology, and due to the very similar requirements in syngas clean up to FT and methanol synthesis, the minimum economic scale for mixed alcohols synthesis is expected to be similar to that of FT synthesis, corresponding to 100,000 t/yr BTL fuel output, or 1,520 odt/day biomass input.

### 2.5 Syngas fermentation

A variety of microorganisms can use syngas as an energy and carbon source to produce ethanol, with some forming butanol, acetate, formate and butyrate[12]. These include *Acetobacterium woodii, Butyribacterium methylotrophicum, Clostridium carboxidivorans P7, Eubacterium limosu, Moorella and Peptostreptococcus productus*[13]*.* Current syngas fermentation efforts are predominantly focused on ethanol production. The process operates at low pressures (atmospheric to 2 bar) and low temperatures (most use near 37°C, although some species can survive and grow in temperatures ranging from 5°C to 55°C), with the exact reactor conditions and pH depending on the type of microorganism used.

The main requirement for syngas for fermentation is the avoidance of tars or hydrocarbons (to within a similar level as for FT synthesis), as they inhibit fermentation and adversely affect cell growth. The biological process is not sensitive to many of the other requirements for the chemical catalytic processes, and most of the above organisms grow better on CO than $H_2$. As a result, the syngas $H_2$ to CO ratio can be low, i.e. a water-gas shift reaction after gasification is not needed. However, many of these requirements, such as the tolerance to sulphur, will depend on the particular type of organism used.

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[9] Pers. comm. Haldor Topsoe
[10] Pamela Spath and David Dayton (2003) "Bioproducts from Syngas"
[11] P.L. Spath and D.C. Dayton (2003) "Preliminary Screening — Technical and Economic Assessment of Synthesis Gas to Fuels and Chemicals with Emphasis on the Potential for Biomass-Derived Syngas" NREL
[12] Curt R. Fischera, Daniel Klein-Marcuschamera and Gregory Stephanopoulos (2008) "Selection and optimization of microbial hosts for biofuels production" Metabolic Engineering, Vol 10, Issue 6, pp 295-304
[13] Anne M Henstra , Jan Sipma, Arjen Rinzema and Alfons JM Stams (2007) "Microbiology of synthesis gas fermentation for biofuel production" doi:10.1016/j.copbio.2007.03.008

The minimum economic scale for syngas fermentation is expected to be considerably smaller than conventional FT processes, at around 30,000 t/yr ethanol output[14], which corresponds to 290 odt/day biomass input[15].

## 2.6 Summary

As shown in Table 2, the different syngas conversion routes have different efficiencies, of which there are several measures:

- Thermal efficiency: the energy content of the desired liquid(s) divided by the energy content of the syngas input to the reactor
- Syngas CO conversion: % of the CO in the syngas that is reacted in a single pass, or with recycling
- Selectivity: the proportion of the products that are in the desired range

**Table 2: Syngas to liquids efficiency[16]**

| Name | Thermal efficiency | Syngas CO conversion | Selectivity |
|---|---|---|---|
| Fischer-Tropsch synthesis | ~60% [17] | Able to achieve 50-90% conversion of CO in the syngas with recycling of the off-gas back into the catalyst input stream | The gasoline product fraction has a maximum selectivity of 48% (using a Fe catalyst), although under actual process conditions is only 15-40%. The maximum selectivity of the diesel product fraction is closer to 40% (using Co) |
| Methanol synthesis | ~79% [18] | Per pass, the maximum conversion is 25%, although actual values are only 4-7%. Can convert 99% of the syngas to methanol with recycling | >99.5% selectivity for methanol |
| Mixed alcohols synthesis | 62-68% [19] | Single pass conversions are generally 10-40%, but producing mainly methanol[20] | Selectivity to methanol, ethanol and higher alcohols varies due to hydrocarbon production, but on a $CO_2$ free basis is in the range 60-90% |
| Syngas fermentation | Not stated | Depends on the mass gas-liquid transfer rates, microorganism growth and activity, and if recycling is used[21] | Given the correct microorganism, solely ethanol can be produced (100% selectivity) |

A summary of the syngas requirements for each syngas conversion process is given in Table 3.

[14] Pers. Comm. Ineos Bio

[15] Calculated with 90% availability from 30,000 t/yr of ethanol, 400 litres / odt of biomass input and an ethanol density of 0.789g/ml. From Rice, G. (2008) "INEOS Bio Energy: A breakthrough technology for clean bioenergy from wastes", 2nd ICIS Bioresources Summit, Co Durham

[16] Pamela Spath and David Dayton (2003) "Bioproducts from Syngas"

[17] Thermal efficiency of Sasol's slurry phase FT process is around 60%, and since it is a slurry based process, inherently recycles the reactants. Syngas CO conversion is 75%. Single pass FT always produces a wide range of olefins, paraffins, and oxygenated products such as alcohols, aldehydes, acids and ketones with water or $CO_2$ as a by-product. Product selectivity can also be improved using multiple step processes to upgrade the FT products. P.L. Spath and D.C. Dayton (2003) "Preliminary Screening — Technical and Economic Assessment of Synthesis Gas to Fuels and Chemicals with Emphasis on the Potential for Biomass-Derived Syngas" NREL

[18] Gao et al. (2008) "Proposal of a natural gas-based polygeneration system for power and methanol production" Energy 33, 206–212

[19] Institute for Energy and Environment (2007) "WP5.4 Technical Assessment" for RENEW – Renewable Fuels for Advanced Powertrains, Deliverable D 5.3.7

[20] NREL (2007) "Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass", S. Phillips, A. Aden, J. Jechura, and D. Dayton, T. Eggeman, National Renewable Energy Laboratory

[21] Pers. Comm. Ineos Bio use a single pass reactor, with the off-gas combusted to produce power for internal needs and export

**Table 3: Syngas requirements for FT, methanol, mixed alcohol syntheses and syngas fermentation. See Section 7 for references**

| **Conversion** | **Fischer-Tropsch** | | **Methanol** | | **Mixed Alcohol** | | | | **Fermentation** |
|---|---|---|---|---|---|---|---|---|---|
| **Products** | Olefins + $CO_2$ | Paraffins + $H_2O$ | Methanol | Methanol | Mixture of ethanol and higher alcohols | | | | Ethanol |
| **Catalyst** | Fe | Co | $Cu/ZnO/Al_2O_3$ (Gas contact) | Cu/ZnO (Liquid contact) | Alkali/Cu /ZnO($Al_2O_3$) | Alkali/ZnO /$Cr_2O_3$ | Alkali/CuO /CoO | Alkali/$MoS_2$ | Biological |
| Temp (°C) | 300-350 | 200-250 | 220-275 | 225-265 | 275-310 | 300-425 | 260-340 | 260-350 | 20-40 |
| Pressure (bar) | 20-40 | 10-40 | 50-100 | 50 | 50-100 | 125-300 | 60-200 | 30-175 | 1-2 |
| $H_2$/CO ratio | 0.6 - 1.7 | Slightly >2 | Unimportant | | 1 - 1.2 | | | | Not sensitive |
| ($H_2$-$CO_2$)/ (CO+$CO_2$) ratio | Unimportant | | Slightly >2 | Low ratios ~0.68 | Same as methanol (gaseous) | Same as methanol (gaseous) | Same as FT (Co catalyst) | Unimportant | Unimportant |
| $CO_2$ | <5% | | 4-8% (very slow reaction without any $CO_2$, but also inhibited if too much present) | | | | | <5% (avoid promotion of methanol) | Aids initial growth rates |
| $H_2O$ | Low (slowly oxidises catalysts, very large amounts inhibit Fe based FT synthesis) | | Low (excessive amounts block active sites, reducing activity but increasing selectivity) | | | | | Same as FT (Co catalyst) | Most reactors use an aqueous solution |
| **Hydrocarbons** | Recycle to produce smaller molecules (to improve efficiency) | | Recycle to produce smaller molecules (to improve efficiency) | | | | | | None |
| $C_2H_2$ | Low (inert) | | Low (inert) | <5ppmv | | | | | Unknown |
| $CH_4$ | <2% (inert) | | Low (inert) | | | | | | Low (inert) |
| **$N_2$** | Low (inert) | | Low (inert) | | | | | | Low (inert) |
| **HCN** | <10ppb (poison) | | <10ppb (poison) | | | | | | Unknown |
| **$NH_3$** | <10ppb (poison) | | <10ppb (poison) | | | | | | Can help organism growth |
| **$NO_x$** | <100ppb (poison) | | <100ppb (poison) | | | | | | <40ppmv, since >150ppmv inhibits bacterial enzymes |
| **Sulphur** (COS, $H_2S$, $CS_2$) | <100ppb (most important poison) | <60ppb (most important poison) | <100ppb (poison, permanent activity loss) COS only a poison in liquid phase Zn can scavenge 0.4% of its weight in S while maintaining 70% activity | | | | | Resistant, 50-100ppmv is actually needed | Tolerant (up to 2% $H_2S$), since S can help certain organisms' growth |
| **Halides** (HCl, Br, F) | <10ppb (poison, can lead to structural changes in the catalyst) | | <1ppb (poison, leads to sintering) | <10ppb (poison, leads to sintering) | | | | Same as FT (Co catalyst) | Should be removed, although some organisms tolerant to Cl compounds |
| **Alkali metals** (Na, K) | <10ppb (promotes mixed alcohol reaction) | | Low (avoid due to promotion of mixed alcohol reaction) | | | | | | Unknown |
| **Tars** | Concentration below dew point (otherwise condense on surfaces) | | Concentration below dew point (otherwise tars will condense on catalyst and reactor surfaces) | | | | | | Must be removed – similar requirements to FT |
| **Particulates** | <0.1 ppm | | <0.1 ppm | <0.1 ppm | | | | | Must be removed |
| Particulate size | <2µm | | Unknown | Low | | | | | Must be removed |
| **Other trace species:** | Unimportant | | Avoid: As, P, Pb (lower activity, as with other heavy metals), Co (form $CH_4$, activity reduced), $SiO_2$ (promotes wax with surface area loss), free $Al_2O_3$ (promotes DME) , Ni and Fe (promote FT) | | | | | Co (beneficial methanol to ethanol conversion) | Must be removed |

Chemical key: $H_2$ = Hydrogen, CO = Carbon monoxide, $CO_2$ = Carbon dioxide, $H_2O$ = Water, $C_2H_2$ = Acetylene, $CH_4$ = Methane, $CH_3OH$ = Methanol, $N_2$ = Nitrogen, HCN = Hydrogen cyanide, $NH_3$ = Ammonia, $NO_x$ = Nitrous oxides, COS = Carbonyl sulfide, $H_2S$ = Hydrogen sulphide, $CS_2$ = Carbon bisulphide, HCl = Hydrogen chloride, Br = Bromine, F = Fluorine, Na = Sodium, K = Potassium, $SiO_2$ = Silica, Co = Cobalt, Cu = Copper, Fe = Iron, Ni = Nickel, As = Arsenic, P = Phosphorous, Pb = Lead, Zn = Zinc, $Al_2O_3$ = Aluminium Oxide (Alumina), Cr = Chromium, $Cr_2O_3$ = Chromium Oxide, $MoS_2$ = Molybdenum Sulphide

From the descriptions above and Table 3, it is clear that for all of the processes, there are always some species present in the raw syngas that must be removed through gas cleaning. Regardless of the gasifier technology, there are always elements present in biomass feedstocks, such as S and Cl, which produce gases that need to be removed after gasification. Nevertheless, some types of gasifier are much less suitable than others: updraft gasifiers produce very large quantities of tars in the syngas (10-20% by weight[22]), which must be removed for any of the syngas conversion processes. This level of tar removal is technically challenging, and expensive. As a result, we have not considered updraft gasifiers further.

Most of the catalytic conversion processes require a $H_2$ rich syngas; however, most gasifiers produce a CO rich syngas when using biomass feedstocks. Therefore, the syngas requires a degree of water gas shift reaction to adjust the $H_2$:CO ratio, adding to costs. The exception is syngas fermentation, where either CO or $H_2$ can be used by the organisms (often with a preference for CO), thereby avoiding the need for a water gas shift reaction. However, as current developers are not selecting gasifier technologies solely on this basis, we have not used this criterion to exclude any gasifier types.

For all of the processes, reduction in the volume of inert components in the syngas reduces the requirements for the volume of downstream equipment, and so reduces costs. As a result, oxygen blown or oxygen enriched gasification is being considered by many developers currently working on liquid fuel production from syngas. However, as several developers are considering steam blown systems, and because many developers started with air blown systems before moving to oxygen and steam, then this criterion has not been used to exclude any gasifier types.

The minimum syngas throughput needed to make these processes economically viable does help to determine which types of gasifier might be most suitable. Figure 1 below shows the likely scale of operation of different gasifier types[23]. At the minimum scale for conventional FT synthesis of 100,000 t/yr fuel output (1,520 odt/day biomass input in the graph units), only pressurised fluidised bed and entrained flow systems would be appropriate. If the minimum scale is reduced to around 300 odt/day biomass input, corresponding with the minimum scale of syngas fermentation or new FT process technologies, atmospheric CFBs and plasma gasification systems might also have potential. As a result, we will consider all entrained flow, fluidised bed and plasma gasification systems in this review.

22 Lin, J-C.M. (2006) “Development of an updraft fixed bed gasifier with an embedded combustor fed by solid biomass” Journal of the Chinese Institute of Engineers, Vol 29, No 3, pp 557-562

23 Adapted from E Rensfelt et al (2005) “State of the Art of Biomass Gasification and Pyrolysis Technologies” www.ecotraffic.se/synbios/konferans/presentationer/19_maj/gasification/synbios_rensfelt_erik.pdf and from “International Status & Prospects for Biomass Gasification” presentation, Suresh P. Babu (2005), and Westinghouse Plasma Corp torches sizes

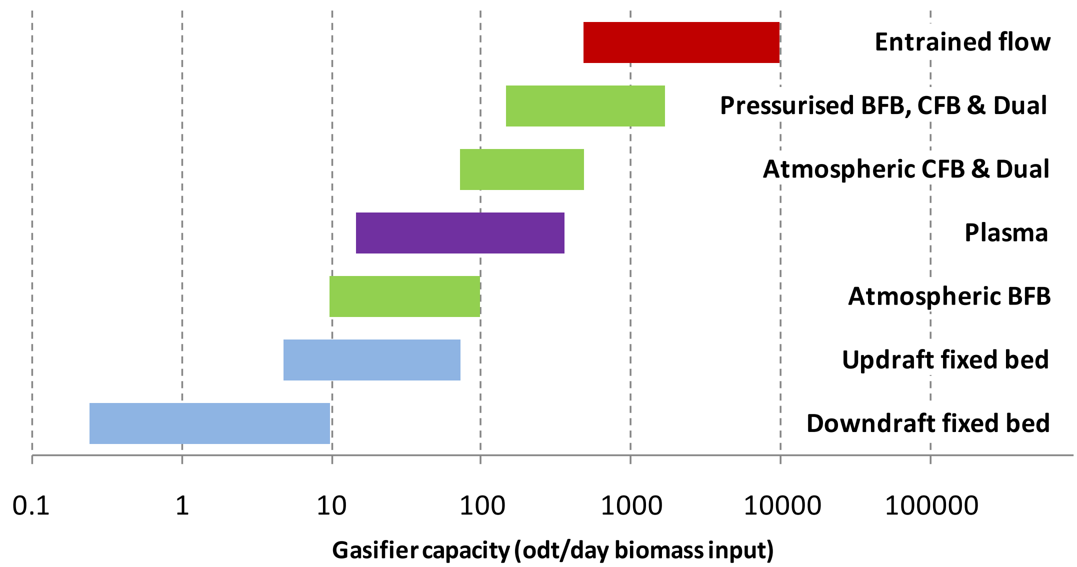



**Figure 1: Gasifier technology capacity range[24]**

Given that some current project developers are considering using modular systems, with several gasifiers together, it is conceivable that smaller scale gasifiers could be used. However, we have identified only one developer of a downdraft gasification technology (ZeroPoint Clean Tech) that mentions that their modular process may be suitable for use with distributed catalytic fuels production in the future[25]. Given the large number of downdraft gasifiers that would be needed to achieve the minimum economic scale within a modular system (at least thirty $2MW_{th}$ downdraft gasifiers), we have not considered fixed bed gasifiers further.

The requirements of the different syngas-using processes were also used to determine the information collected for the different gasifiers regarding syngas composition, as shown in the Annex and summarised in Section 4.2.

[24] Adapted from E Rensfelt et al (2005) "State of the Art of Biomass Gasification and Pyrolysis Technologies" www.ecotraffic.se/synbios/konferans/presentationer/19_maj/gasification/synbios_rensfelt_erik.pdf and from "International Status & Prospects for Biomass Gasification" presentation, Suresh P. Babu (2005), and Westinghouse Plasma Corp torches sizes

[25] See ZeroPoint Clean Tech's corporate website at: http://www.zeropointcleantech.com/technology.html

# 3 Gasifiers available and in development

In this section, we review gasifier technologies that may be suitable for liquid fuel production, now or in the future. We have included technologies that are:

- Of a type likely to be suitable for liquids fuels production, as identified in Section 2 above. This means that we have considered entrained flow, bubbling fluidised bed, circulating fluidised bed, dual fluidised bed, and plasma gasifiers, and have excluded updraft and downdraft gasifiers.
- Likely to be available in the short-medium term. This means that we have included gasifier technologies at or beyond pilot scale only. This excludes most university work and non-adiabatic pilot plants
- A commercial technology, or likely to become one – this excludes developers that no longer exist or are no longer active
- Suitable for UK biomass feedstocks – this excludes those using only black liquor feedstock

For each technology, we present a summary of information about the developer, the technology, the status of development and the feedstocks that have been used and tested. Further information on each gasifier is given in the annex, with details about the gasifier operating conditions, syngas characteristics, feedstock requirements, costs, and past, current and future plants and their applications. The technologies covered in the tables in this section are then used in subsequent sections for comparison of generic gasifier types. For each gasifier type, we also list technologies that have not been included in our comparison, for the reasons given above. This is useful to assess related technologies and the history of the sector.

### 3.1 Entrained flow gasifiers

Table 4 shows the principal developers with entrained flow gasifier technologies designed for use with biomass, and at the pilot scale or beyond. Full details of their technologies are given in the annex.

**Table 4: Entrained flow gasifier technologies**

| Name | Technology | Status of development | Feedstocks |
|---|---|---|---|
| **CHOREN** | 'Carbo-V' – involves low temperature gasification to produce gases and coke, which are then fed separately into the EF high temperature gasifier. Pressurised, directly heated, oxygen-blown EF. Syngas used for FT diesel synthesis | Their 'Alpha' pilot plant (3odt/day biomass) was built in 1997, and has been producing FT diesel since 2003. The 'Beta' plant (198odt/day) is being commissioned, with FT production due to start by the end of 2009.<br>A four module 'Sigma' plant (totalling 3,040odt/day of biomass) is planned for 2012/2013, with four further Sigma plants in Germany to follow | Currently use mainly wood (forest chips, sawmill co-product, recycled). Plastics & MSW have been tested. Could also use straw briquettes (max 5–10 % share), miscanthus, waste cereal products, energy crops.<br>Mix needs drying to <15% moisture content and milling to less than 50mm |
| **Range Fuels** | 'K2' – separate reactors for "devolatilisation" (low temperature gasification) and "reforming" (high temperature gasification). Indirectly heated with steam. Syngas used for ethanol/mixed alcohols | Their 4$^{th}$ generation pilot plant in Denver, Colorado has been operational since the start of 2008 (using 5odt/day biomass).<br>The first phase of a commercial 125odt/day biomass to ethanol plant near Soperton, Georgia, began construction in 2007, and is on track to begin production in 2010.<br>Further commercial units will use 625 or 1,250odt/day | Timber and forestry residues - development plant currently using Georgia pine and hardwoods.<br>Plant accepts high moisture content biomass (40-50%), of varying sizes, for pre-treatment |
| **Karlsruhe Institute of Technology** (FZK/KIT), with Siemens/ Future Energy and Lurgi | 'bioliq' process – involves decentralised pyrolysis to produce a bio-oil (Lurgi), transported to central pressurised, directly heated, oxygen-blown EF gasifier (Future Energy). Syngas used for FT synthesis | Future Energy own a 12odt/day pilot in Freiberg, Germany, and also supplied the commercial 300odt/day coal and wastes "Gaskombinat Schwarze Pumpe" (GSP) EF gasifier. Future Energy and FZK are now working on the bioliq process: Lurgi's pyrolysis stage of the 12odt/day biomass pilot plant was completed in 2007. Presently being extended to include gasification by 2011, with gas cleaning and FT synthesis to follow | Future Energy's previous plants tested a wide variety of biomass, and operated on coal and wastes.<br>bioliq process will use wood, wheat and rice hays and straws. Their focus is on more difficult biomass, like straw, which have high ash contents. Requires chopping before pyrolysis step |
| **Mitsubishi Heavy Industries** | Biomass Gasification Methanol Synthesis (BGMS) – slagging, atmospheric, directly heated, oxygen & steam blown EF gasifier. Syngas used for methanol synthesis | A 2odt/day pilot plant was constructed in the Kawagoe Power Station of Chubu EPCO, Japan, with testing started in 2002.<br>A feasibility study for a 100odt/day plant conducted, but there have been no recent developments | Have tested wood chips and waste wood. Dried biomass is pulverized to 1 mm before gasification |

| | | | |
|---|---|---|---|
| **Pearson Technology** | Pearson Technology process: EF gasifier, indirectly heated using superheated steam reforming. Syngas used for mixed alcohols production, primarily ethanol | A 4odt/day testrig and a 26odt/day pilot have been constructed in Aberdeen, Mississippi.<br>They have a partnership in Hawaii with ClearFuels, and a 43odt/day validation plant started construction in 2006. Further Hawaii plants planned at 100-345odt/day.<br>They are also partnered with Gulf Coast Energy, with a 5odt/day pilot running on wood since Aug 2008 in Livingston, Alabama, and future scale-up plans include a 1,400odt/day plant in Cleveland, TN | Drying and grinding required. Have tested waste wood, sawdust, rice straw and hulls, bagasse, manure, lignite and creosote. Could use MSW, and other waste biomass |

Several other technology developers with related technologies have not been listed above, as they are not focusing on biomass or on UK biomass feedstocks:

- CHEMREC: Black liquor gasification. CHEMREC has made considerable progress in Sweden and the US at 3 sites, and is planning construction of a commercial scale plant in the US, along with DME production in Piteå, Sweden[26]. However, the UK does not produce any black liquor, and the slurry gasification technology CHEMREC uses cannot be easily adapted to take dry biomass
- Current and potential technologies for co-gasification of coal and biomass, for example:
    - Shell: might enter the BTL market with its Shell Coal Gasification Process (SCGP) – a merger of Krupp Uhde's and Shell's solid fuel gasification technology. Shell has been carrying out biomass co-gasification at the 250$MW_e$ Buggenum plant in the Netherlands since 2002. This has used up to a 30% share of biomass (although 5-10% is a more usual share), and the main feedstocks tested are dried sewage sludge, chicken manure, and sawdust. Feedstock requirements are <1mm and ~5% moisture. Shell will also be carrying out 40% biomass co-gasification in 4 SCGP gasifiers (to be built by Uhde) at the new NUON Magnum 1200$MW_e$ coal power plant in the Netherlands from 2011[27], although has recently faced delays due to emissions permits applications[28]
    - GE is currently co-gasifying 5% biomass with coal in its Texaco Gasifier at the 220$MW_e$ Tampa Electric Polk Station in the US, using a slurry feed system
    - Uhde has also been co-gasifying 10-20% biomass with coal in its PRENFLO gasifier at its 320$MW_e$ Puertollano plant in Spain, although the plant has had poor availability[29]
    - ConocoPhillips (e-gas gasifier) may also enter the market with their EF pulverised coal technology
    - CHOREN also have EF coal technology, called CHOREN Coal Gasification (CCG). CHOREN may use this single stage technology for biomass directly, if the feedstock requirements could be met[30]

[26] Corporate website (2009) Available online: http://www.chemrec.se/Chemrec%20home.aspx
[27] Hans Linhardt (2007) "LA Basin IGCC Project now Nuon Magnum: Dutch utility Nuon awards Uhde contract for coal gasification plant". Available online: http://www.glggroup.com/News/LA-Basin-IGCC-Project-now-Nuon-Magnum-10639.html
[28] Pers. Comm. Shell
[29] Pers. Comm. Uhde
[30] Pers. Comm. CHOREN

### 3.2 Bubbling fluidised bed gasifiers

Table 5 shows the principal developers with BFB technologies designed for use with biomass at the pilot scale or beyond. Full details of their technologies are given in the annex.

**Table 5: Bubbling fluidised bed technology developers**

| Name | Technology type | Status of development | Feedstocks |
|---|---|---|---|
| **Carbona** (a subsidiary of Andritz) | RENUGAS: Pressurised, directly heated, oxygen and steam-blown BFB as part of a biomass gasification plant with the syngas used in gas engines for CHP | RENUGAS was originally developed by the Gas Technology Institute, and has been tested in the Tampere, Finland pilot plant from 1993, using a variety of biomass wastes (72odt/day) and evaluating hot-gas filtration for IGCC applications.<br>A 84odt/day bagasse plant in Hawaii closed in 1997 after feedstock handling issues.<br>The Skive plant (100-150odt/day wood) has been operating with 1 Jenbacher engine since mid 2008, and fully integrated plant operation with all 3 engines should start in early 2009.<br>Testing is also currently occurring at the 18-36odt/day GTI facility in Chicago, for a future FT biodiesel plant at the forestry supplier UPM's site. VTT is providing hot-gas tar reforming catalysts | Plants use mainly wood pellets, or chips, although wide range of feedstocks tested at GTI |
| **Foster Wheeler Energy** | 'Ecogas' – atmospheric, directly heated, air and steam-blown process, with syngas used in a boiler | Process testing at VTT was carried out in 1997, then a brief 25odt/day demo at Corenso's Varkaus plant, before a full commercial 82odt/day plant was built on the same site in 2001<br>Have also tested MSW derived fuels at VTT's 5odt/day pilot plant, with the technology bought from Powest Oy and Vapo Oy. Their joint venture planned to develop a 274odt/day plant at Martinlaasko, but the permit was denied in 2003 | Plastics and aluminium. MSW-RDF also tested |
| **Energy Products of Idaho (EPI)** | Pressurised, directly heated, oxygen/steam blown gasifier. APP has integrated this into their 'Gasplasma' process with syngas polishing using a Tetronics plasma converter. Syngas used for heat and power | EPI built 4 plants in the 1980's ranging from 9-134odt/day for heat & power applications. Most of these have now closed<br>Panda Ethanol started construction of a 1$^{st}$ generation ethanol plant in Hereford, Texas in 2006, including a 1040odt/day cattle manure gasifier to provide internal heat & power, but the project has suffered delays.<br>Advanced Plasma Power (APP)'s 1.6odt/day test facility in Farringdon, UK was relocated to Marston Gate, Swindon, with upgrading of the plasma converter and installation of gas engines in 2008. APP plans to scale up to 164odt/day MSW | Past plants used wood chips, agricultural and industrial waste and sewage sludge. APP currently use RDF feedstock, scale up will use MSW. Hereford plant will use cattle manure if completed |

| | | | |
|---|---|---|---|
| **Enerkem** | 'BioSyn' pressurised, directly heated, air & oxygen blown BFB, with syngas used for modular methanol and ethanol production | A 4odt/day pilot plant has been in operation since 2003 in Sherbrooke, Quebec.<br>Construction of the 30odt/day Westbury commercial scale plant was completed in Dec 2008, and is now in commissioning. Fuel production modules will be added as the next step<br>Construction of a third plant taking in 228odt/day MSW in Edmonton, Alberta will begin soon, and other possible projects include a 913odt/day plant in Varennes using RDF, and a 432odt/day MSW plant in Pontotoc, Mississippi | 20 feedstocks tested in the pilot plant (mainly wastes and woods)<br>Demo plant is using treated wood from electricity poles.<br>Future plants will use MSW or RDF |
| **Iowa State University** | Biomass Energy Conservation Facility (BECON) – Indirect batch heating for steam atmospheric BFB | A 5odt/day input pilot "BECON" was built in 2002.<br>Iowa are currently partnered with ConocoPhillips for syngas catalytic ethanol production R&D and testing, along with fast decentralised pyrolysis, and replacement of natural gas burning.<br>Also partners with Frontline Bioenergy | Tested switch grass, discarded corn seeds and wood chips. Will test corn stover and other residues |
| **ThermoChem Recovery International (TRI),** own MTCI Manufacturing and Technology Conversion International technology | 'PulseEnhanced' technology is an atmospheric, steam blown gasifier, with indirect heating (a small proportion of the syngas is pulse burnt to provide the gasification heat). Remaining syngas currently used for heat and power, or FT diesel in the future | Several black liquor gasifiers have been built by MTCI: a 12odt/day pilot in 1992; the 30odt/day New Bern demo in 1996; the 120odt/day Big Island demo in 2001 (which failed); and their 69odt/day Trenton Normapac plant which has been operational from 2003<br>Partnership with Rentech to test a 5odt/day biomass gasifier, cleanup and FT synthesis at the Southern Research Institute<br>Two other proposed projects were awarded $30m grants from the US DOE:<br>• Flambeau River Biofuels taking in 580odt/day wood to make 16,500t/year of FT diesel from 2010 (with possible expansion to 1,900odt/day)<br>• New Page Corp, Wisconsin Rapids taking in 500odt/day biomass from 2012 | Past plants only used black liquor.<br>New plants will use forestry residues |

### 3.3 Circulating fluidised bed gasifiers

Table 6 shows the principal developers with CFB technologies designed for use with biomass at the pilot scale or beyond. Full details of their technologies are given in the annex.

**Table 6: Circulating fluidised bed technology developers**

| Name | Technology type | Status of development | Feedstocks |
|---|---|---|---|
| **Foster Wheeler Energy** | Air-blown, atmospheric directly heated CFB, with syngas used for co-firing in lime kilns or in pulverized coal boilers to produce heat and power | 4 commercial gasifiers were built in the 1980s at Pietarsaari, Norrsundet, Karlsborg and Rodao lime kilns. ranging in size from 70-170odt/day of bark<br>The Lahti, Finland gasifier takes in up to 336odt/day biomass input, producing 7-23$MW_e$ at the Kymijärvi coal power plant for the town since 1998. A similar plant was built for Electrabel in Ruien, Belgium<br>There are plans for new Lahti plant with 2 modules, taking in ~768odt/day of waste | Have operated with wood chips, bark, sawdust, recycled wood waste, RDF, plastics, railway sleepers and tyres. Will also be using MSW. Able to handle 20-60% moisture content |
| **Växjö Värnamo Biomass Gasification Center (CHRISGAS)** | 'Bioflow', a joint venture between Foster Wheeler Energy and Sydkraft, built the original IGCC plant using a pressurised, air blown, directly heated CFB, with hot gas clean up, and gas turbine CHP | The 86odt/day Värnamo IGCC demonstration was halted in 2000, as it was uneconomic. The plant was reopened in 2005 for the CHRISGAS project, aiming to upgrade to a steam/oxygen blown system (rather than air), with a hot gas filter, catalytic high temperature reformer and syngas conversion to biofuels (instead of heat & power).<br>Operation in 2011 is dependent on finding further funding, and future plans for a 860odt/day plant could be realised by 2013 | Wood chips, pellets, bark and straw tested. Dried, crushed, and pressurised with auger screws before fed into gasifier |
| **VTT** Technical Research Centre of Finland | Ultra-Clean Gas (UCG) project – pressurised, directly heated, oxygen & steam blown fluidised bed. Planned FT diesel production | VTT has been heavily involved in biomass gasification R&D since the 1980s, with several pilots and ongoing research programs.<br>A 2.5odt/day input pilot development unit (first phase) came online in 2006.<br>NSE Biofuels, a Stora Enso/Neste Oil joint venture, is demonstrating its BTL chain at the Varkaus mill, Finland using a 60odt/day Foster Wheeler CFB, and VTT's gasification and cleaning expertise. This second phase plant will verify operation during 2009/10.<br>A third phase 1520odt/day commercial scale plant is planned for 2013, and further plants from 2015 onwards | Main focus forest industry residues and by-products. Will also take bark, energy crops, refuse-derived fuels and peat |
| **CUTEC** Institute | 'Artfuel' process: atmospheric, directly heated, oxygen & steam blown biomass CFB gasifier, gas cleanup and FT plant | Their pilot is a 400$kW_{th}$ biomass capacity (2.7odt/day), and was completed in 2008.<br>Full process chain operation has just begun, testing feedstocks and ash removal. Their future plans are a 4-10$MW_{th}$ plant (27-68odt/day) | Successfully tested sawdust, wood pellets, wood chips, and chipboard residues<br>Plan to test straw pellets, and sunflower seed residue. Will also look at energy crops |

| | | | |
|---|---|---|---|
| **Fraunhofer** Institute | Atmospheric, directly heated, air blown CFB gasifier with catalytic gas treatment. Syngas used in an IC engine for heat & power | Their pilot (taking in 2.4odt/day of biomass) was commissioned in Oberhausen, Germany in 1996.<br>In 2002, Fraunhofer looked to establish a demonstration plant using ~53odt/day biomass, but this did not go ahead | Pilot uses clean forestry wood chips. Planned demo would have taken wood chips, bark, coarse lumber shavings or sawdust. Belt drying |
| **Uhde** | High Temperature Winkler (HTW) gasifier from Uhde, licensed from Rheinbraun. Directly heated, pressurised, oxygen & steam blown. Syngas used for heat & power, and in TUB-F concept will make methanol for conversion to gasoline and diesel using Lurgi's MtSynfuel technology | Previous coal pilots and demonstrations were operated, before building the 576odt/day peat plant in Oulu, Finland in 1988.<br>The PreCon process (using MSW) was licensed to Sumitomo Heavy Industries, who built a 15odt/day MSW plant in Japan.<br>TUB-F (Technische Universitat Bergakademie Freiberg) is developing a large-scale BTL gasoline and diesel concept, but both the gasification and the synthesis processes are still in the planning stages | Uhde are mainly focused on coal/lignite, but have adapted their gasifier designs for peat and MSW feedstocks.<br>TUB-F will be using waste wood and straw |

KBR's TRIG technology (Kellogg Brown and Root's Transport Gasifier) developed with Southern Company is a CFB designed for either air blown IGCC or oxygen/steam blown fuel applications, using low rank coal feedstocks[31]. KBR may enter the BTL market if it develops.

[31] Corporate website (2009) Available online: http://www.kbr.com/technology/Coal-Gasification/Default.aspx

### 3.4 Dual fluidised bed gasifiers

The developers in Table 7 have dual fluidised bed gasification technologies, designed for use with biomass at the pilot scale or beyond. Indirect heating is provided by material exchange with a parallel combustion chamber. Full details of their technologies are given in the annex.

**Table 7: Dual fluidised bed technology developers**

| Name | Technology type | Status of development | Feedstocks |
|---|---|---|---|
| **REPOTEC/ TUV** (Vienna University of Technology) | Fast internally circulating fluidised bed (FICFB). Atmospheric steam BFB gasification with separate air blown CFB char combustion chamber heating the sand (indirect heating). Used for District CHP and slipstream fuels testing | FICFB technology created at TUV, with a testrig and 0.5odt/day pilot, now developed by REPOTEC<br>A 40odt/day plant started operation in Nov 2001 in Güssing, Austria, and has demonstrated high availabilities. TUV are testing uses for the syngas (FT, methanol synthesis and in fuel cells), as well as further R&D for optimisation and tar cleanup.<br>REPOTEC designed a 53odt/day plant in Oberwart, Austria, but the project was handed over to BEGAS in 2004, although TUV have remained involved. Currently in commissioning<br>REPOTEC also conducted a feasibility study for a 500odt/day plant in Gothenburg | Only tested wood chips and wood working residues |
| **SilvaGas** | SilvaGas process: atmospheric, indirectly heated. CFB steam gasification with parallel air blown CFB char combustion chamber providing heated sand. Syngas used for heat & power, although will also produce FT liquids in the future | A commercial scale demonstration plant (using 350odt/day of wood) was successfully operated in Burlington, Vermont from 1997 to 2002, with the syngas used in the wood boiler. US DOE funding ended before a new gas turbine was installed, and the plant was said to be not economic at these low efficiencies.<br>Biomass Gas & Electric now developing a 540odt/day wood wastes project in Forsyth County, Georgia, and two other plants are in an early planning stage with Process Energy<br>Rentech announced in May 2009 that they will be using a SilvaGas gasifier in their Rialto, California plant, to make FT liquids and power from ~800odt/day urban waste wood in 2012 | Tested clean wood chips and pellets.<br>Other possible feedstocks are straw, switch grass, poultry litter, MSW, waste wood, papermill sludge |
| **Taylor Biomass Energy** | Taylor Gasification Process: same technology as SilvaGas. Syngas will be used for ethanol production or heat & power | Taylor will be providing the 300-400odt/day biomass gasifier in a DOE funded ethanol project in Colwich, Kansas, proposed by Abengoa Bioenergy in 2007.<br>They also planned to build a waste gasification to power facility in Montgomery, NY in 2009, with a potential future bio-refinery upgrade | Will be using biodegradable wastes and waste wood.<br>Only drying required |
| **ECN** | MILENA: Compact, indirectly heated, dual-bed CFB steam gasifier and air blown BFB char combustor. Hot gas cleaning, then syngas methanation to produce bio-SNG | A lab scale 25kW (0.12odt/day) rig was built in 2004, for automatic operation testing with gas cleaning and methanation.<br>Their 800kW pilot plant (taking in 3.8odt/day biomass) started operation in Sep 2008, and is currently in the process of initial testing<br>ECN plans to license a 10MW (48odt/day) demo in 2012-2015, with a long term goal of installing a 1GW plants (4,800odt/day) from 2018 | Testing of dry beech wood, grass and sewage sludge in the lab scale.<br>Pilot only using wood pellets.<br><15mm size needed |

### 3.5 Plasma gasifiers

The developers in Table 8 have plasma gasification technologies designed for use with biomass (mainly in the form of wastes) at the pilot scale or beyond. Note that technologies using plasma for other downstream processes, e.g. syngas reforming, are included in the category for the gasifier technology used. Full details of the plasma technologies are given in the annex.

**Table 8: Plasma gasifier technology developers**

| Name | Technology type | Status of development | Feedstocks |
|---|---|---|---|
| **Westinghouse Plasma** Corp (WPC), a subsidiary of Alter-NRG | Plasma Gasification Vitrification Reactor (PGVR) – combination of an atmospheric pressure, moving bed gasifier with WPC plasma torches. Syngas used for electricity generation, Coskata to use syngas fermentation to ethanol | WPC technology has been used in several waste to power applications, with pilots built since 1990<br>In 2002, built a 150-210odt/day MSW plant in Utashinai and a 18odt/day plant in Mihama-Mikata, Japan.<br>SMS Infrastructure is currently constructing two 54odt/day hazardous waste plants in India.<br>Geoplasma's St Lucie plant plans have been down-scaled from 2,250 to 150odt/day of MSW.<br>Other modular plants are planned at up to scales of 1,900odt/day using MSW or hazardous waste.<br>Coskata is building its WPC pilot plant in Madison, Pennsylvania, to produce syngas for fermentation to ethanol. The pilot will use 1.2odt/day of wood and wastes from early 2009, with their first modular 1,500odt/day commercial plant planned for 2011 | MSW, paper and plastic wastes. Also able to take sewage sludge, oil, coal/water slurries, coal and petroleum coke. No preparation required |
| **Plasco** Energy Group | Plasco Conversion System – low temperature gasification, with plasma gasification then vitrifying the solids and refining the syngas. Used for electricity generation | A 3.5odt/day R&D facility in Castellgali, Spain was constructed in 1986<br>A 70odt/day MSW demonstration plant has been operational since Feb 2008 in Ottawa, Canada, exporting 4.2$MW_e$ of power.<br>Plasco plans to build a modular 280 odt/day plant in Ottawa, and a modular 140odt/day plant in Red Deer, Canada | Use sorted MSW and plastics, providing high enough calorific content and low mineral matter (e.g. glass, ceramics) |
| **Startech** Environmental Corporation | Plasma Converter System (PCS) – atmospheric, extreme temperature plasma converts waste into syngas and vitrified solid. Used for electricity, hydrogen, methanol or ethanol | Numerous small plants have been in operation since 2001 using wastes at 3.8-7.5odt/day scale, with three plants producing methanol in Puerto Rico<br>Startech has extensive worldwide plans, with plants up to 150odt/day using specialised wastes. This includes a joint venture signed with Future Fuels Inc. in 2006 to build several "spent tyres to ethanol" plants | MSW, industrial and hazardous wastes, incinerator ash and coal. Waste is shredded for uniformity and decreased volume |

| | | | |
|---|---|---|---|
| **Solena** Group | Plasma Gasification and Vitrification (PGV) reactor – with 3 plasma torches. Used for atmospheric Integrated Plasma Gasification Combined Cycle (IPGCC) process, plans for methanol and FT aviation fuels | In the period 2002-2008, plants were planned at up to 250odt/day MSW, but none of these projects appear to have been built, and very little information is available.<br>Solena claim to have several ongoing projects:<br>• March 2008: discussions with Rentech to convert waste into FT liquid aircraft fuel in California. A plant was planned for 2011 operation, using 1,125odt/day MSW, farm and wood wastes<br>• Partnership with Bio Fuel Systems to develop micro-algae as a feedstocks for making FT liquids<br>• March 2009: a 40$MW_e$ power plant for the Port Authority of Venice, taking in 360odt/day algae | Waste streams, such as MSW or industrial and hospital wastes, and tyres. Also able to use coal, coal wastes and oil wastes |
| **InEnTec** | Plasma Enhanced Melter (PEM) – waste falls through an atmospheric gasification chamber onto a pool of molten glass, heated with plasma torches. Used for heat & power, plans for hydrogen, methanol and ethanol production | Several small plants have been built since 1996 at 1-25odt/day scale, however, it is reported that many have had operational and emissions problems<br>InEnTech's planned projects include:<br>• Dow Corning's plant in Midland, Michigan, to take in 15odt/day of liquid hazardous waste. Design of the facility began in 2007 and was expected to be online in mid 2008<br>• July 2008 announcement of Sierra BioFuels plant (owned by Fulcrum BioEnergy) in Storey Country, Nevada to convert 218odt/day of MSW into ~10.5m gallons of ethanol per year for cars and trucks. Expected to start operation in 2010 | Operated on radioactive, hazardous, industrial, municipal, tyre, incinerator ash and medical waste streams, and have also tested PCBs and asbestos. Shredded to 2-4 inches |

# 4 Comparison of gasification technologies

This section compares the different gasifier types based on the review of gasification technologies in Section 0 and supplementary information from the literature. Entrained flow, bubbling, circulating and dual fluidised bed and plasma gasifiers are compared in terms of:

- Feedstock requirements – which gasifier types are most suitable for which feedstocks? What feedstock preparation is needed for each type?
- Ability and potential to meet syngas quality requirements – what quality of syngas is produced? Does this make particular gasifier types more suitable for particular syngas conversion processes?
- Development status and operating experience – how advanced are the developers of each gasifier type? Have there been failed projects, and if so, why?
- Current and future scales – can the gasifier type meet the required scale now or in the future?
- Costs – what data are available on the costs of the gasifier types? What conclusions can be drawn from this?

The comparison provides the basis for the conclusions to be drawn in section 5, on which of the gasifier types might be suitable for liquid fuels production, in particular in the UK.

## 4.1 Feedstock requirements

### 4.1.1 Introduction

There are a large number of different biomass feedstock types for use in a gasifier, each with different characteristics, including size, shape, bulk density, moisture content, energy content, chemical composition, ash fusion characteristics, and homogeneity of all these properties.

Feedstock moisture contents above 30% result in a lower gasification thermal efficiency, as energy is needed to evaporate the water, with the resulting steam also affecting the gas composition. Higher moisture contents also reduce the temperatures that are achieved, increasing the proportion of syngas tars in the syngas due to incomplete cracking[32]. However, drying feedstocks to less than 10% requires ever increasing energy inputs[33], and hence a moisture contents in the 10-20% range are preferable[34].

Ash is the inorganic material (or mineral content) in biomass which cannot be gasified. It ranges from less than 1% (on a dry mass basis) in wood to above 20% in some animal manures and herbaceous crops (e.g. rice straw)[35]. Low-ash content feedstocks (<5%) are usually preferable to minimise disposal issues. Ash composition is also important, since feedstocks with low ash melting points can be difficult to gasify in some reactors. This is particularly true for fluidised beds, since melting ash can make bed particles adhere (agglomerate), causing the bed to 'freeze' – requiring a shut-down and clean-out or major

[32] Williams et al. (2007) "$H_2$ Production via Biomass Gasification", AEP Project, Task 4.1 Technology Assessments of Vehicle Fuels and Technologies, PIER Program, California Energy Commission, prepared by ITS-Davis
[33] Carlo Hamelinck (2004) "Outlook for Advanced Biofuels" Utrecht University Thesis
[34] Williams et al. (2007) "$H_2$ Production via Biomass Gasification", AEP Project, Task 4.1 Technology Assessments of Vehicle Fuels and Technologies, PIER Program, California Energy Commission, prepared by ITS-Davis
[35] Williams et al. (2007) "$H_2$ Production via Biomass Gasification", AEP Project, Task 4.1 Technology Assessments of Vehicle Fuels and Technologies, PIER Program, California Energy Commission, prepared by ITS-Davis

overhaul[36]. Catalytic bed additives, such as olivine or dolomite, can be used to prevent sand bed agglomeration[37], but this is an additional expense. Whilst woody biomass feedstocks usually meet the ash requirements, crop residues (such as straw and husks) may have to be first screened for their ash melting characteristics.

Besides feedstock moisture and ash properties, the size of the biomass fed into the gasifier can have a large influence on the gasification reaction – the required sizing is mainly a function of feeding rate, residence time, tar production, temperature and gasifier efficiency, which need evaluation for each individual gasifier and feedstock. Detailed testing information is scarce; however, in general, it is desirable to use a feedstock that is fairly uniform in size, shape and density[38]. Loose crop residues should usually be compacted to provide the desirable bulk density to facilitate solids flow into the gasifier, and avoid feeding problems.

Preparation of biomass, such as drying and/or sizing is needed to some extent for most combinations of feedstock and gasifier type. Some gasifier type and feedstock combinations require more pre-treatment, in the form of an additional biomass conversion step, to make the biomass suitable for use. This approach is being also considered in order to use a diverse and variable range of feedstocks, to mitigate feedstock supply and price risks. Plant economics can be greatly improved through the use of lower cost feedstock, and in addition to this, achieving the potential bioenergy deployment cited in many studies will require use of a wide range of feedstocks, not all of which will be the most suitable feedstocks for gasification. Pre-treatment does, however, add to costs and energy requirements, which must be compared with those of using alternative feedstocks.

The principal feedstock preparation steps for biomass gasification include:

- **Sizing:** smaller particles have a larger surface area to volume ratio, and the gasification reaction occurs faster when there is a larger biomass surface area. Smaller particles can also be suspended in gas flows more readily, and if very small, the particles may act like a fluid. Achieving the correct feedstock sizing for the gasifier is important. Crude sizing operations include chipping, cutting and chopping, but in order to get very small ground particles, pulverising milling equipment is needed – as shown in Figure 2, this is an energy intensive process. A screening process is often used to ensure any remaining larger particles and extraneous materials are removed
- **Drying:** the removal of moisture contained within the biomass by evaporation, typically using temperatures between 100°C and 120°C. Drying requires a significant amount of energy in order to evaporate the large mass of water. This heat can be provided externally, or extracted from the gasifier syngas or other plant process steps. Gasification efficiency increases with drier biomass, but drying costs also increase quickly below 10% moisture[39]

[36] Williams et al. (2007) "H2 Production via Biomass Gasification", AEP Project, Task 4.1 Technology Assessments of Vehicle Fuels and Technologies, PIER Program, California Energy Commission, prepared by ITS-Davis
[37] Zevenhoven-Onderwater et al. (2001) "The ash chemistry in fluidised bed gasification of biomass fuels. Part II: Ash behaviour prediction versus bench scale agglomeration tests" Fuel 80, 1503-1512
[38] R. Ramos Casado, & L.E. Esteban Pascual (2008) "Biomass Feedstocks Preparation Methods For Energy Production And Its Economic Evaluation" CIEMAT
[39] Hamelinck et al. (2004) "Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential" Energy 29, 1743–1771

- **Torrefaction:** a mild thermal treatment (approximately 30 minutes at between 200°C and 300°C, in the absence of oxygen) resulting in a low-oxygen content, dry and relatively brittle product. As shown in Figure 2, torrefied wood is much easier to grind than untreated wood, using 80% less energy for a given sizing, and with a significant increase in milling plant capacity[40]
- **Pyrolysis**: the thermal degradation of biomass in the absence of oxygen, whereby the volatile parts of a feedstock are vaporised by heating. The reaction forms three products: a vapour that can be condensed into a liquid (pyrolysis oil), other gases, and a residue consisting of char and ash. Fast pyrolysis processes are designed and operated to maximise the liquid fraction (up to 75% by mass), and require rapid heating to temperatures of 450°C to 600°C, and rapid quenching of the vapours to minimise undesirable secondary reactions[41]. The resulting liquids and solids can be ground together to form a bio-slurry for gasification
- **Low temperature gasification / autothermal pyrolysis:** reducing the operating temperature of a gasification reaction, in the presence of some oxygen, to around 400-500°C results in a tar-rich gas, and solid chars. An alternative description of this process is as a pyrolysis reaction, but only with enough oxygen to partially combust enough biomass to maintain a temperature between 400-500°C. The char can then be ground and fed into a higher temperature gasification reaction chamber. To avoid condensation of tars in the gas between these connected steps, the gas temperature is not lowered, and the low temperature gasifier and high temperature gasifier have to be operated at the same pressure. Whilst high pressure gasifier technology is mature, there is little experience with operating low temperature gasifiers at pressure (for example, CHOREN's Beta plant will use rotary drums up to a maximum of only 5 bar pressure).

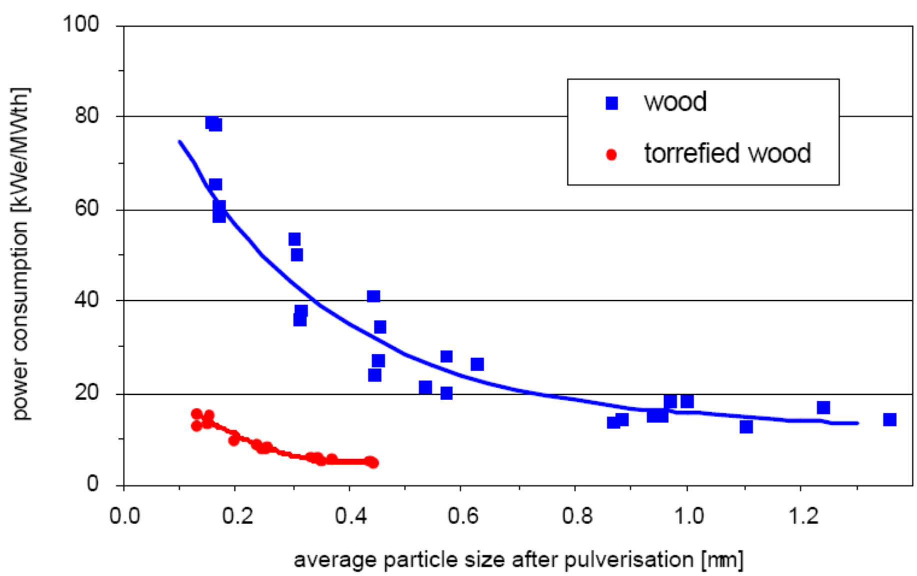



**Figure 2: Milling power consumption vs. required particle size[42]**

[40] Van der Drift et al. (2004) "Entrained Flow Gasification of Biomass: Ash behaviour, feeding issues, and system analyses" ECN
[41] Bridgwater et al. (2002) "A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion" Renewable and Sustainable Energy Reviews 6, 181–248
[42] Van der Drift et al. (2004) "Entrained Flow Gasification of Biomass: Ash behaviour, feeding issues, and system analyses" ECN

### 4.1.2 Entrained flow gasifiers

Demonstration biomass EF gasification plants have focused on using wood (wood chips, forestry residues, sawdust, waste wood, etc) as the preferred feedstock, although other materials tested include plastics, RDF pellets, sorted MSW, sewage sludge, straws and grasses. In general, EF gasifiers can accept a mixture of feedstocks, but under the designed operating conditions, this mixture should not change significantly over time, hence feedstock storage is usually necessary to ensure the supply of quality controlled biomass is achieved. The biomass received usually undergoes a process of drying, storage, blending and sizing.

Due to the ash found in most biomass, the directly heated EF gasifiers (CHOREN, KIT and MHI) are slagging reactors: melting ash flows down the reactor surfaces (forming a protective slag layer from the heat) before being cooled into granules and easily removed from the system[43]. However, ash viscosity is of critical importance to the reactor design, and changes in ash compositions can lead to changes in slag removal rates, and hence changes in reactor temperature and performance[44]. This means that entrained flow gasifiers can use feedstocks such as straw, but in low and constant proportions (e.g. a maximum of 10% straw for CHOREN).

Due to a short EF residence time, large feedstock particles would lead to unconverted biomass, and a high feedstock moisture content would lower gasification efficiency[45]. EF gasifiers therefore have the most stringent feedstock requirements of the gasifier types considered. A typical EF biomass gasifier needs a fuel with about 15% moisture content. EF coal gasifiers need a particle size of 50-100µm, however because biomass is much more reactive than coal, biomass particles can be sized as large as 1mm[46]. However, due to the fibrous nature of biomass, biomass particles must be smaller than 100µm if existing coal-based pneumatic feeders are used, and grinding biomass down to this size is highly energy intensive. As shown in Figure 2, electricity consumption starts to rise significantly if wood is milled to sizes below 1mm. Pulverisation of wood to particles of 200µm requires as much as 10% of its contained energy.

To use particles sized at 1mm or larger, the feeding system needs to be changed to a screw feeder. This is a simpler and more efficient feeding mechanism, but with less responsive second-by-second control than a pneumatic feeder[47]. There is little experience with using screw feeders for EF gasifiers; hence if large biomass particles are to be used, and changes in equipment and plant design are to be avoided, pre-treatment conversion steps have to be used instead. These pre-treatment technologies are not yet mature, but most EF gasifier based projects are taking this approach:

- In the KIT/FZK bioliq process, decentralised pyrolysis plants first produce oil and char, which are ground together to form an energy dense slurry for transport. On arrival at the centralised plant, this can then be pneumatically fed directly into a large EF gasifier

[43] Boerrigter, H. & R. Rauch (2006) "Review of applications of gases from biomass gasification", ECN Research
[44] Williams et al. (2007) "H2 Production via Biomass Gasification", AEP Project, Task 4.1 Technology Assessments of Vehicle Fuels and Technologies, PIER Program, California Energy Commission, prepared by ITS-Davis
[45] Olofsson (2005) Initial Review and Evaluation of Process Technologies and Systems Suitable for Cost-Efficient Medium-Scale Gasification for Biomass to Liquid Fuels, Umeå University and Mid Swedish University
[46] Van der Drift et al. (2004) "Entrained Flow Gasification of Biomass: Ash behaviour, feeding issues, and system analyses" ECN
[47] Van der Drift et al. (2004) "Entrained Flow Gasification of Biomass: Ash behaviour, feeding issues, and system analyses" ECN

- In CHOREN plants, the first stage low temperature gasification is used to produce a tar rich gas which is fed directly into the EF gasifier, and the char is easily ground and fed in separately
- Range Fuels also uses a devolatilisation (low temperature gasification) reactor as a first stage before higher temperature steam gasification of the entrained gases and char particles
- ECN and others are investigating torrefaction to significantly reduce feedstock moisture and oxygen content, along with milling energy requirements[48], allowing very small particle sizes and hence allow pneumatic feeding. CHOREN are also testing torrefaction as a feed preparation stage in order to be able to use a wider range of feedstocks directly in a high temperature gasification reactor, without the need for a low temperature gasification step first – this would allow CHOREN to use their CCG coal gasification technology directly

### 4.1.3 Bubbling fluidised bed gasifiers

Existing BFB biomass gasification plants have a wide variety of preferred feedstocks, with wood pellets and chips, waste wood, plastics and aluminium, MSW, RDF, agricultural and industrial wastes, sewage sludge, switch grass, discarded seed corn, corn stover and other crop residues all being used.

There is a significant danger of bed agglomeration in both BFB and CFB gasifiers when using feedstocks with low ash melting temperatures, e.g. certain types of straws. A suitable mix of feedstocks with higher ash melting temperatures may allow safe operation even at high gasification temperatures, or alternatively, mineral binding products such as dolomite can be added to the inert bed material to counteract the agglomeration problem[49].

As with CFBs, typical BFBs use storage and metering bins, lock hoppers and screws, and are tolerant to particle size and fluctuations in feed quantity and moisture. However, the noticeable difference is in the feedstock sizing – BFBs can accept chipped material with a maximum size of 50-150mm. Unlike EF, CFBs are tolerant to fluctuations in feed quantity and moisture – the BFB gasifiers considered can take feed moisture contents of 10-55%, although 10-15% is optimal from a pre-treatment energy viewpoint[50].

### 4.1.4 Circulating fluidised bed gasifiers

Like EF, CFB biomass gasification has generally used woody feedstocks, although more unusual feedstocks such as bark, peat and straw have also been the preferred choice for certain plants. Other materials briefly tested include plastics, RDF, waste wood and shredded tyres.

In general, CFBs are fuel flexible[51], being able to change feedstocks when desired, and are able to accept wastes (with some modifications to remove foreign objects). Typically, the feedstocks must be sized to less than approximately 20mm. Unlike EF, CFBs are tolerant to fluctuations in feed quantity and

[48] Van der Drift et al. (2004) "Entrained Flow Gasification of Biomass: Ash behaviour, feeding issues, and system analyses" ECN

[49] Zevenhoven-Onderwater et al. (2001) "The ash chemistry in fluidised bed gasification of biomass fuels. Part II: Ash behaviour prediction versus bench scale agglomeration tests" Fuel 80, 1503-1512

[50] Hamelinck, C.N and A.P.C. Faaij (2006) "Production of methanol from biomass", Ecofys & Utrecht University

[51] Olofsson (2005) Initial Review and Evaluation of Process Technologies and Systems Suitable for Cost-Efficient Medium-Scale Gasification for Biomass to Liquid Fuels, Umeå University and Mid Swedish University

moisture – the CFBs considered are able to accept feed moisture contents of 5-60%, although 10-15% is optimal from a pre-treatment energy viewpoint [52].

#### 4.1.5 Dual fluidised bed gasifiers

Dual FB biomass gasifiers mainly use woody feedstocks (chips, pellets, wood residues); although other materials such as herbaceous crops, grasses and sewage sludge have been tested. Taylor Biomass Energy will be sorting MSW onsite for use in their planned commercial plants.

Since a dual fluidised bed gasifier is based on a CFB or BFB gasification chamber, combined with a CFB or BFB combustion chamber (see Table 9), the input feedstock requirements will follow those of the gasification chamber design discussed above.

**Table 9: Dual fluidised bed gasifier designs**

| Gasifier | **Gasification chamber** | Combustion chamber |
|---|---|---|
| REPOTEC/TUV | **BFB** | CFB |
| SilvaGas | **CFB** | CFB |
| Taylor Biomass Energy | **CFB** | CFB |
| ECN MILENA | **CFB** | BFB |

#### 4.1.6 Plasma gasifiers

Plasma gasification has almost exclusively focused on waste feedstocks, with existing plants gasifying MSW, auto-shredder residue, tyres, incinerator ash, coal and hazardous, medical, industrial and radioactive wastes. Other feedstocks tested include PCBs, asbestos, sewage sludge, oil, coal/water slurry, petroleum coke, paper, plastics and metals.

As plasma gasifiers can accept almost any material, the main feedstocks used have been those that other processes cannot use, and/or those with a gate fee (i.e. negative costs). This may include those where it is too difficult or expensive to separate out further valuable recyclable material for sale. The organic content is gasified, and the inorganic content is vitrified[53], often needing to earn a co-product credit to justify economic viability. However, plasma gasification may become economically viable with non-waste feedstocks in the future.

The flexible operation of the plasma torches, by ramping up or down the input electrical power or the rate of plasma flow, allows any variations in the feedstock quantity, moisture and composition to be accommodated, maintaining a constant gasifier temperature[54]. Plasma gasifiers can therefore accept feedstocks of variable particle size, containing coarse lumps and fine powders, with minimal feed

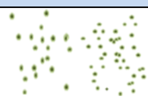
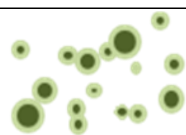
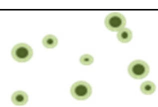
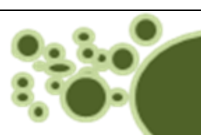
[52] Hamelinck, C.N and A.P.C. Faaij (2006) "Production of methanol from biomass", Ecofys & Utrecht University
[53] Pierre Carabin & Jean-Rene Gagnon (2000) "Plasma Gasification and Vitrification of Ash – Conversion of Ash into Glass-like Products and Syngas" PyroGenesis Inc, Canada
[54] Gomez et al. (2009) "Thermal plasma technology for the treatment of wastes: A critical review" Journal of Hazardous Materials 161, 614–626

preparation[55] – size reduction and drying are not usually required, and heterogeneous feedstocks are acceptable[56]. However, in general, feedstocks with higher average moisture or inorganic contents lead to lower gasification reaction and syngas temperatures, and lower efficiency, and feedstocks with lower average carbon contents lead to a lower syngas quality and/or heating value[57]. The sorting of wastes to remove glass, metals and inert materials before input to the plasma reactor is therefore sometimes a preferred feedstock preparation, as is the case for Plasco and InEnTec.

### 4.1.7 Summary

The requirements of different gasifier types vary considerably: from EF gasifiers requiring small particle sizes, an optimal moisture content and a consistent composition over time, to plasma gasification which can accept nearly all biomass feedstocks with minimal or no pre-treatment. CFB and BFB, and Dual systems have intermediate feedstock requirements, being able to accept larger particle sizes and a wider range of moisture contents than EF, but also requiring care over the use of feedstocks with low ash melting temperatures, such as agricultural residues. The feedstock requirements for each gasifier type are summarised in Table 10.

**Table 10: Summary of feedstock requirements**

| Gasifier | Size | Moisture | Composition | Other |
|---|---|---|---|---|
| **EF** |  <1mm | 15% | Should not change over time. Limited proportion of high-ash agricultural residues | Pre-treatment steps being used |
| **BFB (and Dual with BFB gasifier)** |  <50-150mm | 10-55% | Can change over time Care needed with some agricultural residues | |
| **CFB (and Dual with CFB gasifier)** |  <20mm | 5-60% | Can change over time Care needed with some agricultural residues | |
| **Plasma** |  Not important | Not important | Not important, can change over time. Higher energy content feedstocks preferred | Used for a variety of different wastes, gate fees common |

[55] Westinhouse Plasma Corp (2002) "Westinghouse Plasma Coal Gasification & Vitrification Technology" Power Generation Conference, Hershey, PA
[56] The Recovered Energy System (2009) "Discussion On Plasma Gasification" Available online: http://www.recoveredenergy.com/d_plasma.html
[57] Williams et al. (2007) "H2 Production via Biomass Gasification", AEP Project, Task 4.1 Technology Assessments of Vehicle Fuels and Technologies, PIER Program, California Energy Commission, prepared by ITS-Davis

### 4.2 Ability and potential to achieve syngas quality requirements

As stated in Section 2.6, no gasifier technology is able to directly meet the strict syngas quality requirements for liquid fuels production without gas cleanup – however, some gasifiers produce slightly more suitable syngas than others. This can lead to decreased requirements for certain components in the syngas cleanup and conditioning, with corresponding reduced or avoided costs. This section will therefore examine the main trends in the syngas composition of each gasifier type.

As a reminder from Section 2, the ideal syngas for cobalt FT synthesis would contain a ratio of $H_2$ to CO of around 2:1, with no methane, tars, hydrocarbons, particles, impurities or inert gases such as nitrogen. As an illustration of the variation in syngas compositions, the available data for the raw syngas produced by each gasifier technology, using its main preferred feedstock, is shown in Table 11. These compositions vary widely within the same gasifier type, due to different feedstocks, sizings and moisture contents, process temperatures, pressures, oxidants, residence times and presence of bed catalysts. However, since the indirectly heated gasifiers (EF: Range, Pearson; BFB: Iowa, TRI; and all of the Dual gasifiers) all use steam, they will share certain similarities in syngas composition regardless of the gasifier type, and hence are discussed separately.

#### 4.2.1 Entrained flow gasifiers

Due to the high temperatures present within an EF gasifier, hydrogen and carbon monoxide are strongly favoured over methane within the gasification reactions[58]. $CO_2$ yields are reduced at higher temperatures, and tars and hydrocarbons are cracked into smaller components. Since most of the EFs considered in this analysis are pressurised and oxygen blown, the syngas has low concentrations of inert gases (e.g. nitrogen), and typically has high % volumes of $H_2$ and CO, with very low amounts of methane, hydrocarbons and tars[59]. The result is a high quality syngas that needs very little cleaning for tars.

#### 4.2.2 Bubbling fluidised bed gasifiers

BFBs operate at lower temperatures than EF gasifiers; hence the main difference between the gasifier types is the presence of methane, hydrocarbons and tars in the BFB syngas. Those gasifiers using oxygen still have fairly high levels of $H_2$ and CO, but those using air always have at least 38% nitrogen dilution[60], leading to much reduced levels of $H_2$ and CO. The use of oxygen therefore increases syngas quality, but is expensive, requiring an air separation unit. The syngas is high in particulates (from attrition of the smaller pieces of bed material, ash and soot/fine coke particles)[61]. Particle removal technology is mature and inexpensive, but there are still some challenges in the removal of particles at high temperature.

[58] Haryantoa et al. (2009) "Upgrading of syngas derived from biomass gasification: A thermodynamic analysis", Biomass & Bioenergy 33, 882-889

[59] Olofsson, I., Nordin, A. and U. Söderlind (2005) "Initial Review and Evaluation of Process Technologies and Systems Suitable for Cost-Efficient Medium-Scale Gasification for Biomass to Liquid Fuels", Umeå University and Mid Swedish University

[60] Opdal, O.A. (2006) "Production of synthetic biodiesel via Fischer-Tropsch synthesis: Biomass-To-Liquids in Namdalen, Norway", Norwegian University of Science and Technology thesis

[61] Olofsson, I., Nordin, A. and U. Söderlind (2005) "Initial Review and Evaluation of Process Technologies and Systems Suitable for Cost-Efficient Medium-Scale Gasification for Biomass to Liquid Fuels", Umeå University and Mid Swedish University

**Table 11: Syngas composition of gasification technologies. See Section 7 for references**

| Technology type | Gasifier | Gasifier heating | Oxidant | $H_2$ | CO | *$H_2$:CO ratio* | $CO_2$ | $H_2O$ | Methane | Hydro-carbons ($C_{2+}$) | Nitrogen ($N_2$) | HCN, $NH_3$, $NO_x$ | Sulphur (COS, $H_2S$, $CS_2$) | Halides (HCl, Br, F) | Alkalines (Na, K) | Tars | Particulates (ash, soot) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **EF** | CHOREN | Direct | $O_2$ | 37.2% | 36.4% | *1.02* | 18.9% | 7.3% | 0.06% | | 0.1% | | | | | very low | |
| | KIT | Direct | $O_2$ | 23% | 43% | *0.53* | 11% | | <0.1% | | 5% | HCN 3.4mg/$Nm^3$ $NH_3$ 0.4mg/$Nm^3$ | | 1.7mg/$Nm^3$ | | "none" | |
| **BFB** | Carbona | Direct | $O_2$/steam | 20% | 22% | *0.91* | ? | | 5% | | | | | | | | |
| | EPI | Direct | $O_2$ | 37.5% | 40% | *0.94* | 15% | 3% | <1% | | 3% | | | | | | |
| | Enerkem | Direct | Air | 6-12% | 14-15% | *0.4-0.8* | 16-17% | | 3-4% | 2.9-4.1% | 36-58% | | | | | | |
| **CFB** | Foster Wheeler | Direct | Air | 16.0% | 21.5% | *0.74* | 10.5% | | ? | | 46.5% | | | | | | |
| | CHRISGAS | Direct | Air | 11% | 16% | *0.69* | 10.5% | 12% | Methane & $C_{2+}$ 6.5% | | 44% | | | | <0.1ppm | <5g/$Nm^3$ | dust <2ppm |
| | CUTEC | Direct | $O_2$/steam | 31.6% | 22.0% | *1.44* | 33.6% | | 7.9% | $C_2H_2$ 0.6%, $C_2H_4$ 1.2% | 3% | | | | | 9.5g/$Nm^3$ | dust 12g/$Nm^3$ |
| | Fraunhofer | Direct | Air | 18% | 14% | *1.29* | 16% | 10% | 3% | | 39% | | | | | | |
| | Uhde | Direct | $O_2$/steam | 30.1% | 33.1% | *0.91* | 30.6% | | 5.7% | $C_6H_6$ 770ppm | 0.4% | 90ppm $NH_3$ | $H_2S$ 0.03% | 0ppm HCl | | | |
| | ECN BIVKIN | Direct | Air | 18% | 16% | *1.13* | 16% | | 5.5% | 2.38% | 42% | $NH_3$ 2200mg /$Nm^3$ | $H_2S$ 150mg /$Nm^3$ | HCl 150mg /$Nm^3$ | | 0.12% | |
| **EF** | Pearson | Indirect | Steam | 51.5% | 24.1% | *2.14* | 17.8% | | 5.8% | | 0.5% | | | | | | |
| **BFB** | Iowa | Indirect | Steam | 26% | 39% | *0.67* | 18% | | 11% | | | | | | | | |
| **BFB** | TRI | Indirect | Steam | 43.3% | 9.2% | *4.71* | 28% | 5.6% | 4.7% | 9% | | 0% | | | | low | |
| **Dual** | REPOTEC | Indirect | Steam | 38-45% | 22-25% | *1.6-1.8* | 20-23% | | 9-12% | $C_2H_4$ 2-3%, $C_2H_6$ 0.5%, $C_{3+}$ 0.5% | 2-3% | 1000-2000ppm $NH_3$ | $H_2S$ 40-70ppm, other 30ppm | | | 2.3g/$Nm^3$ | 5-10g /$Nm^3$ |
| | SilvaGas & Taylor | Indirect | Steam | 22% | 44.4% | *0.50* | 12.2% | | 15.6% | $C_2H_4$ 5.1%, $C_2H_6$ 0.7% | | | | | | | |
| | ECN MILENA | Indirect | Steam | 18.0% | 44.0% | *0.41* | 11.0% | 25.0% | 15.0% | $C_2H_6$ 1%, others 5% | 4.0% | $NH_4$ 500-1000 ppmv | $H_2S$ 40-100ppmv | | | 40g/$Nm^3$ | |
| **Plasma** | Westing-house | Direct | None | 15.9% | 40.4% | *0.39* | 3.6% | 37.3% | ? | | none | | | | | | |
| | Startech | Direct | None | 52.0% | 26.0% | *2.00* | | | <1% | <0.5% | 16% | | | | | | |
| | Solena | Direct | None | 42.5% | 45.3% | *0.94* | 4.3% | 0.01% | ? | $C_2H_4$ 2.56% | 5.2% | | $H_2S$ 0.11% | HCl 0.05% | | | |
| | InEnTec | Direct | None | 36.5% | 46.8% | *0.78* | 11.8% | 1.5% | ? | | 3.3% | | | | | | |

#### 4.2.3 Circulating fluidised bed gasifiers

CFBs also operate at lower temperatures than EF gasifiers, hence like BFBs, methane, hydrocarbons and tars are all present in the syngas. The syngas quality can vary considerably, depending on the operating conditions. Again, using air as the gasification oxidant leads to heavy dilution by nitrogen, and only those CFBs using oxygen have high levels of $H_2$ and CO. CFBs are capable of producing similar proportions of $H_2$ and CO in the syngas to BFBs, and also have higher rates of throughput – although both are less than EF[62]. The syngas is very high in particulates (from the suspended bed material, ash and soot), and their rapid transport and circulation can result in equipment erosion.

#### 4.2.4 Dual Fluidised Bed and other steam blown, indirectly heated gasifiers

The presence of steam in the gasification reaction promotes the production of hydrogen, but also promotes methane (which can often reach levels of 10% or higher). Once formed, methane is stable at lower temperatures; thereby its production detracts from the $H_2$ and CO in the syngas. Methane can be reformed, but at an efficiency loss. However, by using steam, there is no nitrogen dilution in the syngas, and the high levels of hydrogen reduce the need for a downstream water gas shift reaction. Depending on the gasification reactor design (CFB or BFB), the syngas from Dual fluidised bed gasifiers will be high or very high in particulates[63].

#### 4.2.5 Plasma gasifiers

Plasma gasification usually takes place in the absence of a gasification oxidant, with some gas (e.g. air, oxygen, nitrogen, noble gases) only present to produce the plasma in the jet or arc, for the provision of heat. Extremely high temperatures (greater than 5,000°C) ensure that the feedstock is broken down into its main component atoms of carbon, hydrogen and oxygen. These quickly re-combine to form hydrogen and carbon monoxide gases, thereby producing a very high quality syngas, with no methane, hydrocarbons or tars[64]. Other plasma gasifiers work at lower temperatures (from 1,500°C to 5,000°C, but still well above EF conditions), producing some tars and hydrocarbons, which are then immediately cracked. Plasma torches have highly adjustable power outputs, hence temperatures and syngas components can be controlled. Since plasma gasification usually uses waste feedstocks, chlorides levels can be high, which can lead to high levels of impurities (such as dioxins and metals) in the syngas, although many of the heavier elements are vitrified and hence safely removed.

#### 4.2.6 Summary

In terms of the presence of methane, hydrocarbons and tars, the order of gasification temperatures dictate that Plasma gasifiers produce the best quality syngas, followed by EF, and finally Dual, CFB and BFB gasifiers. The quality of the syngas from a fluidised bed gasifier is still significantly higher than that

[62] Olofsson, I., Nordin, A. and U. Söderlind (2005) "Initial Review and Evaluation of Process Technologies and Systems Suitable for Cost-Efficient Medium-Scale Gasification for Biomass to Liquid Fuels", Umeå University and Mid Swedish University

[63] Ingemar Olofsson, Anders Nordin and Ulf Söderlind (2005) "Initial Review and Evaluation of Process Technologies and Systems Suitable for Cost-Efficient Medium-Scale Gasification for Biomass to Liquid Fuels", Umeå University and Mid Swedish University

[64] The Recovered Energy System (2009) "Discussion On Plasma Gasification" Available online: http://www.recoveredenergy.com/d_plasma.html

of the updraft gasifiers excluded in Section 2.6. Avoiding nitrogen dilution is another important consideration, which is automatically achieved in an EF, Plasma or Dual fluidised bed gasifier, but only occurs in a CFB or BFB gasifier if oxygen or steam is used as the gasification oxidant. Steam gasification gives higher hydrogen syngas levels, but also higher levels of methane. Particulates are an issue for CFB, BFB and Dual technologies, whereas impurities coming from the feedstock are an issue for all technologies.

## 4.3 Development status and operating experience

### 4.3.1 Entrained flow gasifiers

The two most advanced EF biomass gasifier developers are two of the main players in thermochemical biofuels routes, having received significant government funding and investor interest, along with participation of major industrial partners. These developers are constructing their demonstration plants, although both have experienced delays.

- CHOREN's 3odt/day pilot plant has been operational since 2003, and its 200odt/day demonstration plant is now due to start gasifier operation followed by FT diesel production by the end of 2009. The plant has been delayed by a year due to modifications to meet the safety findings in the Baker report[65], which would be incorporated from the start in future plants. CHOREN still have ambitious future plans for scale-up to 3,040odt/day by 2012/2013, with wider deployment in Germany. CHOREN partners include Shell, Volkswagen and Daimler
- Range Fuels built a 5odt/day pilot in 2008, and a 125odt/day demonstration plant is due to be gasifying biomass for subsequent production of ethanol and mixed alcohols in 2010. The scale of this plant has been halved from the original plans of 20m gal/yr of production by late 2009, with the company stating that this was a result of problems with lead times for equipment sourcing. Further commercial plants at 1,250odt/day input scale are planned, but with no clear timescale yet

In addition to this, there are three other EF gasification technology developers concentrating on biofuels production, but are currently at a smaller or less developed stage in developing the key biomass conversion process steps (Pearson, FZK/KIT and Mitsubishi Heavy Industries). Pearson and Mitsubishi have pilot plants at <5odt/day, with construction of Pearson's scale up to 43odt/day scale progressing slowly. KIT/FZK are building and verifying each stage of their 12odt/day pilot plant – the pyrolysis step was completed in 2007, and the 85bar Siemens/Future Energy gasifier is expected to be integrated with the pyrolysis step by 2011, with gas cleaning and fuel synthesis steps to follow. Note that the gasifier reactor is not a new technology: it has been in commercial operation using up to 306odt/day of coal and wastes at the Schwarze Pumpe plant in Germany since 1984, for methanol production. In general, plants based on EF technology should benefit from the extensive experience with coal to liquids EF gasification routes, with their highly developed process integration.

Other successful EF technology developers are investigating co-gasification – Shell, Uhde and GE (and possibly ConocoPhillips, Hitachi) could move into biomass gasification if the future market for BTL

[65] Pers. Comm CHOREN

appears to be commercially attractive. CHOREN could also use their CCG coal gasification technology in the future with biomass.

ARLIS Technology, a high-temperature, oxygen-blown vertical vessel EF was jointly developed by TRE Terra Recycling und Entsorgung GmbH, Wiesenburg and Power Plant GmbH, Freiberg. The technology was going to be integrated into a waste wood IGCC plant of V.I.A. Biomasse-Heizkraftwerk GmbH & Co. Kirchmöser KG. The basic engineering started, but the project failed because of the insolvency of TRE[66].

### 4.3.2 Bubbling fluidised bed gasifiers

Several BFB gasifiers have been built for heat and power production since the 1970s, but only at modest scales. There are now plans for scale up to larger scales, and also to use of BFB gasifiers for liquid fuels production. Experience to date has been based on both atmospheric and pressurised systems, but many of these have been air blown, with current development focusing on the use of oxygen/steam oxidants in pressurised systems. There are a number of biomass BFB gasification technology providers, three of which have commercial heat and power plants, with plans for fuel production:

- Carbona/Andritz's Skive CHP plant started in mid-2008, using 100-150odt/day wood. Support research on gas conditioning is also ongoing at GTI, with the goal of developing the technology for a future very large (1,440odt/day biomass input) FT biodiesel plant with forestry supplier UPM
- Enerkem's BioSyn process is being commissioned at the 30odt/day Westbury plant, with a 228t/day plant starting construction in Edmonton in 2009, and plans for several other larger syngas to ethanol plants using wastes. BioSyn has the longest development history of any biomass gasifier, with demonstration heat and power plants built back in the 1970s
- TRI have received grants for two projects in the US (Flambeau Rivers and Wisconsin Rapids) to make ethanol from wood, and will be carrying out pilot FT testing with Rentech
- EPI have previous experience with small plants for heat and power, and are involved in a large project for cattle manure gasification. The syngas produced will be used to power Panda Ethanol's 1st generation ethanol plant (instead of gas or coal), but will not be directly converted to ethanol. However, construction is currently on hold, due to delays and costs overruns leading to a loan default[67], i.e. not as a result of problems not related to the gasifier. Advanced Plasma Power has plans for a heat and power plant in the UK using 137odt/day of MSW, incorporating EPI's gasification technology followed by plasma reforming to clean the syngas

BFB technology has suffered some set-backs in the past. These include:

- Stein Industry/ASCAB: Basic gasifier research started in 1980 with a 2odt/day wood BFB gasifier. In 1983, the plant capacity was increased to 8.5odt/day. In 1986, a 51odt/day pressurized fluidized bed system was installed in France. As of 2002, Stein has abandoned the process[68]

[66] Kees W. Kwant and Harrie Knoef (2004) "Status of Gasification in countries participating in the IEA and GasNet activity" Novem and BTG, Netherlands
[67] Bioenergy Business (2009) "Panda Ethanol subsidiary goes bankrupt" http://www.bioenergy-business.com/index.cfm?section=americas&action=view&id=11838
[68] Ciferno, J.P. & J.J. Marano (2002) "Benchmarking Biomass Gasification Technologies for Fuels, Chemicals and Hydrogen Production" Prepared for U.S. Department of Energy National Energy Technology Laboratory by $E^2S$

- The closure of GTI's RENUGAS 84odt/day bagasse plant in Hawaii in the mid 1990s due to feedstock handling problems[69]
- TRI/MTCI's black liquor gasifier at Georgia-Pacific's Big Island paper mill is also no longer operating, since the cost of upgrading the reformer after specification problems occurred was too great[70]. Another MTCI project started with V.I.A. Biomasse-Heizkraftwerk GmbH & Co. Kirchmöser KG to burn syngas in an existing waste wood combustion plant ran into serious difficulties with the permitting authorities[71]

Enerkem were also due to supply a 247odt/day RDF gasifier for Novera's 12MW$_e$ power plant in Dagenham, London – although planning was granted in 2006, Novera withdrew from the UK's New Technologies Demonstrator Programme and were still looking for additional funding. The project was sold to Biossence in Apr 2009[72], who are developing several waste to power projects in the UK[73], and are partnering with New Earth Energy[74]. However, little information regarding this pyrolysis + gasification technology is available, and although large plants are planned, there do not appear to be any pilot scale plants built to date.

#### 4.3.3 Circulating fluidised bed gasifiers

CFB technology has been used in a number of commercial biomass gasification plants since the 1980s. As with BFB, most of the experience is with air-blown, atmospheric gasifiers for heat and power, with development only now focusing on pressurised oxygen blown systems. Foster Wheeler is the main player, through the direct offerings of their commercial gasification equipment in heat and power applications, backed up by their participation and technology provision within international research projects:

- Foster Wheeler Energy's (formerly Ahlstrom's) CFB technology has been commercial and using biomass since the mid 1980's, although mainly for fossil-fuel displacement in heat and power applications. New, larger plants are planned, such as the new ~768odt/day MSW gasification plant in Lahti, Finland
- VTT, Finland are running the Ultra-Clean Gas project with the aim of developing a pressurised, oxygen/steam blown CFB gasification technology for liquid biofuels production. Building on VTT's history of CFB pilots and testing, the second phase of the project is the 12MWth (60odt/day) Stora Enso/Neste Oil joint venture at the Varkaus mill, with the gasifier supplied by Foster Wheeler. Full plant operation is expected in 2010, and construction is progressing well. Future scale-up plans are a 1,522odt/day BTL plant by 2013

[69] Suresh Babu (2003) "Biomass Gasification For Hydrogen Production – Process Description And Research Needs" IEA Thermal Gasification Task Leader Gas Technology Institute
[70] TRI website (2009) Available online: http://www.tri-inc.net/plants.html
[71] Kees W. Kwant and Harrie Knoef (2004) "Status of Gasification in countries participating in the IEA and GasNet activity" Novem and BTG, Netherlands
[72] **Bioenergy & Waste News (2009)** "Novera sells off gasification project to focus on wind power" Available online: http://www.newenergyfocus.com/do/ecco.py/view_item?listid=1&listcatid=119&listitemid=2512
[73] Biossence: The Process (2009) Available online: http://www.biossence.com/process
[74] Bioenergy & Waste News (2008) "Dorset waste firm sets up renewable energy business" Available online: http://www.newenergyfocus.com/do/ecco.py/view_item?listid=1&listcatid=105&listitemid=1753

- The original 86odt/day Värnamo IGCC "Bioflow" joint venture with Sydkraft was in operation from 1993-1999, but was unviable after this testing period[75]. Operation was halted until ownership passed to the Växjö Värnamo Biomass Gasification Center in 2003. As part of the EU CHRISGAS project, funding was provided for oxygen/steam upgrading, gas cleaning tests and FT fuels production – however, only some of the tests were completed within the project timeframe. A new rebuilding plan and consortium structure has recently been drawn up, and Swedish Energy Agency funding has been provided for ongoing costs, but they are still looking for additional funding to complete the conversion of the plant for BTL production

There are also other pre-commercial CFB gasifier developments involving biofuels production at several European research institutions, but which appear to only be progressing slowly:

- CUTEC recently built a 2.7odt/day full BTL chain pilot, with future scale-up to 100t/day mentioned
- Fraunhofer Umsicht 2.4odt/day pilot has had little development since 1996
- TUB-F plan to combine Lurgi's MtSynFuel methanol catalysts with Uhde's High-Temperature Winkler (HTW) gasifier to produce a full BTL chain, but so far only feasibility studies of the basic engineering and costs have been conducted. The HTW gasifier was developed for coal gasification (with several plants built), and some MSW co-firing tests were conducted at Berrenrath. In 1998, a 576odt/day peat HTW was built in Oulu, Finland for ammonia production, although the peat inhomogeneity, high tar content of the syngas and pipe blockages all caused initial problems

Several other CFB gasifier technology developers are no longer active in the area of gasification, having shelved, merged or transferred their technology, or licence ownership and marketing efforts. The examples below give an indication of the past development of the CFB sector:

- ECN 'BIVKIN' gasifier: ECN is now developing the Dual FB MILENA gasifier, after stopping development of the air blown 500kWth (2.4 odt/day biomass) 'BIVKIN' CFB in 2004. This change in research focus occurred because of the rise in interest in Dual gasifiers for producing bio-SNG. Valuable experience with feedstock testing has been carried over[76]
- Lurgi: has three operational commercial-scale atmospheric, air-blown CFB plants[77]:
  - 100$MW_{th}$ waste in Ruedersdorf, Germany
  - 85$MW_{th}$ for co-firing in the AMER plant in Geertruidenberg, Netherlands was started up in 2000, and rebuilt for 2005, but still suffers cooler fouling problems
  - 29$MW_{e}$ plant in Lahden, Netherlands has been operational since 2002
  - (Lurgi's plant built in 1987 in Pols, Austria is no longer in operation)

  However, Lurgi is no longer developing this biomass CFB technology, having sold the rights to Envirotherm. Envirotherm advertise the technology, but have not sold or planned any projects using the CFB technology to date[78]. Lurgi were acquired by Air Liquide in 2007, and are still involved in BTL via their involvement in the decentralised pyrolysis and syngas conversion stages of the KIT process

[75] S. Babu (2006) "Work Shop No. 1: Perspectives on Biomass Gasification", IEA Bioenergy Agreement, Task 33: Thermal Gasification of Biomass
[76] C.M. van der Meijden, H.J. Veringa, A. van der Drift & B.J. Vreugdenhil (2008) "THE 800 KWTH ALLOTHERMAL BIOMASS GASIFIER MILENA" ECN
[77] Babu et al. (2001) "First Meeting of IEA International Energy Agency Thermal Gasification of Biomass Task in Germany", Technical University Dresden, Available online at: http://media.godashboard.com/gti/IEA/IEADresden11_21_01.pdf
[78] Corporate website (2009) Available online: http://envirotherm.de/content/e39/e137/index_eng.html

- Despite successful pilot plant operation, TPS Termiska Processor AB (Studsvik Energiteknik) was unable to commercialise its CFB technology. TPS had several plants constructed or planned, which were not successful[79]:
    - The EU-sponsored IGCC ARBRE project constructed in Eggborough in the UK failed due to technical difficulties in commissioning leading to continual delays, and the bankruptcy of the plant owners
    - A lack of funding led to the World Bank-sponsored BIG-GT Brazil project never starting
    - Two TPS 15$MW_{th}$ CFB gasifiers were installed in the Aerimpianti plant located in Greve, Italy in 1992, processing refuse derived fuel (RDF) and using the syngas for cement kilns. However, the plant suffered from slag accumulation on the boiler tubes leading to prolonged outages, and also a shortage of operating funds, and is no longer operating

  There have been no other recent developments, and the main technical leads of TPS are now members of the CHRISGAS project team
- Babcock Borsig Power GmbH in Germany was one of the largest waste-to-energy equipment suppliers, with a substantial incineration and combustion experience. Their subsidiary, Austrian Energy built a 10MWth CFB at Zeltweg, Austria in 1998 to replace 3% of a power station's coal use, but the coal station shut in 2001. After Babcock declared insolvency in 2002, their CFB process was then marketed under Austrian Energy & Environment, who now only focus on biomass combustion[80]
- Kvaerner: a CFB gasifier was installed at Kvaerner's Södracell Värö paper mill in Götaverken, Sweden in 1987. The plant was fuelled by 30MWth of bark and wood wastes, with the syngas used for co-firing in a lime kiln. Enriched air tests were conducted in 2003, increasing capacity. However, the gasifier is seen as a one-off, since Kvaerner never built any further plants due to low oil prices, and sold off their pulping and power division to Metso Corporation. Metso still operate the Värö gasifier, and installed a slipstream gas cleaning test rig at the site in 2008, but seem to be more focused on large scale demonstration of syngas cleaning than actual gasifier development[81]

#### 4.3.4 Dual fluidised bed gasifiers

Although Dual fluidised bed gasifiers utilise CFB and/or BFB technologies, the combined process is still considered to be at the development stage, compared to the commercial individual CFB or BFB technologies. There is current interest in Dual fluidised bed systems due to the avoidance of nitrogen dilution in the syngas, without the cost of using pure oxygen. Dual systems have been tested since the 1980s at pilot scale, followed by the larger heat and power demonstration plants:

- REPOTEC/TUV's 40odt/day CHP plant has been successfully operating at high availabilities in Güssing, Austria since 2001, using the Fast Internally CFB technology created at TUV. They have also conducted small slipstream studies, converting syngas to liquid fuels
- A similar CHP plant in Oberwart, Austria was designed by REPOTEC for 53odt/day, but after contract availability negotiations broke down, the project was handed over to the utility BEGAS in 2004, who

[79] Juniper Kees W. Kwant and Harrie Knoef (2004) "Status of Gasification in countries participating in the IEA and GasNet activity" Novem and BTG, Netherlands
[80] Juniper (2007) "Commercial Assessment: Advanced Conversion Technology (Gasification) for Biomass Projects" for Renewable East
[81] Pekka Saarivirta (2008) "Development and experience of Biomass Gasification in Metso Power", International seminar on Gasification in Malmö, Sweden

still continued to work with TUV. Construction was completed in 2007, and the commissioning process started in Nov 2008[82]

- The SilvaGas (previous FERCO) process at 350odt/day of wood was operated at the McNeil site in Burlington, Vermont from 1997, with the syngas successfully co-fired in the wood combustion boiler. Further US DOE funding in support of full IGCC implementation (including gas cleaning and a new high efficiency gas turbine to replace the boiler) did not occur, and the existing plant proved to be uneconomic for electricity production, and was shut down in 2001. FERCO also failed to raise further capital with disputes between investors, and filed for bankruptcy in Nov 2002[83]

Several larger commercial plants have been planned for some time (again only for heat and power production), but construction is yet to commence:

- Biomass Gas & Electric: a 540odt/day SilvaGas waste wood plant in Forsyth, Georgia is still thought to be in an advanced stage of planning[84]
- Biomass Gas & Electric has planned 730odt/day SilvaGas plant in Tallahassee, Florida for distributing syngas via the gas network, but withdrew their environmental permit application in Feb 2009 under strong local opposition, and are no longer pursuing the project[85]
- Taylor Biomass's 370odt/day MSW and construction waste wood plant in Montgomery, New York was due to start construction in 2007 for operation in 2010, with possible upgrading to ethanol production[86]

One encouraging announcement made by Rentech in May 2009 is their intention to build a large BTL plant in Rialto, California. This will be using a SilvaGas gasifier to convert an estimated 800odt/day of urban waste wood into 600barrels of FT liquids/day, and export 35$MW_e$ of power, with operation starting in 2012[87].

The group of Dual technologies also have several other possible projects mentioned (such as SilvaGas for Process Energy, Taylor Biomass for Abengoa), and the ECN MILENA 3.8odt/day pilot plant, operational since 2008, has fairly ambitious scale-up goals (480odt/day by 2015). Dual fluidised bed gasifiers have had a sporadic development in the past, but recent successful demonstrations and interest in BTL applications are promising.

#### 4.3.5 Plasma gasifiers

Plasma gasification plants have been built on a small scale for commercial waste treatment and power applications in the past decade, but are yet to reach a large scale. Several developers are already using or planning to use modular systems in the future. The two largest developers, Westinghouse Plasma and Plasco, are active in the waste to electricity sector:

[82] Hermann Hofbauer, Reinhard Rauch (2008) "Gasification Survey Country: Austria" IEA 33
[83] Joseph Cain (2009) "BIOMASS ELECTRIC FACILITY IN TALLAHASSEE: *HISTORY OF BIOMASS DEVELOPMENT IN BURLINGTON VERMONT*" Chair: Committee on Public Affairs, Tallahassee Scientific Society
[84] Juniper (2007) "Commercial Assessment: Advanced Conversion Technology (Gasification) For Biomass Projects", report for Renewables East
[85] Bruce Ritchie (2009) "Tallahassee biomass plant withdrawn" Available online: http://bruceritchie.blogspot.com/2009/01/tallahassee-biomass-plant-withdrawn.html
[86] Taylor Biomass Energy (2009) Available online: http://www.taylorbiomassenergy.com/
[87] Rentech, In F2Q09 Earnings Call Transcript (2009) Available online: http://seekingalpha.com/article/137259-rentech-inc-f2q09-qtr-end-03-31-09-earnings-call-transcript?page=-1

- Westinghouse Plasma Corp was the earliest plasma developer, and has several years operating experience with its commercial MSW power plants in Japan. WPC are building two hazardous wastes plants in India. Waste2Tricity, its UK licensee, has plans for a 114odt/day MSW plant
- Plasco has developed a 70odt/day MSW plasma gasifier module that has been operational since 2008 in Ottawa, Canada, with plans for 140-280odt/day modular plants for power applications

Other developers have technologies at a much smaller scale, and have primarily focused on waste destruction in the past. InEnTec have built many plants, but only at the 10-25odt/day scale, and these appear to be based on a batch process rather than continuous feeding. Startech has built several 3.8-7.5odt/day units for processing hazardous or medical wastes, and larger power units are being planned for Panama and Poland. Some of these smaller plants have faced serious operational difficulties[88]:

- InEnTec's mixed radioactive and hazardous waste gasifier in Richland, Washington closed in 2001 due to operational problems with the plasma arc equipment as well as financial difficulties
- InEnTec's Hawaii Medical Vitrification facility near Honolulu violated its emissions permit, and also was down for 8 months due to damage of the arc equipment
- Brightstar Environmental, a joint venture between Energy Developments Limited and Brightstar Synfuels, had an MSW pilot facility in Wollongong, Australia. This closed in April 2004 because of financial and technical problems, with material handling issues and high levels of char particles. The company was planning 2 projects in Australia and had planning permission for UK plants in Derby and Kent, but no longer exists

There are a few plasma gasifiers operational as fuel synthesis pilots, with an interesting emerging trend for plasma gasifier technologies to be used in conjunction with developers of novel feedstocks (e.g. algae, tyres) or syngas uses (e.g. syngas fermentation):

- Three Startech units (totalling 19odt/day) are reported to be operational in Puerto Rico, producing methanol since 2008. A joint venture has also been set up with Future Fuels to build plasma gasification to ethanol plants using tyres
- Coskata is building its syngas fermentation to ethanol pilot in Madison, Pennsylvania using a Westinghouse Plasma gasifier. Operation is expected in 2009 taking in 1.2odt/day of biomass, and commercial modular plants are planned from 2011 taking in 1,500odt/day
- Solena are considering partnering with Rentech to convert waste into FT jet fuel. A Californian facility was proposed for operation by 2011, taking in 1,125odt/day of MSW, farm and wood wastes, although discussions are still ongoing. Solena have also considered algae gasification
- Fulcrum BioEnergy will be using an InEnTec gasifier in its Sierra BioFuels plant, Nevada to convert 218odt/day of MSW into ~10.5m gal/year of ethanol for cars and trucks from 2010

Many proposed projects have not materialised due to failure to secure emissions permits, sufficiently large waste streams and revenue agreements, or funding for the initial high capital costs.

- Solena planned plants for Rome, Puerto Rico and Galicia, but nothing appears to have been built[89]

[88] Greenaction for Health and Environmental Justice and Global Alliance for Incinerator Alternatives (2006) "Incinerators in Disguise: Case studies of Gasification, Pyrolysis and Plasma in Europe, Asia and the United States. Available online: http://www.greenaction.org/incinerators/documents/IncineratorsInDisguiseReportJune2006.pdf

[89] Solena Group (2006) "Introduction to Renewable Energy Production Program for Bio-Power in Puerto Rico", presentation at the University of Turabo

- Geoplasma's St Lucie plant was planned to be built in 2010, with 6 WPC gasifiers taking in 2,250odt/day of MSW. However, in Oct 2008 it was announced that a lower risk strategy will be pursued, with only a 150-450odt/day demo[90], without any mining of the adjacent landfill
- In 2001, Waste to Energy LLC proposed building a $192million, 260odt/day plant to produce 12.5$MW_e$ and 38m gal/year ethanol in Oahu, Hawaii. However, the project was abandoned in 2008 after failure to negotiate a supply of MSW, and lack of interest from the County Council[91]
- Wheelabrator Technologies' proposal for a $125m waste-to-energy plant for Hilo, Hawaii was rejected in 2008 because the full cost would have had to be borne by the County Council[92]
- Pollution permits for an InEnTec gasifier in Red Bluff, California were cancelled in Dec 2005[93]

#### 4.3.6 Summary

Bubbling fluidised bed, circulating fluidised bed and plasma gasifiers are established technologies for heat and power production from biomass or wastes. Some projects have failed in the past, often as a result of a lack of sustained commitment of adequate resources by the stakeholders involved to fully resolve issues associated with bringing large scale plants online.

Most of the BFB and CFB plants built to date are atmospheric and air blown, and so not optimal for liquid fuel production, with work ongoing on pressurised oxygen or steam blown systems. For all technologies, there are now several technology developers working on gasifiers for liquid fuel applications, but these vary considerably in size and experience. Entrained Flow and Dual fluidised bed gasifiers are the only gasifier types with any pilot or field operating data regarding the production of high quality syngas suitable for liquid fuels. The development status for each gasifier type is summarised in Table 12.

[90] Eric Pfahler (1 Oct 2008) "Geoplasma Inc may scale back on St Lucie trash zapping plan", TC Palm http://www.tcpalm.com/news/2008/oct/01/geoplasma-proposes-cuts-on-vaporizing-trash/
[91] Nanea Kalani Pacific Business News (2008) "Plan to zap Oahu trash fizzling out" Available online: http://www.bizjournals.com/pacific/stories/2008/10/20/story3.html
[92] Rod Thomson (2008) "Panel kills waste-to-energy plant", Available online: http://archives.starbulletin.com/2008/05/08/news/story09.html
[93] PR Newswire (2008) "InEnTec Medical Services LLC Cancels Permits to Build a Waste Recycle and Power Production Facility Near Red Bluff, California" Available online: http://www.bio-medicine.org/medicine-news-1/InEnTec-Medical-Services-LLC-Cancels-Permits-to-Build-a-Waste-Recycle-and-Power-Production-Facility-Near-Red-Bluff--California-21854-1/

**Table 12: Stage of development of gasifier technology types**

| Gasifier type | Heat & power applications | BTL applications | Developers |
|---|---|---|---|
| **EF** | No past commercial heat and power applications using dedicated biomass | Construction of biomass BTL demonstration plants ongoing. Most significant experience so far in integrating biomass gasification with fuel production, as a result of coal to liquid fuels experience | Several developers, with differing company sizes, and some large players having established designs based on fossil feedstocks. Participation by large industrial players in several projects |
| **BFB** | Well established heat and power applications, but only to modest scales using biomass | Currently scaling up to larger systems, and BTL applications, with plants under construction | Technology developers are smaller companies, with only a few interested in BTL |
| **CFB** | Well established heat and power applications, good experience in scaling up CFB for biomass | Early days of BTL applications, currently undergoing testing at pilot plants | Limited number of developers, one dominant (strong research base, with large industrial players onboard), others small |
| **Dual** | Earlier stage of technology development, heat and power applications successfully demonstrated | Early days of BTL applications, carrying out slipstream testing at a CHP plant | Few and small technology developers, but some interested in BTL |
| **Plasma** | Established power applications, but focused on MSW and waste feedstocks. Limited experience with other biomass | Very early days of scaling up to larger systems, some very small waste destruction plants also testing liquid fuels production | Several technology developers of different sizes, and many interested in BTL |

## 4.4 Current and future plant scale

Biomass gasifiers of widely varying scales have been built and operated over the past few decades. Figure 3 plots the plant size versus the date of first operation for each of the developers mentioned in the tables above, as a representation of their scale, and the scale of the future planned plants. The gasifiers included are those that predominately utilise biomass or MSW feedstocks, and are those used for heat and power applications as well as those currently targeted for BTL.

It should be noted that:

- All future plants (shaded in grey in Figure 3) have been plotted if they are given in company literature, including those contingent on the performance of smaller, earlier plants
- Where no date is given for plants to be built in the future, they have been plotted at the right hand side of the graph as 2015 or beyond
- Where plants are currently under construction now but with no end date given, they have been plotted as 2010
- Some of the plants shown have or will have modular systems with several gasifiers – those plants known to be modular are CHOREN's Sigma plants, Foster Wheeler's new Lahti plant, Plasco's Ottawa and Red Deer plants, and Westinghouse Plasma's plants at Utashinai, St Lucie, New Orleans, and for Coskata's commercial plant.

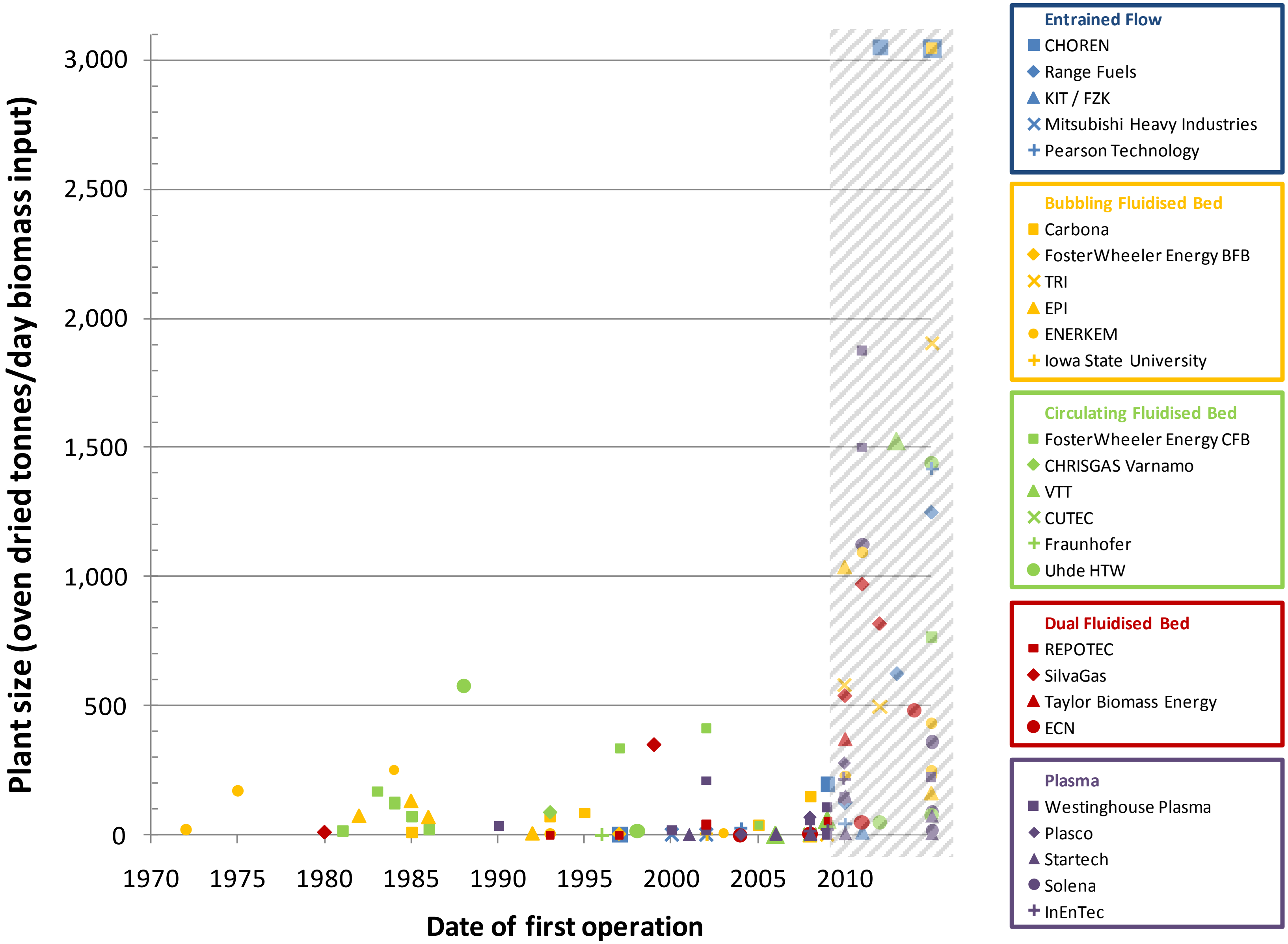



**Figure 3: Biomass gasification plant size and year of first operation. The size given is for the whole plant biomass input (the total of all gasifier modules)**

Figure 3 shows that:

- There have been three main waves in biomass gasification development: the first plants were installed in the mid 1980's for heat and power applications, then a new wave of technologies around the turn of this century to produce syngas with little or no nitrogen, and the recent wave of construction for BTL applications and subsequent expected ramp-up
- There are no commercial biomass gasification plants currently operating at or above the required minimum economic scale for catalytic fuels synthesis of 1,520odt/day
- Very few plants have been built at the same size. Plants tend to be individually sized according to syngas application and individual site demands or constraints, along with the type and quantity of available feedstocks
- CFB biomass gasifiers have been commercially mature for heat and power applications since the 1980's, but have as yet not progressed to very large scale (above 600odt/day input). Current lack of commercial development is probably due to unfavourable economics and competition from conventional fuels, and the fact that Foster Wheeler Energy is now focused on R&D of its pressurised, oxygen/steam blown CFB gasifier for BTL applications with VTT and Stora Enso/Neste Oil
- The historical picture is similar for BFB biomass gasifiers, although with earlier initial development in the 1970's, and at a slightly smaller scale compared with CFB. However, several BFB plants are currently in construction
- Dual fluidised beds have been developed at small scales over a long time, and are expected to be moving to larger scales in the near future. Despite the relatively few developers, the REPOTEC/TUV Güssing demonstration has been successful, and there are a number of planned projects, including a SilvaGas/Rentech BTL plant
- EF biomass gasification is the newest technology type, having only been developed recently for BTL applications. It is currently at a small scale, but will be progressing very rapidly to much larger scales in the next few years, and benefits from experience with coal feedstocks and co-firing
- Plasma gasification plants have mainly been at a small scale in the past, but several much larger plants are planned in the near future, with consideration of use for BTL

Bearing in mind the minimum economic scales for syngas fermentation of 290odt/day biomass input, or Velocys FT synthesis of 300odt/day, all the technology types are expected to be capable of scaling up to reach the minimum economic scale using a single gasifier in the near future. If the scaling down of the catalytic technologies using a Velocys type approach were not viable, the minimum scale for these syngas conversion processes would be 1,520odt/day biomass input. All technologies except Dual fluidised bed and Plasma have a plant planned using a single gasifier at around this scale (the larger plasma plants are modular). Note that the CFB and BFB technologies at this scale would be pressurised systems; operation of atmospheric CFBs, BFBs and Dual FBs is thought to be technically feasible up to 300-400$MW_{th}$ (1,500-2,000odt/day)[94], but this upper limit has never been explored. Developers have

[94] Tjimenson, M (2000) "The production of Fischer-Tropsch liquids and power through biomass gasification" Utrecht University, The Netherlands

been wary of building these large plants due to project risk[95], with high capital costs and a lack of large, stable feedstock supply markets[96].

However, as several planned plants use modular systems, all technologies could be used to achieve the minimum economic scale. Most of the very large planned plants will actually use multiple gasifiers as part of a modular system, rather than a single large gasifier. For example, CHOREN's Sigma plant, taking in a total of 3,040odt/day biomass, is designed to use 4 parallel lines, each with 1 high temperature EF gasifier fed by 4 first stage low temperature gasifiers taking in 190odt/day biomass.

The advantages of a modular system are:

- A plant can add extra units in order to scale up its capacity as the process is proven
- Plant availability will be higher since it is possible to still operate the other gasifiers whilst carrying out maintenance or repairs on an individual gasifier. However, the redundancy concept also depends – as with many other aspects – on conditions such as the type of feedstock, plant scale, process stability needed by the syngas demand, and performance guarantees
- Different gasifiers can be optimized for different feedstocks in order to use a mix of resources

The feedstock pre-treatment and syngas processing for a modular plant will be the same as that for a single gasifier plant, and will therefore have the same economies of scale, but a disadvantage of using smaller gasifiers is the increase in gasifier capital costs, due to the loss of economies of scale.

### 4.5 Costs

In this section, we review the availability of data on gasifier costs, and assess how this can be used to compare the gasifier types.

We reviewed the literature on costs of gasifier technologies, including academic papers and theses, company presentations, and a number of broader EU and US studies. As comparing the costs of different technologies involves making common assumptions about technologies with different configurations at different stages of development, we focused on a small number of reputable published reports, which have attempted to reconcile these differences. These are:

- RENEW – "Scientific Report: COST ASSESSMENT" completed in 2008 by Muller-Langer et al. at the Institute for Energy and Environment, for the Renewable Fuels for Advanced Powertrains Project. This aimed to give the typical costs for each step of a BTL fuel chain, and discover which technology concepts and EU regions hold the most promise. They covered biomass, capital, consumption and operation related costs, along with expected by-product revenues, and used Sankey diagrams of the energy flows and process efficiencies within the BTL plant. Behind this, individual cost, sizes and scale factors for the major system components were explicitly given, based on academic references mainly from the period 2000-2003

[95] Hamelinck et al. (2004) "Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential" Energy 29, 1743–1771
[96] Ghosh et al. (2006) "Scaling up biomass gasifier use: an application-specific approach", Energy Policy 34, 1566–1582

- "Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential", written in 2003 by Hamelinck et al. at Utrecht University and ECN. This aimed to assess oxygen and pressure blown gasification, along with various FT options, and covered capital costs (based on cost, scale and scale factors for major system components) along with operation related costs and by-product revenues
- "Future prospects for production of methanol and hydrogen from biomass", written in 2002 by Hamelinck and Faaij at Utrecht University. This aimed to assess various plant concepts with different levels of power and methanol or hydrogen production, and covered capital costs (based on cost, scale and scale factors for major system components) along with operation related costs and by-product revenues

From these reports, we can draw out information on

- The costs of some of the gasifier types when used for BTL applications; such as low temperature gasification followed by EF, decentralised pyrolysis followed by EF, atmospheric CFB and Dual gasifiers, and pressurised BFB, CFB and Dual gasifiers. Costs for plasma gasifiers or atmospheric BFBs were not available in the literature to the same level of detail, but estimates using heat and power application data have been made
- The relative capital costs of different components, from each of the various process steps of biomass pre-treatment, gasification, syngas cleanup and conditioning, fuel synthesis and upgrading, along with plant utilities
- The effect of changing some of the process parameters, e.g. pressure, gasification oxidant used

However, the extent to which we can directly compare the costs of gasification plants either within or between these references is limited, for several reasons:

- Each gasifier has a **different system concept** in terms of feedstock preparation, scale, fuel synthesis and plant integration, and many analyses do not fully state all underlying assumptions. Some concepts use a different feedstock and in a different form, one concept imports oxygen, concepts also vary in the amount of power they choose to export instead of fuel production, and in their use of different fuel synthesis reactors and catalysts, along with different feedback loops back into the earlier stages of the plant (for syngas recycling or using heat for feedstock drying or power generation)
- Each of the systems compared is at a **different stage of development**, from those where detailed engineering designs for a plant at large scale have been completed, to early stage concepts which combine data from different systems, and sometimes use related technologies as proxies. These earlier concepts often have poor efficiencies due to poor system integration, and may underestimate the true project costs or be overly optimistic regarding which components (and their size and number) can achieve successful, reliable, clean syngas production, due to a lack of project experience
- The **uncertainty** in the costs given in these references is around plus or minus 30%, due to the application of the Study estimate or Factored estimate method, which is based on the knowledge of major items of equipment
- Many of the costs given in these references for the major system components are based on **quotes from different years**, and hence these quotes are based on material costs from that time, and

furthermore, the components may well be at an earlier stage of development or at a smaller scale compared to what is available today

- The analyses give economic results for **different plant scales**. It is therefore necessary to use scale factors for each component in order to re-scale the whole plant to the required biomass input size. Although most of the plants given are of a similar scale, this re-scaling process (usually to a smaller plant scale) may be an approximation if the maximum sizes of components mean that instead of downsizing, fewer replicated components are used instead
- The assumptions regarding the BTL plant **associated costs vary considerably** between analyses. The non-equipment costs such as site preparation, services, insurance, contingency etc can have a large impact on biofuel project costs. Engineering project costs have risen dramatically since the cost data referenced by the three reports were published – the increase from 2004 to 2008 was almost by a factor of 2. Recent falls in engineering project costs due to the global recession have only been modest (around 10% in the last year), although they may continue to fall in the short term

Despite these limitations, there are some overall conclusions that can be drawn from the data:

1. ***Total capital costs for a gasification plant at the minimum economic scale for FT synthesis (1,520odt/day or 320MW$_{th}$ biomass input) are estimated to range from £138-207m, including feedstock pre-treatment but excluding syngas conversion to the final fuel.*** Dual and some EF gasifier plant concepts are likely to be at the lower end of this range, whereas Plasma gasifiers are very likely to be at the top of this range. Within the total capital cost of a gasification plant, the installed cost of the gasification step is estimated to be between £20-55m.

2. ***Operating costs for gasification plants are estimated to be of the order of 3.5 – 5.7% of capex, per year, excluding biomass costs.*** These vary according to particular labour and consumption related costs (e.g. chemicals, bed materials). Other costs not included within this range are insurance, admin, and contingencies (estimated to total 3.3% of capex). Furthermore, using imported oxygen instead of onsite production has a major impact on operating costs, increasing them well above the range given. In most cases, biomass costs will be significantly larger than the above operating costs. For example, for a low temperature gasification followed by EF concept, RENEW calculates that biomass costs (wood chips) contribute € 49/GJ of FT diesel, compared to operating & other costs of € 7/GJ. Biomass costs will be higher still for lower efficiency systems, which have to take in more biomass to produce the same syngas output.

3. ***Offsite pre-treatment can add considerably to the system capital cost.*** As an example of the effect of offsite pre-treatment, the RENEW project modelled the bioliq process, with 5 decentralised pyrolysis plants producing a bio-slurry for a central EF gasification plant. In this process, the pyrolysis plants are the only pre-treatment steps required, but their £68m forms 36% of the total system capital costs. Other gasification plants considered at this scale with onsite drying, chipping/grinding and handling only have pre-treatment costs of around £30m, or 16-22% of the total capital cost.

   The other gasifier concepts considered include the feedstock preparation that is required in order to achieve a form suitable for the particular gasifier. However, it may be the case that pre-treatment technologies are used in addition to this, in order to benefit from the reduced transport costs of densified biomass. There are three main options for feedstock pre-treatment before arrival at the gasifier site: pelletisation, torrefaction and fast pyrolysis. The characteristics and costs of a facility are presented for individual pre-treatment densifying technologies in Table 15, to show what impact they would have on overall gasification costs. These costs are taken from the 2008 report on densification technologies by NNFCC[97], adjusted to 2009 costs and scaled; we have not reviewed these technologies as part of this study, and transport costs are not included. Note that these costs only refer to offsite pre-treatment; the costs of onsite pre-treatment for more difficult feedstocks would be much lower as a result of economies of scale, and the potential for process integration e.g. use of process heat.

**Table 13: Costs of offsite feedstock pre-treatment (2009 £m)[98]**

| | Pelletisation | Torrefaction | Fast pyrolysis |
|---|---|---|---|
| Product | Biomass pellets | Torrefied pellets | Bio-oil |
| Net energy efficiency | 89% | 86% | 66% |
| Capital cost at 200odt/day biomass input | 3.1 | 5.6 | 9.6 |
| Capital cost for 7-8 200odt/day plants to supply 1,520odt/day gasifier input | 23.7 | 43.2 | 74.6 |

4. ***Pressurised systems significantly reduce the costs of syngas clean up and overall capital costs[99].*** Capital costs decrease for a large part because of decreasing gas volume in the cleaning section. The extra costs for air or oxygen compression are more than outweighed by smaller syngas cleanup equipment and reduced compression costs downstream, and hence pressurised systems have a lower total capital cost than atmospheric systems.

5. ***System efficiency has a major impact on the costs of clean syngas production.*** Concepts which use a gasifier with a high cold syngas efficiency, and successfully integrate heat recovery and use in the syngas cleanup and feedstock drying steps will produce more clean syngas for every odt of biomass input than concepts with inefficient components or poor heat integration. In general, the plant efficiency increases as the gasification pressure increases, because of lower internal power needs (per unit clean syngas output), leading to cheaper syngas production costs. Plasma gasifiers use a considerable amount of electricity in their plasma torches, adding considerably to the other parasitic plant loads. The total internal power requirement is usually generated using a proportion of the syngas output. Therefore, plasma gasifiers are likely to have a markedly lower biomass to syngas efficiency compared to the other gasifier types.

6. ***Clean up cost estimates vary considerably.*** From the examination of components within the various concepts considered, the main steps that are likely to be found in a gasification plant include cracking, reforming or removal of tars and other hydrocarbon gases, dust and particle filtering,

[97] Evans, G. (2008) "Techno-Economic Assessment of Biomass "Densification" Technologies", NNFCC
[98] Evans, G. (2008) "Techno-Economic Assessment of Biomass "Densification" Technologies", NNFCC
[99] Hamelinck et al. (2004) "Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential" Energy 29, 1743–1771

scrubbing or catalytic absorption of contaminants such as sulphur, nitrogen and fluoride compounds, adjustment of the $H_2$:CO ratio via a Water-Gas-Shift reaction, and $CO_2$ removal. However, the data seen in the literature for gas clean up costs does not match the information found about the relative syngas quality of the different gasifier types. This is likely to primarily be a result of the different level of detail in which systems have been modelled, the different plant concepts, and because the required syngas cleanup and conditioning is dependent on the syngas produced from the gasifier, which in turn is dependent on the feedstock, the gasifier type and operating conditions. Syngas cooling via heat exchangers and pressurisation also needs to occur at various stages in the process. A detailed analysis of the costs of gas cleaning for each of the syngas uses is beyond the scope of this review, however, a few interesting points to note are[100]:

- The energy efficiency of clean up systems where the gas is dry (e.g. hot gas cleaning) is slightly higher than wet cleaning systems (e.g. water scrubbers), since temperatures can remain higher throughout the whole clean up chain, and less steam is needed. However, this is balanced by a slightly higher capital investment, such that the resulting syngas production costs are roughly the same
- A water gas shift reactor can cost up to an estimated £10m for the plant scale considered, although the need for this step is reduced in most of the steam-blown Dual systems, and when using the syngas for mixed alcohols production, or Fe-based FT synthesis
- Removing the $CO_2$ fraction of the syngas prior to FT fuel synthesis improves both selectivity and efficiency, but due to the accompanying increase in investment, this does not result in lower product costs. Achieving the correct $CO_2$ proportion (4-8%) is more important for methanol synthesis, hence cleanup costs will be likely to be higher, since the raw syngas usually has at least 10% $CO_2$ (except for plasma gasification)

Overall, the costs data available does not point to a clear winner, in terms of the gasifier with the lowest costs of production of clean syngas. This is reflected by the industry activity, with development activity ongoing in each of the technologies and gasifier types.

[100] Hamelinck et al. (2004) "Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential" Energy 29, 1743–1771

# 5 Conclusions

## 5.1 Suitable gasifier technologies for liquid fuels production

The information on individual gasification technologies, and comparison of the generic types of gasifier given above, enables us to make a judgement on their suitability for liquid fuels production, their relative merits and time to market. Table 14 brings together the information from the previous sections, to give an approximate ranking of each gasifier type in terms of feedstock flexibility, syngas quality, status of development, potential for scale up, and cost. This considers the best options within each gasifier type i.e. pressurised and oxygen/steam blown systems for fluidised bed gasifiers.

**Table 14: Gasifier type comparison, with each type ranked from ● (poor) to ●●●● (good)**

| Gasifier type | Feedstock tolerance | Syngas quality | Development status | Scale up potential | Costs |
|---|---|---|---|---|---|
| **EF** | ● Preparation to <1mm, 15% moisture, low ash %, composition unchanging over time | ●●● Very low $CH_4$, $C_{2+}$ and tars, high $H_2$ and CO | ●●● Constructing BTL demos, integration and large scale experience, large industrial players | ●●●● Very large gasifiers and plants possible | ●●● High efficiency. Expensive pre-treatment if decentralised |
| **BFB** | ●●● <50-150mm, 10-55% moisture, care with ash | ●● $C_{2+}$ and tars present, high $H_2$ and CO only if O2 blown. Particles | ●● Past heat & power applications, modest scale up, some BTL interest | ●●● Many large projects planned | ●● Possible higher gasifier capital costs and lower efficiency |
| **CFB** | ●●● <20mm, 5-60% moisture, care with ash | ●● $C_{2+}$ and tars present, high $H_2$ and CO only if O2 blown. Particles | ●● Extensive heat & power expertise, research & scale up, but few developers, particularly for BTL | ●●● Many large projects planned | ●●● Possible higher gasifier capital costs |
| **Dual** | ●●● <75mm, 10-50% moisture, care with ash | ●● $C_{2+}$ and tars present, high $H_2$, but high $CH_4$. Particles | ● Few and small developers, early stages, only very recent interest in BTL | ●● Some projects planned, but only modest scale up | ●●● Potential for low syngas production costs |
| **Plasma** | ●●●● No specific requirements | ●●●● No $CH_4$, $C_{2+}$ and tars High $H_2$ and CO | ●● Several developers, many power applications, early stage of scale-up | ● Only small scale, modular systems | ● Very high capital costs, low efficiency |

All of the technology types considered have the potential for liquid fuels production from biomass, although within the fluidised bed technologies, this is likely to be limited to the pressurised, and oxygen or steam blown systems. As none of the developers have a plant in commercial operation with liquid fuels production, no single developer or technology type is a clear winner at this stage.

For several of the criteria above, all of the technologies have the potential to meet the requirements of liquid fuels production:

- From the table above, feedstock requirements vary considerably between gasifiers, with plasma being the most tolerant, down to entrained flow with very stringent requirements. However, the cost estimates show that the costs of additional onsite pre-treatment needed for EF do not result in higher total plant costs than the other technologies. Similarly, the costs of achieving the sizing and moisture requirements for CFB and BFB do not have a large impact on the syngas production costs. There is not enough data available on the cost of plasma gasification to compare the benefits of increased feedstock tolerance with cost. Feedstock tolerance is unlikely to be a determining factor in the choice of gasifier technology, as all types can ultimately accept a range of feedstocks with little implication on overall production cost
- All of the gasifiers can achieve the required syngas quality for fuels production, albeit with varying levels of syngas clean up and conditioning. The effect on clean up and conditioning costs of varying syngas qualities is not clear from the data available
- Despite the different levels of development of the gasifier types, all types have developers actively working on the commercialisation of systems suitable for liquid fuels production, at or beyond the pilot stage
- All of the gasifiers can be scaled up to achieve the minimum economic scale for FT synthesis, either as a single gasifier, or combining a small number of gasifier modules. Modular systems may not have the same economies of scale as single systems, but could have benefits in terms of use of different feedstocks, and of availability
- Based on the data available on gasification plant costs, and the uncertainty in this data, it is not possible to differentiate clearly between the gasifier types on the basis of syngas production costs. We estimate from an approximate comparison of these data that the costs of syngas production from each type is similar, within the uncertainty of the studies reviewed. For all gasifier types, more detailed analysis of a particular system concept would be needed to give a accurate comparison of the economics, paying particular attention to pre-treatment costs, plant efficiency (as this has an impact on biomass costs) and syngas clean up steps

However if we take into account all of the criteria, in particular the status of development and experience of the developers, we can draw some conclusions on the likelihood of success of each technology in the near term:

- Entrained flow gasification is the most advanced towards commercialisation, with developers having pilot plants in operation for fuels production, and larger scale demonstration plants operating currently or planned to operate in the very near term (CHOREN, Range Fuels and Pearson). The developers involved in entrained flow gasification and their partners have significant commercial and technical experience in gasification and liquid fuels production. Despite having high pre-treatment costs in some cases, entrained flow has the greatest potential for scale up to very large plants, and therefore potentially low costs, due to economies of scale
- BFB gasification benefits from a longer history of biomass gasification than entrained flow. There are several commercially focused players in BFB gasification, with pressurised and oxygen blown

systems in development (Carbona, EPI, Enerkem). These are aimed at fuels production, and the developers have planned biofuel demonstration projects, either alone or with biofuels companies. It is anticipated that these should provide the first performance data for large scale BFB processes
- CFB gasification also has a relatively long history of biomass gasification, but much of the experience is not with the pressurised and oxygen blown systems needed for fuels production. Nevertheless, there are several players involved in CFB gasification for fuels, including the strong VTT and Foster Wheeler collaboration, used in the NSE Biofuels (Stora Enso/Neste Oil joint venture) project
- Dual FB gasification benefits from the experience gained with BFB and CFB, although is at an earlier stage of development than EF, BFB and CFB. Dual FB systems are only currently operating in small scale heat & power applications, and they still need to be demonstrated at pressure – however, if developed, these pressurised systems have the potential to produce low cost, nitrogen free syngas. The players involved have a shorter track record of experience, but have successfully operated plants at high availabilities, and some have plans for liquid fuels production in the future
- Plasma gasifiers are very promising in terms of good syngas quality, along with the additional benefits of feedstock flexibility without pre-treatment. However, the technology has so far only been developed for the thermal destruction of wastes with power production, and developers have little experience in projects for liquid fuel production. The lack of public domain data on economics, and lack of consideration in other studies means that this option has been given less consideration to date for application to a broader range of biomass feedstocks. However, non-waste feedstocks are now being considered by Coskata in their pilot using a Westinghouse Plasma gasifier

There remains a clear need for the biomass to liquids sector to reduce technical risk through demonstration and develop a better understanding of the economics of biomass to liquids systems. This will be crucial to attracting project developer and investment interest.

## 5.2 Gasifiers for the UK

Liquid fuel production in the UK via gasification is likely to use the same technologies that are most successful for this application worldwide, with few factors making particular technology types more favourable for the UK. The reasons for this are given below:

- Scale – the UK is likely to use the same scale of plants as those in other countries, at the minimum economic scale or above, rather than the smaller plants sometimes proposed on the grounds of lower UK resource availability. Plants may achieve the required input scale through use of UK or imported feedstocks, use of offsite pre-treatment options, and may be based on modular systems to allow use of separate gasifiers tuned to different feedstock inputs. Note that the use of densification technologies does not necessarily imply entrained flow gasification must be used: some densified feedstocks can be used in the other gasifier types. If the minimum economic scale of liquid fuels production can be reduced, for example through FT process development, the technology would likely find wider use in the UK, as well as in other countries
- Feedstocks – UK biomass resources are limited compared with many other countries, but there is still a large existing waste resource, and potential for significant energy crop resources in the future.

Current wastes availability, combined with increasing landfill taxes, may encourage projects based on wastes, which may favour plasma gasification (although other technologies could be used)

- Fuel market – current diesel demand and production levels in the EU could favour the production of a biofuel for diesel blending/replacement rather than for gasoline, although this may change in the future. As a result, FT routes could be considered in the near term rather than mixed alcohols, ethanol or methanol routes for UK plants. However, there is European activity in developing syngas to ethanol routes through the activities of Ineos Bio
- Existing activity – none of the leading developers of gasification technology, and few biofuels companies planning to use the technology are based in the UK. As a result, there is unlikely to be a particular technology that would be used because of existing experience. However, there is some recent UK activity in using these gasifier types for waste to heat and power, such as the APP/EPI pilot, which could give experience in particular technologies in the future

Given that the majority of the biomass gasification activity described in this report is outside the UK, in terms of developer location and announced plants, it is likely that the next few years of development will not be UK based. During this time, it is likely that some developers and technologies will prove more successful than others, narrowing the range of technologies available, and giving more information about economics and performance in operation. This will make it easier for UK developers to see which technologies have proved successful, and are best suited to the particular requirements of their project.

Nevertheless, the UK may be an influential player in the future development of the area because of activities of companies such as Oxford Catalysts (Velocys) and Ineos Bio, and pyrolysis activity, for example through the Carbon Trust Pyrolysis Challenge. The gasification and pyrolysis pilots would provide general project development related skills that might be applicable to biomass to liquids, and bring to bear UK strengths in engineering and petro-chemicals. We also have strengths in supporting research, such as in pyrolysis, and in process intensification.

Given the cluster of activities that is emerging in the UK in this area, there may be economic opportunities to be gained from the UK developing a more strategic position in the sector and investing in supporting the development of technologies and skills in pilot or demonstration activities

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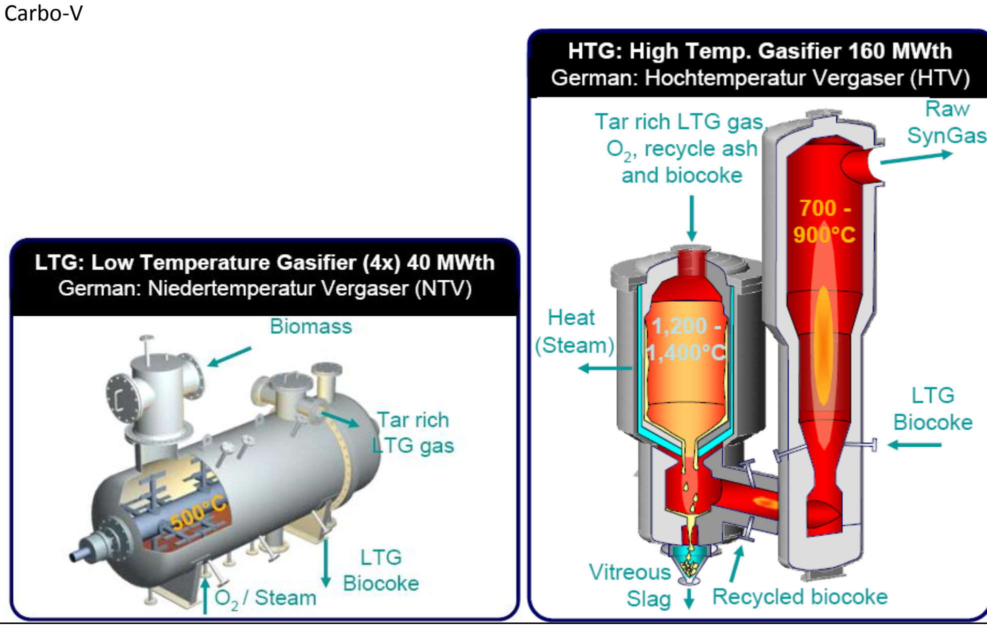
# 6 Annex

## 6.1 Entrained flow gasifiers

### 6.1.1 CHOREN

| | |
|---|---|
| **Basic information** | |
| Technology provider | CHOREN Industries GmbH |
| Location | Freiburg, Germany |
| Information sources | http://www.choren.com/en/ |
| Background and links | Set up in 1990 as UET Umwelt und Energietechnik Freiberg GmbH, before merging with an engineering firm to form CRG Kohlenstoffrecycling GmbH in 1993, then biomass suppliers to form CHOREN. Cooperation partners now include Daimler AG, Volkswagen AG and Shell provides the FT technology |
| **Gasifier type** | |
| Technology type | Entrained Flow |
| Technology name | Carbo-V |

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| Technology overview | 3 stage process:<br>• Pre-conditioning of biomass - mixing and drying to 15% moisture content, then low temperature gasification with rotary stirring to produce volatile gases (containing tar) and char/biocoke<br>• Partial oxidation - gases combusted with a calculated amount of oxygen at the top of the gasification chamber at high temperatures, above the ash melting point. This section of the reactor is water-cooled, and slag protected<br>• Chemical quenching - char is pulverized and blown into the middle of the entrained flow gasification chamber, creating syngas in an endothermic reaction (causing a temperature drop). The remaining char in the form of dust is removed from the syngas, and fed back into the high temperature section of the gasifier where the contained ash melts to form a layer of protective slag on the inner walls of the combustion chamber |
| Method of heat provision to the gasifier | Direct |
| Oxidant | Oxygen |
| **Gasifier operating data** | |
| Temperature | 1st stage 400-500°C, 2nd 1200-1500°C, 3rd 700-900°C |
| Pressure | 5 bar |
| Scale and output | • Alpha plant is 1,000 odt/yr biomass input (=3odt/day biomass at 90% availability, although because pilot, likely to be lower) – known that ~1$MW_{th}$ input capacity<br>• Beta plant is 65,000 odt/yr biomass input (=198odt/day biomass), or 45 $MW_{th}$ input. Enough to |

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| | produce 13,000tons/yr of FT biodiesel "SunDiesel", i.e. 21.8MW diesel output<br>• Sigma plant will take 1,000,000 odt/year biomass input (=3,044odt/day biomass), or 640MW$_{th}$ | | |
| Efficiency (%) | Cold gas efficiency is high at 81.4%, overall thermal efficiency of 90.5% (some heat used for drying) | | |
| Reliability issues | Not disclosed | | |
| **Development and commercial status** | | | |
| Pilot scale plants | Alpha pilot plant constructed 1997, 17000hrs operation by 2004. Fitted with methanol synthesis in 2002, then FT in 2003. Oct 2003 saw commissioning of bio-coke 1st stage. Alpha plant is no longer in operation | | |
| Commercial scale plants | Beta plant built in 2007, commissioned on 17$^{th}$ April 2008 - however, due to the Baker report safety recommendations, CHOREN have been set back a year in completely refitting the beta plant site. FT production should commence in the second half of 2009 | | |
| Future plans | • Gamma plant using 4 multiple lines of 160MW$_{th}$ capacity is planned for Schwedt, to produce 200,000t/yr of BTL fuels from 2013 onwards (needing 1Modt/yr biomass input). Five Sigma plants will be built in Germany in total<br>• CHOREN also state that Carbo-V could also be commercialised for CHP applications<br>• Carrying out tests on torrefaction (instead of low temperature gasification), which would enable them to use the resulting material directly in the EF combustion chamber (no stage 3 required), and would open up feedstock choice significantly<br>• In Nov 2008, CHOREN Industries and Norske Skog entered into an agreement for collaboration in the evaluation of second generation biofuel production in Norway | | |
| Time to commercialisation | Expect SunDiesel production by the end of 2009 | | |
| Target applications | Onsite FT synthesis (integrated BTL plant) | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 37.2% $H_2$, 36.4% CO, ratio 1.02 | Tars | Extremely low due to high gasification temperatures |
| $CO_2$ (% by vol) | 18.9% | Hydrocarbons (methane, $C_2H_4$, and higher) | methane 0.06% |
| $H_2O$ (% by vol) | 7.3% | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | 0.1% $N_2$ | Others | |
| Syngas clean up | Important that syngas is homogeneous/accurately specified in order to optimise the several syngas cleanup steps:<br>• Selexo cleanup (provided by Linde)<br>• Scrubber with water, and soda<br>• Remove S with hydrogen peroxide<br>• Pressurise gas<br>• Carry out WGS using catalyst<br>• Remove $CO_2$ using a scrubber<br>• Pass syngas over active carbon or charcoal, to reduce any remaining heavy metals and S compounds down to ppbv levels | | |
| **Feedstock requirements** | | | |
| Main feedstocks | Mainly wood: wood chips from forest timber and plantations, sawmill coproduct, recycled wood<br><br>The Sigma plant will initially be operated with recycled wood and wood energy crop, some of which will be imported. CHOREN has decided to set itself strict sustainability criteria right from the start. It is planned to gradually increase the share of short rotation coppice in feedstock to at least 50% | | |
| Other potential feedstocks | Other possible feedstocks for the Carbo-V process are straw briquettes (straw max 5–10 % share), whole plant briquettes, miscanthus, waste cereal products, energy crops<br>Other materials tested in the EF chamber in the Alpha pilot plant (before the Carbo-V 1$^{st}$ stage added) include plastics, “dry stabilate” (dried, sorted and ground MSW), ground meat and animal bones, lignite and black coal | | |
| Ability to accept a mixture | Yes | | |

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| of feedstocks | |
| Ability to accept feedstocks varying over time | No, feedstocks are stored in order to provide non-varying supply |
| Ability to accept wastes | Only waste wood, not the organic fraction of MSW. CHOREN have successful tested plastic-derived RDF pellets, and if they were to introduce torrefaction as stage 1, they should be able to use wastes. Theoretically, this makes sense for torrefied wood, but may add to process steps and costs if need to sort MSW or industrial wastes to first form a "dry stabilate" |
| Pre-treatment required | Drying, storage, mixing, shredding in stage 1 |
| Feedstock properties (energy content, moisture content, size etc) | • Target 15% moisture content. In practice the typical biomass composition may comprise fresh lumber (35-50% moisture) or woody energy crops (willows or poplars), wood residues (15-45% moisture) or recycled/waste wood (12-18% moisture) or dried straw<br>• Size of initial received feedstock must be < 120x50x30 mm, and must be milled to less than 50mm before entering the first stage |
| **Capital and operating costs** | |
| Costs | Capital costs: EUR 25,300,000 for 30$MW_{th}$ & 10$MW_e$ output plant<br>Operational costs: EUR 5,387,000 for 30$MW_{th}$ & 10$MW_e$ plant, does not include revenues from heat and electricity as German specific<br><br>Investment costs: EUR 3,000 to 3,500 /kW FT output<br>Goldman Sachs forecasts costs to be $2000 / tonne of FT capacity<br><br>Beta plant total investment costs about €100 million |

### 6.1.2 Range Fuels

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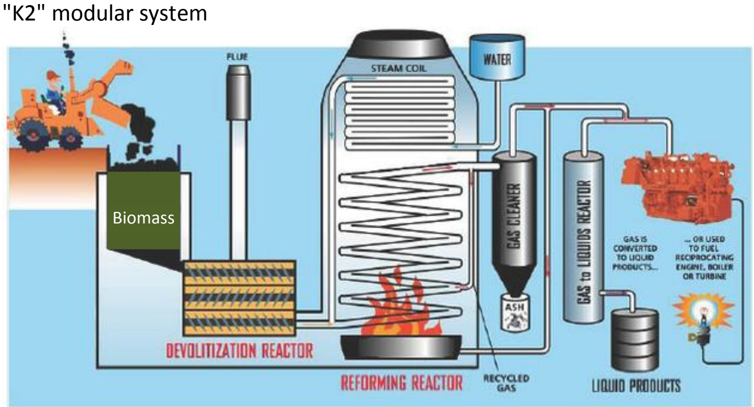
|---|---|
| **Basic information** | |
| Technology provider | Range Fuels Inc |
| Location | Broomfield, Colorado, USA |
| Information sources | http://www.rangefuels.com |
| Background and links | Formerly Green Energy, formerly Kergy Inc, founded by Khosla Ventures<br>Ron Klepper, now an advisor at Range, had run his own company, called BioConversion Technology (BCT), and targeted the gasification technology at coal as well as biomass feedstocks. Range Fuels technology is based on BioConversions' designs<br>Georgia plant participants: Merrick and Company, PRAJ Industries Ltd., Western Research Institute, Georgia Forestry Commission, Yeomans Wood and Timber; Truetlen County Development Authority; BioConversion Technology; Khosla Ventures; CH2MHill, Gillis Ag and Timber. Also conducting field trials of switchgrass cultivars and high-biomass sorghum hybrids with Ceres |
| **Gasifier type** | |
| Technology type | Entrained Flow |
| Technology name | "K2" modular system<br> |
| Technology overview | Based on a gasifier and ethanol reactor developed by Robert (Bud) Klepper, originally called the Klepper Pyrolytic Steam Reforming Gasifier (PSRG) with a Staged Temperature Reaction Process (STRP) and the Klepper Ethanol Reactor. Entrained flow principle, but features two separate reactors: a devolatilisation reactor (low temperature gasification) and a reforming reactor (gasification).<br><br>Gas entrained biomass passes through the devolatisation reactor which raises the temperature of the incoming materials up to 230°C. At this temperature, a substantial portion of the oxygen is consumed as the more reactive fraction of the biomass undergoes devolatisation. The temperature of the feed continues to increase until it combines with steam super-heated to approximately 815°C. The result is the production of syngas with substantial fractions of CO and $H_2$. In order to optimise the calorific value of the syngas, the process steam and syngas are used to entrain additional feedstock. Finally, the syngas passes over a proprietary catalyst and produces a mix of alcohols including ethanol, methanol, propanol and butanol. The products are processed to maximise the ethanol yield and then separated. The ideal moisture content of the feedstock is 40-50%<br><br>Another unique feature specific to the Klepper system is that the cyclones and water condenser are integrated and contained within the biomass gasification chamber. This design conserves space and reduces the loss of heat energy.  Very high conversion efficiency, while at the same time, keeping the tar content in the produced gas extremely low (and no slagging) |
| Method of heat provision to the gasifier | Indirect |
| Oxidant | Super-critical steam and some of the produced syngas are used to propel the feedstock through the segregated steam reforming reactor. This technique raises the calorific value of the syngas by not diluting the product syngas with nitrogen or carbon dioxide, nor does it require a costly separate supply of oxygen or the elevated temperatures and “run-away” pyrolysis issues associated with oxygen |
| **Gasifier operating data** | |
| Temperature | The devolatilisation reactor slowly raises feed material temp to 230°C (below combustion) until a |

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| | substantial portion of the contained oxygen has reacted with more reactive material in the feed. The feed material temperature is then raised to e.g. 340°C, prior to combination with super heated steam (815°C) and a subsequent rise in temperature to react with the carbonaceous feed material and produce syngas | | |
| Pressure | Pressurised, but exact value unknown | | |
| Scale and output | Demonstration plant under construction will produce 10m gallons of methanol and ethanol each year, using 125odt/day of wood | | |
| Efficiency (%) | 75% thermal on average, the highest of any small-scale system | | |
| Reliability issues | First phase was scaled back from the original projections of 20m gals of production by late 2009 "The lead time for equipment was longer than we had been given indications of early on". Latest loan guarantee will ensure construction is finally completed | | |
| **Development and commercial status** | | | |
| Pilot scale plants | Range Fuels continues to optimize the conversion technology (that will be used in their first commercial cellulosic ethanol plant near Soperton, Georgia) using a 4th generation pilot plant in Denver, Colorado that has been operational since the first quarter of 2008. This pilot has demonstrated a 5odt/day partially integrated process, and 2.5odt/day long-term integrated operation.<br><br>The pilot PSRG+STRP system was ordered by Rentech Inc in Dec 2005, for its FT CoalTL pilot in the Sand Creek facility in Commerce City, Colorado, for operation by the end of 2006. Specifications are 10-15 barrels/day of FT diesel, naphtha and jet fuel, using a K2 gasifier capable of processing 25-35 tons/day of coal. However, there is no public knowledge of the K2 process, no published data on biomass testing (only coal), and no sales or upscaling of the Keppler Ethanol Reactor reported to date | | |
| Commercial scale plants | First phase of a commercial cellulosic ethanol plant near Soperton, Treutlen County, Georgia, is under construction (started in Nov 2007) and on track to begin production in 2010. This is expected to produce 113,000 tonnes of ethanol and methanol each year (or 10m gallons), using 125odt/day from the nearby timber industry | | |
| Future plans | Second phase plans to use 625odt/day feedstock to produce < 30m gal/yr, with engineering work to start in early 2009. Around ~40 million gallons/year of ethanol and about 9 million gallons/year of methanol expected from future commercial units. The planned third phase is expected to use 2,625 t/day (1,250odt/day) to make 100 million gallons/year. The Georgia facility is expected to be the first of several, larger, facilities in the state. Range Fuels' long term aim is to produce 1 billion gallons/year | | |
| Time to commercialisation | Soperton, Georgia plant expected to be mechanically ready in the first quarter of 2010, with volume production to begin in the second quarter of 2010 | | |
| Target applications | Integrated catalytic ethanol production onsite | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | | Tars | |
| $CO_2$ (% by vol) | | Hydrocarbons (methane, $C_2H_4$, and higher) | |
| $H_2O$ (% by vol) | | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | | Others | |
| Syngas clean up | | | |
| **Feedstock requirements** | | | |
| Main feedstocks | Waste timber and forest residues - development plant currently using Georgia pine and hardwoods as well as Colorado beetle-kill pine<br>New Soperton plant can take wood chips, switchgrass, olive pits, sugarcane and cornstalks | | |
| Other potential feedstocks | | | |
| Ability to accept a mixture of feedstocks | Has been testing the technology using a single feedstock at a time, but plans to look at using varying feedstocks, such as municipal solid waste | | |
| Ability to accept feedstocks varying over time | See above | | |
| Ability to accept wastes | See above | | |

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| Pre-treatment required | Drying and crushing |
| Feedstock properties (energy content, moisture content, size etc) | Feedstock deliveries to the plant can have a relatively high moisture level, in the neighbourhood of 40% to 50%. Can also accept feedstock of varying sizes |
| **Capital and operating costs** | |
| Costs | 28 Feb 2007: $76m Technology Investment Agreement (grant) from the US DOE (1 of 6 cellulosic ethanol awards)<br>Soperton plant also funded with $170m venture capital<br>20 Jan 2009: Secured a conditional commitment for an $80m loan guarantee from the U.S. Department of Agriculture - allowing completion of plant construction |

### 6.1.3 Karlsruhe Institute of Technology

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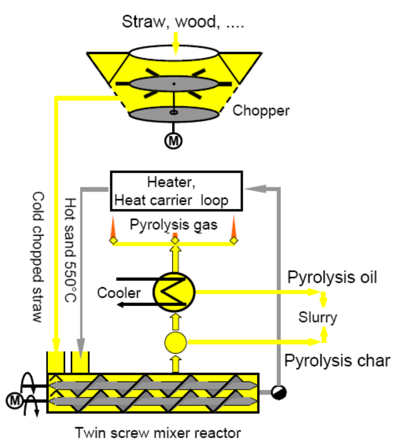
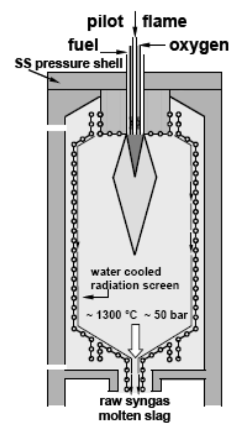
| **Basic information** | |
| Technology provider | Karlsruhe Institute of Technology (KIT) |
| Location | Forschungszentrum Karlsruhe and Freiburg, Germany |
| Information sources | http://www.lurgi.com http://www.future-energy.de http://www.fzk.de |
| Background and links | Joint project with Lurgi AG and Future Energy GmbH, run by the Karlsruhe Institute of Technology (KIT). KIT founded by University of Karlsruhe (Technical University) and Forschungszentrum Karlsruhe GmbH (FZK). Future Energy and Lurgi have a cooperation agreement with Forschungszentrum Karlsruhe to develop a novel technology for the production of BTL incorporating pyrolysis, the well established "Gaskombinat Schwarze Pumpe" (GSP) gasification process and FT synthesis<br><br>Lurgi originally founded in Feb 1897, acquired by Air Liquide Group in July 2007. Acquired the Multi-Purpose Gasification (MPG) process in 1998 from SVZ Schwarze Pumpe, in cooperation with Future Energy GmbH<br>Future Energy GmbH bought its GSP EF process knowledge from Babcock Borsig Power (formerly Noell-KRC), and Future Energy was acquired by Siemens Power Generation Group in May 2006 |
| **Gasifier type** | |
| Technology type | Entrained Flow |
| Technology name | bioliq (decentralised pyrolysis, followed by centralised gasification and fuel synthesis) |

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| Technology Overview | 1st decentralized stage: Flash pyrolysis technology, originally developed by Lurgi and Ruhrgas (LR-mixer reactor) operates at 500°C to turn biomass into pyrolysis oil and coke in a dual screw mixing reactor. The oil and ground coke are mixed to form a liquid suspension whose energy density is comparable to that of crude oil. This bioliqSynCrude can then be transported much longer distances to central large-scale gasifiers<br>2nd centralized stage: the gasification stage will create syngas from the bioliqSynCrude. The Multi-Purpose Gasifier (MPG) developed from Future Energy's GSP gasifier is EF, oxygen-blown, and equipped with a castable-lined cooling screen cooled with pressurized water whose internal surface is protected from corrosion and erosion by means of a slag layer. The crude syngas and the slag are drawn off via a quench at the bottom end of the reactor<br>3rd stage: Syngas purification using Lurgi's Rectisol and Purasol processes. Syngas already at high pressure, so no costly compression step will be needed before fuel synthesis |
| Method of heat provision to the gasifier | Direct |
| Oxidant | Oxygen |
| **Gasifier operating data** | |
| Temperature | Testing: 1200-1600°C,<br>Planned pilot: >1400°C |
| Pressure | Testing: 26bar,<br>Planned pilot: 80-85bar |
| Scale and output | Testing: 3-5$MW_{th}$<br>Planned integrated pilot plant will take biomass input of 0.5odt/hr (12odt/day), i.e. up to 5 $MW_{th}$ capacity |

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| Efficiency (%) | |
| Reliability issues | |
| **Development and commercial status** | |
| Pilot scale plants | Lurgi AG and FZK signed a cooperation contract for the first stage (fast pyrolysis) of a pilot plant in Aug 2006. The research project was sponsored by the German government. The first stage of the pilot plant completed in 2007 was successful<br>Lurgi and KIT signed the contract for the realisation of the second stage (gasification) in June 2007. Future Energy GmbH is also in an alliance with FZK, and closely cooperating with Lurgi to build the new 85bar gasifier. With the project now entering this second stage, the pilot plant is being extended by the process steps for synthesis gas generation (with Future Energy), gas cleaning and fuel synthesis to demonstrate the technical viability of the overall process, improve it and prepare its commercialization.<br><br>Testing of gasifying the bioliqSynCrude under different conditions has already been carried out at the Future Energy 3-5$MW_{th}$ pilot plant in Freiburg. Siemens Power acquired the Future Energy gasifier technology (Gasification Schwarze Pumpe or "GSP Process"), staff, and test facilities from Sustec. The acquisition included a state-of-the-art pilot scale gasification test facility at Freiburg where potential feedstocks can be tested to better characterize design characteristics for a specific project. |
| Commercial scale plants | The 200$MW_{th}$ Schwarze Pumpe site has a capacity of 700 t/day of lignite and wastes, and was the source of town gas in the former east Germany town. The GSP gasifier installed onsite has a capacity of 15t/hr (306odt/day at 15% moisture), and sits alongside two other gasifiers (FDV and British Gas slagging Lurgi designs). The plant is currently used to gasify coal and waste (in the ratio 4:1) from older gasifiers at the plant, with the syngas from the integrated operation of these 3 gasifiers being used for commercial co-production of methanol and power |
| Future plans | The next part of the joint KIT project covers the engineering, construction, supply, installation and commissioning of the gasification step by Lurgi and Future Energy. Commissioning is planned for autumn 2011. Final steps after 2011 will be gas conditioning and fuel synthesis<br><br>*FZK is also testing a hydrothermal BMG process, operating at about 600°C and 350 bar, in the 100 kg/hr (2.4odt/day) Verena pilot test unit. The tar-free product gas consists of mostly H2 and $CH_4$; the $CO_2$ contained in these gases can be easily separated.* |
| Time to commercialisation | |
| Target applications | Integrated onsite biofuels plant, alongside the centralised gasifier unit. FZK have recently settled on using methanol synthesis, then MTG technology to produce transport fuels, as their preferred future end-use. |

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| **Syngas characteristics and cleanup** | | | |
| Temperature | | Halides (HCl, Br, F) | 1.7mg/$Nm^3$ |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 23% $H_2$, 43% CO, ratio 0.53 | Tars | None |
| $CO_2$ (% by vol) | 11% | Hydrocarbons (methane, $C_2H_4$, and higher) | methane <0.1% |
| $H_2O$ (% by vol) | | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | 0.2% $SO_2$ | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | 5% $N_2$, 3.4mg/$Nm^3$ HCN, 0.4mg/$Nm^3$ $NH_3$ | Others | |
| Syngas clean up | | | |

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| **Feedstock requirements** | |
| Main feedstocks | bioliq process uses beech wood, what straw, rice straw, hay, wheat clay, with a focus on more "difficult" biomass like straw - these have less condensates, more ash (solids)<br>Schwarze Pumpe plant uses mainly lignite, along with waste materials including demolition wood, used plastics, sewage sludge, auto-fluff, MSW, contaminated waste oil, paint and varnish sludge, mixed solvents, tars, and on-site process waste streams. The waste materials are blended with coal at a ratio of 4:1 |
| Other potential feedstocks | Depends on the pyrolysis step as well as the gasification step |

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| Ability to accept a mixture of feedstocks | Gasifier Yes |
| Ability to accept feedstocks varying over time | |
| Ability to accept wastes | Gasifier Yes |
| Pre-treatment required | Decentralised pyrolysis densification - because the organic feed materials have low energy densities, their transport would only be economically feasible over short distances. Hence a first pyrolysis step makes a higher energy density intermediate product in decentralized plants, so that feedstock suppliers only have to travel 25km. |
| Feedstock properties (energy content, moisture content, size etc) | Because any bio-oil that can be pumped and pneumatically atomised with $O_2$ is suitable, the bio-oil quality and yield requirements are lower. All that is required is a bio-oil with 0-39% solids and <3% ash, with a calorific value of between 10-25 MJ/kg, and a density of around 1250kg/$m^3$ |
| **Capital and operating costs** | |
| Costs | An example scenario for the bioliq process has 40 pyrolysis plants (at EUR 20m each taking in 0.2Mt/yr straw), and 1 central gasifier (EUR 500m, producing 1Mt/yr biofuels)<br><br>Estimated production cost breakdown: straw 32%, straw transport 18%, fast pyrolysis 18%, staff 5%, slurry transport 8%, oxygen 5%, gasification and FT synthesis 14%<br><br>The biomass processing costs to obtain fuel will be below €0.5, to which the cost of the biomass has to be added which is currently in the same order of magnitude. This means that the price per litre would be less than €1<br>Rough estimate is Diesel directly from bio-oil €0.4/kg, FT biosynfuel €0.9/kg<br>A more recent study by FZK stated that a 1 Mt/year (2588 odt/day) input plant can produce FT biosynfuel for about €1.04 per kg or €0.8 per litre (US$3.08/gallon US) – this would need oil prices above $100/barrel to be competitive with non-taxed conventional motor fuels |

### 6.1.4 Mitsubishi Heavy Industries

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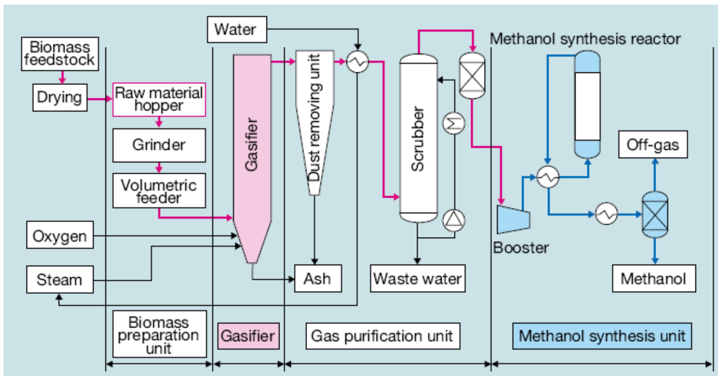
|---|---|
| **Basic information** | |
| Technology provider | Mitsubishi Heavy Industries Inc (MHI) |
| Location | Japan |
| Information sources | http://www.mhi.co.jp/en/power/technology/biomass/ |
| Background and links | Originally founded as Mitsubishi Shipyard and Building Works in 1884, broken up after WWII, but reconsolidated in 1964. Car manufacturing split off in 1970 |
| **Gasifier type** | |
| Technology type | Entrained Flow |
| Technology name | Biomass gasification methanol synthesis system (BGMSS)<br><br> |
| Technology overview | Slagging entrained flow gasifier manufacturer – the "once through" plant consists of a biomass pulverizer, gasifier, gas clean up and methanol synthesis<br>Methanol is synthesized after pulverized biomass is converted into syngas. Heat recovery from the syngas gives rise to the required gasifying steam |
| Method of heat provision to the gasifier | Direct |
| Oxidant | Oxygen and steam |
| **Gasifier operating data** | |
| Temperature | 800-1100°C |
| Pressure | Atmospheric |
| Scale and output | |
| Efficiency (%) | Pilot: Cold gas efficiency was 60-65% and methanol synthesis yield was about 20% by biomass weight<br>It is expected that for a commercial scale plant with heat loss restricted to less than 1%, the energy conversion ratio and methanol synthesis yield will be able to be increased to more than 75% and 40wt%, respectively |
| Reliability issues | |
| **Development and commercial status** | |
| Pilot scale plants | Initial testing was with 0.24odt/day test rig<br>As the final phase before commercialization, in February 2002, MHI, Chubu EPCO, and the National Institute of Advanced Industrial Society and Technology (AIST), supported by the New Energy and Industrial Technology Development Organization (NEDO), jointly started a 2odt/day BGMS test plant project at the Kawagoe Power Station |
| Commercial scale plants | |
| Future plans | A feasibility study for a commercial plant, profitability and plant scale was conducted for sites with different biomass in Japan. It would be feasible to establish one or two sets of commercial plants capable of processing a potential biomass target of 100odt/day in each prefecture. A plant this size can economically supply 19m litres of bio-methanol, or 9,000 tons of DME per year, and it was determined that there is sufficient potential for industrialization. However, there have been no recent developments |
| Time to commercialisation | |
| Target applications | Methanol synthesis |

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| **Syngas characteristics and cleanup** | | | |
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |

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| $H_2$, CO (% by vol), ratio | | Tars | |
| $CO_2$ (% by vol) | | Hydrocarbons (methane, $C_2H_4$, and higher) | |
| $H_2O$ (% by vol) | | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | | Others | |
| Syngas clean up | Removal of ash and surplus steam by gas clean-up | | |
| **Feedstock requirements** | | | |
| Main feedstocks | Test rig: cedar, broadleaf tree wood chips, cedar bark, lumbered wood chips, driftwood, refuse wood and Italian ryegrass tested<br>Will also be using woody biomass in the pilot | | |
| Other potential feedstocks | | | |
| Ability to accept a mixture of feedstocks | | | |
| Ability to accept feedstocks varying over time | | | |
| Ability to accept wastes | Yes | | |
| Pre-treatment required | Drying and pulverising | | |
| Feedstock properties (energy content, moisture content, size etc) | Dried biomass is pulverized to 1 mm | | |
| **Capital and operating costs** | | | |
| Costs | | | |

### 6.1.5 Pearson Technology

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|---|---|
| **Basic information** | |
| Technology provider | Pearson Technology Inc |
| Location | Hawaii (originally Aberdeen, Mississippi) |
| Information sources | http://www.gulfcoastenergy.net/ |
| Background and links | PTI founder, inventor and patent holder is Stanley R. Pearson<br>PTI were acquired by Ethxx International Inc in 2000<br>Partnership since 2002 with ClearFuels Inc to develop, optimize, and commercialize sustainable biorefineries in Hawaii.<br>Gulf Coast Energy formed in April 2007 and are using PTI's technology - Pearson joined their board in Dec 2008 |
| **Gasifier type** | |
| Technology type | Entrained Flow |
| Technology name | Pearson Technology |
| Technology Overview | Multi-stage, entrained flow "reformer". Pre-treated biomass is fed, along with superheated steam, into a gas-fired primary reformer. The reformer is externally heated, so that the product gas is not diluted by nitrogen from the combustion air. Air is also removed from the injected rice straw to minimize dilution of the syngas product with nitrogen. The organic material in the feedstock is efficiently gasified, leaving only the inorganic materials (ash) |
| Method of heat provision to the gasifier | Indirect |
| Oxidant | Steam |
| **Gasifier operating data** | |
| Temperature | Unknown, however EF gasifier, so likely to be in the range 1200-1400°C |
| Pressure | Unknown |
| Scale and output | |
| Efficiency (%) | Cold gas efficiency 81%, with >98% biomass conversion efficiency<br>Gasifier 70.5% thermal efficiency, heat recovery 25.9% thermal efficiency<br>Claim that can produce 215 gallons of ethanol per dry ton of waste wood (net 140 if used to supply parasitic plant fuel and power requirements). This yield of 66% by mass is very high compared to other gasification processes, e.g. BRI 23% by mass yields. |
| Reliability issues | Shutte hammer mill issues taking in wet feedstocks, switched to Marathon Equipment |
| **Development and commercial status** | |
| Pilot scale plants | 5t/day pilot (4odt/day) operated between 2002-2004 in Gridly, California for NREL feasibility study and testing<br>30t/day facility (26odt/day) constructed in Aberdeen, Mississippi<br>50t/day technology validation plant (43odt/day) under development in Hawaii with ClearFuels, construction started in 2006, expected to be finished at the end of 2008<br><br>Fully operational demonstration plant has been running since Aug 2008 at the Gulf Coast Energy facility in Livingston, Alabama – can produce 350,000-400,000gallons/year of ethanol at a ratio of 215 gallons of ethanol per odt wood (hence 5.3odt/day waste wood) |
| Commercial scale plants | |
| Future plans | ClearFuels have plans to build a 7Mgallon year plant (would take 99odt/day of wood), then develop 25 Mgallon/year ethanol facilities in rural areas of Hawaii (would take 354odt/day of wood)<br>PTI also conducted feasibility studies for a 20M gallon/year ethanol plant in Gridley, California using rice straw in 2004<br>Gulf Coast Energy have plans for 5 more sites in and around Alabama |
| Time to commercialisation | |
| Target applications | Onsite FT production of ethanol (recycling loop for other compounds) |
| **Syngas characteristics and cleanup** | |

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|---|---|---|---|
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 51.5% $H_2$, 24.1% CO (ratio 2.14) | Tars | |
| $CO_2$ (% by vol) | 17.8% | Hydrocarbons (methane, $C_2H_4$, and higher) | 5.8% methane |
| $H_2O$ (% by vol) | | Particulates (ppm and size, | |

| | | | |
|---|---|---|---|
| | | e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | 0.5% $N_2$ | Others | |
| Syngas clean up | 5 gas cleanups stages, to remove any ash or tars and $CO_2$ | | |
| **Feedstocks** | | | |
| Main feedstocks | Have tested waste wood, sawdust, rice straw, bagasse, rice hulls, animal manure, lignite and creosote. Could use other feedstocks as switchgrass | | |
| Other potential feedstocks | Could use MSW, and other waste biomass feedstocks | | |
| Ability to accept a mixture of feedstocks | Yes | | |
| Ability to accept feedstocks varying over time | | | |
| Ability to accept wastes | Yes | | |
| Pre-treatment required | Drying and grinding required | | |
| Feedstock properties (energy content, moisture content, size etc) | Drying to a 15% moisture content, and grinding down to approx. 3/16" size (<5mm) | | |
| **Capital and operating costs** | | | |
| Costs | In 2004, ClearFuels closed a $2.4-million Series A round of venture capital funding. Investors included angel investors, Hawaiian Electric Industries, Metropolitan Energy Systems, National Mortgage and Finance, Garage Ventures, Alexander and Baldwin, PacifiCap<br>In 2006, entered MOU's with the owners of both local sugar cane companies, Maui's HC&S and Gay & Robinson on Kauai<br>The syngas is produced at a cost of approximately $1.20 per million BTU's, omission of oxygen results in lower capital costs. Claim that cost of ethanol is US$0.75-0.9/gallon | | |

## 6.2 Bubbling fluidised bed gasifiers

### 6.2.1 Carbona

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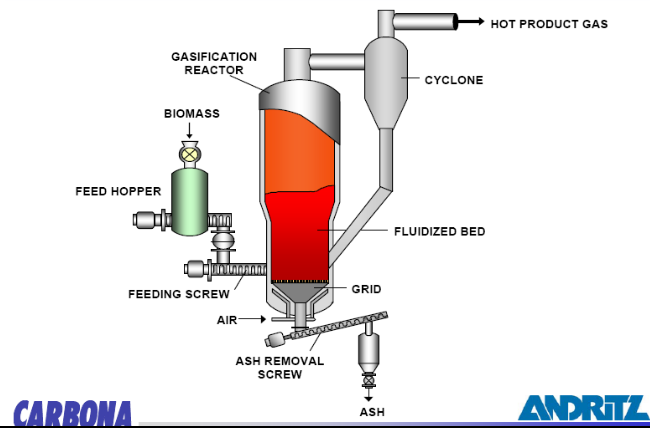
|---|---|
| **Basic information** | |
| Technology provider | Carbona |
| Location | Skive, Denmark |
| Information sources | www.renewableenergyworld.com/rea/magazine/story?id=54341 (no corporate website) |
| Background and links | Enviropower (75% owned by Tampella Power a major Finnish boiler supplier, 25% by Vattenfall) was established in 1989 to develop gasification technologies, and acquired the RENUGAS license from IGT (now Gas Technology Institute, GTI) in 1992. These gasification know-how rights and projects were bought out by management, forming Carbona Inc in Helsinki in 1996.<br>Andritz Oy acquired minority ownership of Carbona in 2006.<br><br>Gasification tech for the Skive plant is provided by Carbona, scope of contract is fuel feeding, gasification, gas cleaning, cooling and distribution. GTI involved in supporting Carbona's commercial applications. GE Jenbacjer AG/Austria supplied 3 JMS620GS engines for low calorific combustion. Technical research centre of Finland (VTT) as a subcontractor licensed its tar reforming tech to Carbona, and participated in design and testing<br>Skive plant owned by Skive Fjernvarme |
| **Gasifier type** | |
| Technology type | Bubbling Fluidised Bed |
| Technology name | RENUGAS<br> |
| Technology Overview | Biomass feed by screws into gasifier, with dolomite used as the bedding material. Air is blown in from below in fast enough to just fluidise the bed – and dry ash is removed from the base of the gasifier. Syngas is drawn off at the top of the gasifier, and any entrained particulates removed with a cyclone and fed back into the bed |
| Method of heat provision to the gasifier | Direct |
| Oxidant | Skive: Air and steam, although oxygen and steam also possible |
| **Gasifier operating data** | |
| Temperature | 850°C |
| Pressure | 2-30bar |
| Scale and output | Skive plant has a nominal 20$MW_{th}$ capacity (5.5$MW_e$ and 11.5 $MW_{th}$ district heat). In fact, able to operate between 30% and 140% load. Biomass input 4.1t/h (3.7odt/hr at 9.5% moisture) at its nominal rating, or 165t/day (150odt/day or 28$MW_{th}$ input) at maximum 140% rating |
| Efficiency (%) | Overall plant performance using wood pellets gives a max 87%, and electrical efficiency of 28% |
| Reliability issues | |
| **Development and commercial status** | |
| Pilot scale plants | Pilots at the GTI:<br>*1974: U-GAS® Pilot Plant, 3 bar – Chicago – 24 t/day coal. 125+ tests conducted, 11,000 hours of operating time, with 3000+ tons of different coal feedstocks processed*<br>*1983: U-GAS® PDU, Chicago. 8 t/day coal, high pressure up to 35 bar. 39 tests conducted, 2000+ hours* |

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| | *of operating time, 80+ tons of different coal feedstocks processed*<br><br>1985: RENUGAS® PDU, 25 bar – Chicago – 10 t/day (9odt/day) biomass. 22 gasification tests, 1800 hours of operating time. Various biomass feedstocks (bagasse, wood chips, whole tree chips, rice straw, alfalfa), RDF and Autofluff; moistures up to 27% tested. Gas treatment for IGCC applications<br><br>1992: 15$MW_{th}$ high pressure (up to 20bar) gasification pilot plant in Tampere, Finland. 26 tests conducted, 3850 hours of operating time with a variety of biomass wastes and mixed fuels such as wood & straw (700+ tons coal, 5300 tons biomass processed). Also evaluated hot-gas filtration for IGCC application. Used 80t/day biomass (72odt/day), or 30t/day coal<br><br>*2003: Fuel flex test facitility, Des Plaines, Illinois, completed shake down in Jan 2005. Can operated as BFB or CFB, up to 27bar, and using 40 ton/day biomass with oxygen (36odt/day) and 24t/day biomass with air (or 20 ton/day coal with oxygen and 12t/day coal with air)* |
| Commercial scale plants | I/S Skive Fjernvarme, a local district heating company in Skive/Denmark decided to implement a new biomass fuelled (up to 149odt/day wood pellets) combined heat and power (CHP) plant based on Carbona's biomass gasification. The Biomass Gasification Gas Engine (BGGE) process applies gas engines to produce electricity (5.5 $MW_e$) from wood derived syngas. The heat produced in the process is recovered as district heat (11.5 $MW_{th}$). The plant construction started in spring 2005, and was operation was due to start in 2006 – although plant commissioning and cold testing actually started in the autumn of 2007, performance testing in spring 2008, with 1040hrs operation to June. Optimised integrated plant systems have already been operated together for one engine, the process of adding the other 2 engines is underway – plant should be fully operational in early 2009<br><br>A second demo project was under discussion with IBIL (a Madras boiler manufacturer): RR Bio IGCC process design basis for Andra Pradesh, India. Fuel woody biomass and chips of 20% moisture, LHV dry 17.5 MJ/kg, feed rate 210t/day (168odt/day). Output net power would have been 12.5$MW_e$, with an electrical efficiency of 37%. However, no developments seem to have occurred<br><br>*The Institute of Gas Technology (now GTI) RENUGAS gasifier was originally demonstrated in 1988 at the Hawaiian Commercial & Sugar Company's Paia sugar factory in Maui, Hawaii, and operated using 100 tonne/day (84odt/day) of bagasse (the biomass remaining after sugarcane stalks are crushed to extract their juice) as the feedstock. However, the project demonstrated limited success with air-blown gasification at about 20 bar and hot-gas filtration to remove carry-over dust. Serious problems were encountered in handling and feeding the low-density, shredded biomass into the gasifier. The project was terminated in 1997* |
| Future plans | Global forestry company UPM, international technology group Andritz and its associated company Carbona intend to start the joint testing project of Carbona's gasification technology at the Gas Technology Institute's Fuel Flex (up to 36odt/day biomass input) pilot plant near Chicago, USA. Lab testing and modification would start in July 2007, finishing at the end of 2008, with estimated total costs are EUR 5-10m. This support research on gas conditioning is undergoing at GTI.<br>The co-operation also covers the design and supply of a commercial scale biomass gasification plant - initial targets are pulp&paper industry and gas for boilers, future targets are biorefineries and biomass IGCC plants. UPM wishes to be large FT biodiesel producer, with plans for its first plant to be based in Europe, producing roughly 5000barrels/day, needing 1Modt/year wood (3,044odt/day) input<br><br>Other recent activities at GTI include:<br>> Patent applications in place for US and EU<br>> Techno-economic analyses underway<br>> Carrying out internal investigations of TI as an appropriate method for producing active Fischer-Tropsch catalysts<br>> Investigation of GTI high-energy glass melting technology as a way to manufacture these catalysts in bulk<br>> Investigation of other areas of application for this approach to preparing catalysts |
| Time to commercialisation | |
| Target applications | Biomass gasification gas engine (BGGE) plant – a dedicated reciprocating engine CHP for district |

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| | heating | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | | Halides (HCl, Br, F) | to engine: 0.003% HCl |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | raw: 22% CO, 20% $H_2$, ratio 0.91<br>to engine: 23.41% CO, 20.71% $H_2$, ratio of 0.88 | Tars | |
| $CO_2$ (% by vol) | to engine: 9.9% | Hydrocarbons (methane, $C_2H_4$, and higher) | produced: methane 5%<br>to engine: methane 0.93%, $C_2H_4$ 0.001%, other higher 0.001% |
| $H_2O$ (% by vol) | to engine: 3.32% | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | to engine: 0.008% $H_2S$ + COS | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | to engine: 41.72% $N_2$, 0.005% $NH_3$ + HCN | Others | |
| Syngas clean up | A novel Ni catalytic cracker reforms tar compounds to H and CO, and ammonia at 900°C. Next, the gas is cooled and passed through bag filters to remove dust, then scrubbed with water where it cools to 30°C while the water content decreases. The heat from the gas removed in the scrubber is also used to generate district heat. Gas heater adjusts relative humidity to 80% before use in gas engines | | |
| **Feedstock requirements** | | | |
| Main feedstocks | Wood pellets mainly, or chips, although huge range of feedstocks tested | | |
| Other potential feedstocks | | | |
| Ability to accept a mixture of feedstocks | | | |
| Ability to accept feedstocks varying over time | | | |
| Ability to accept wastes | | | |
| Pre-treatment required | Feed through lock hopper system, and screws | | |
| Feedstock properties (energy content, moisture content, size etc) | Wood pellets less than 10% moisture, wood chips up to 30% moisture (the wood pellets used have a higher heating value of 20.2MJ/kg) | | |
| **Capital and operating costs** | | | |
| Costs | Skive financed on commercial basis, but as first-of-a-kind demo, receives subsidies. Funded with Public Service Obligation of DK 130MM. The project also receives funding support from the DEA, EC and USDOE<br>Expected plant lifetime of 15 years | | |

### 6.2.2 Foster Wheeler (BFB)

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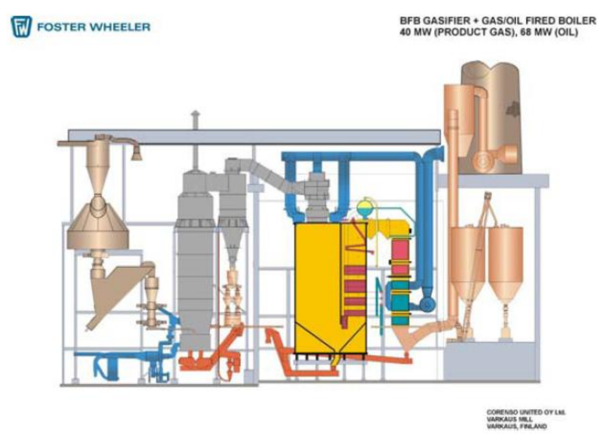
| **Basic information** | |
| Technology provider | Foster Wheeler Energia Oy |
| Location | Espoo, Finland |
| Information sources | http://www.fwc.com/GlobalPowerGroup/EnvironmentalProducts/BiomassGCS.cfm |
| Background and links | Foster Wheeler is an international engineering, construction and project management contractor and power equipment supplier – Foster Wheeler Energia Oy, part of the Global Power Group, is Foster Wheeler's Finnish subsidiary. FW acquired the power generation business of Alhstrom Pyropower Inc (API) in 1995, which included their fluidised bed technology and plants<br><br>Corenso United Oy Ltd (a subsidiary of Stora Enso and UPM-Kymmene) opened a liquid packaging board recycling plant in 1995 at their coreboard mill in Varkaus, Finland. The mill's fibre recycling plant separated used liquid packages and wrappings into their components: separated wood fibre is used for coreboard production and, formerly, the remaining mixture of polyethylene plastics and aluminium would be incinerated in a boiler. However, incineration of this mixture in a normal boiler proved to be very problematic due to the aluminium forming deposits on the heat transfer surfaces and on the grid of the boiler. These layers had to be removed at regular intervals, which caused interruptions in the power production and decreased the availability. In order to solve this problem, Foster Wheeler's BFB technology was developed |
| **Gasifier type** | |
| Technology type | Bubbling Fluidised Bed |
| Technology name | Foster Wheeler BFB 'Ecogas' process<br> |
| Technology Overview | This gasifier utilises reject material from the recycling process for used liquid cartons, which contains plastics and 10-15% aluminium foil. The aluminium is removed from the produced gas (for recovered aluminium processes), whilst the syngas from the plastic material is combusted in a steam boiler |
| Method of heat provision to the gasifier | Direct |
| Oxidant | Air and steam |
| **Gasifier operating data** | |
| Temperature | 600-1000°C |
| Pressure | Atmospheric |
| Scale and output | 40$MW_{th}$ output, with 5.7 ton/day of recyclable non-oxidised aluminium |
| Efficiency (%) | Potential for net electrical efficiencies of up to 40% |
| Reliability issues | High availability |
| **Development and commercial status** | |
| Pilot scale plants | In order to overcome the boiler deposit problems, a new concept based on BFB gasification technology capable of generating power from plastics and recovered aluminium was developed by FW and VTT, with Corenso United Oy Ltd. The process development work started at VTT's test laboratory in 1997, followed by a 15 $MW_{th}$ (25odt/day of packaging wastes) demonstration-scale gasification plant built by FW at the Varkaus mill, Finland. During the tests this demonstration plant was operated for a total of 1,400 hours |

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| | BFB gasification technology has also been developed for wood and MSW derived RDF by FWE and Powest Oy (a subsidiary of Pohjolan Voima Oy). The gasification and gas cleaning process has been extensively tested at a 1$MW_{th}$ pilot plant at VTT (4.8odt/day) | | |
| Commercial scale plants | The Corenso development work resulted in construction of a full-scale BFB gasification plant at the Varkaus mill by FW in 2001, taking in 82odt/day of packaging wastes. The plant has an output of 40 $MW_{th}$, generating 165 GWh of syngas energy from the plastics, and recovering and recycling of 2,100 tonnes of metallic, non-oxidized aluminium out of the syngas each year. This was increased to 50$MW_{th}$ and about 2,500tonnes of recycled Aluminium. | | |
| Future plans | The first MSW based FWE/VTT demonstration plant was planned jointly in 2002 by Powest Oy and Vapo Oy to be located at the Martinlasskso power plant, owned by Vantaan Energia Oy. A 80$MW_{th}$ BFB for solid RDF (274odt/day) was designed to replace about 30% of the plant's current coal consumption. Both Powest and Vapo agreed in March 2003 to transfer the technology to FWE, with FWE to provide the gasification plants for Powest and Vapo's first projects. However, the environmental permit was overturned in Dec 2003, and nothing has developed from this date | | |
| Time to commercialisation | | | |
| Target applications | Syngas is combusted in a steam boiler | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | 200-500°C | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | | Tars | |
| $CO_2$ (% by vol) | | Hydrocarbons (methane, $C_2H_4$, and higher) | |
| $H_2O$ (% by vol) | | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | | Others | |
| Syngas clean up | Unlike the direct use of syngas in the Lahti CFB plant, using high-alkali fuels like straw, or SRF with higher chlorine or heavy metal contents requires dry gas cleaning prior to the boiler (gas cooling, cyclone and filtering systems – with an optional catalyst unit) | | |
| **Feedstock requirements** | | | |
| Main feedstocks | Corenso plant uses aluminium and plastics in the reject material<br>FWE testing at VTT has used demolition wood, MSW based fuels and wood residues | | |
| Other potential feedstocks | | | |
| Ability to accept a mixture of feedstocks | | | |
| Ability to accept feedstocks varying over time | | | |
| Ability to accept wastes | Yes | | |
| Pre-treatment required | Crushing | | |
| Feedstock properties (energy content, moisture content, size etc) | Necessary to obtain particle size of L+H+W <150mm | | |
| **Capital and operating costs** | | | |
| Costs | $10million for the 40$MW_{th}$ Corenso gasifier unit | | |

### 6.2.3 Energy Products of Idaho

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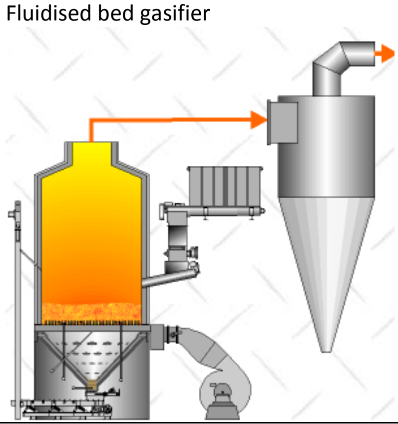
|---|---|
| **Basic information** | |
| Technology provider | Energy Products of Idaho (EPI) |
| Location | Coeur d'Alene, Idaho, USA |
| Information sources | http://www.energyproducts.com/ |
| Background and links | JWP Energy Products was a limited partnership formed in 1973, with Idaho Energy Limited Partnership purchasing the assets and technology in 1994, forming EPI. Its main business is the design and fabrication of fluidised bed combustion systems and boilers, but it also offers biomass gasification systems<br><br>EPI gasifiers are also being used by Advanced plasma Power in th3 UK as part of their Gasplasma process, combining an EPI gasifier with a Tetronics plasma converter. Further information on APP is given in italics throughout this annex.<br><br>*Advanced Plasma Power was founded in Nov 2005 to commercialise the proven Gasplasma technology originally developed by Tetronics Ltd. Tetronics has been in operation for over 40 years, and is using Plasma Arc solutions in 33 sites around the world, mostly in vitrifying incinerator bottom ash and hazardous waste, as well as in metals recovery.* |
| **Gasifier type** | |
| Technology type | Bubbling Fluidised Bed |
| Technology name | Fluidised bed gasifier<br> |
| Technology Overview | EPI gasifier operation: The fuel is fed into the system either above or directly into the sand bed, depending upon the size and density of the fuel and how it is affected by the bed velocities. The wood particles are subjected to an intense abrasion action from fluidized sand. This etching action tends to remove any surface deposits (ash, char, etc.) from the particle and expose a clean reaction surface to the surrounding gases. As a result, the residence time of a particle in this system is on the order of only a few minutes, as opposed to hours in other types of gasifiers<br><br>*Gasplasma process:*<br>*1) valuable recyclable materials removed in a front-end facility*<br>*2) the pre-treated waste feedstock is gasified in an EPI BFB*<br>*3) a Tetronics plasma converter is used to crack the tar and soot impurities in the syngas and 'polish' it, whilst simultaneously vitrifying the ash and inorganic fraction from the gasifier to form Plasmarok. This use of plasma to refine the syngas is different from processes which destroy waste by brute force (single stage plasma gasification* |
| Method of heat provision to the gasifier | Direct<br>The remaining char is oxidized within the bed to provide the heat source for the drying and de-volatilizing reactions to continue |
| Oxidant | The fluidizing medium is usually air; however, oxygen and/or steam are also used |
| **Gasifier operating data** | |
| Temperature | 540-980°C possible, optimum 590-650°C. APP plant uses 900°C |
| Pressure | 19-31bar |
| Scale and output | |
| Efficiency (%) | *APP plant electrical generating efficiencies of 35-40%* |

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| Reliability issues | EPI gasifier has a high degree of commonality with EPI's combustion process (their widely used technology), hence reliability issues significantly less likely | | |
| **Development and commercial status** | | | |
| Pilot scale plants | *Advanced Plasma Power has built a Gasplasma modular test facility in Faringdon, Oxfordshire that uses RDF to produce vitrified gravel (Plasmarok) and syngas for Jenbacher engines to generate power heat and power. In order to bring the Gasplasma tech to market, APP relocated the original pilot plant to Marston Gate, Swindon, taking the opportunity to upgrade the plasma converter and install downstream equipment to show the whole process working This commercial test facility was commissioned in 2008, and is 1/80$^{th}$ scale of the projected commercial capacity. It takes in pre-prepared RDF at a rate of 75kg/hr (1.8t/day, or 1.6odt/day assuming an RDF moisture content of 10%)* | | |
| Commercial scale plants | 1982: constructed a 16MW central heating plant in California. This 19bar (20.5t/hr steam) plant used 77t/day of agricultural wastes – and has since shut down<br>1985: constructed a 28MW wood chip plant in Bloomfield, Missouri – operational status unknown<br>1986: constructed a 6$MW_e$ power plant in Oregon. This 31bar plant is still currently operating, using 27t/hr (648t/day) of bio and industrial waste<br>1992: constructed a 0.75$MW_e$ plant for a New Jersey utility company. This 4.5t/hr steam plant has since closed down | | |
| Future plans | Construction of a 100M gallon ethanol plant by Panda Ethanol started in Hereford, Texas in 2006, using an EPI gasifier, to process 1billion pounds (1245t/day or 1,038odt/day) of manure from the regional cattle industry. The syngas produced will be used to power the 1$^{st}$ generation ethanol plant (instead of gas or coal), and not directly converted to ethanol. Production was expected in the second half of 2007, but the construction loan fell into default as a result of delays and costs overruns. Panda Ethanol agreed a new waiver in September 2008 to allow draws under the construction loan<br><br>*Plans for a larger Gasplasma facility in the UK, taking in 100,000tonnes/yr (241odt/day) of commercial or municipal waste, sorting, recycling and drying, then gasifying the remaining 60,000t/year (164odt/day) of RDF. This plant would produce 10.5 $MW_e$ gross product with a parasitic load of around 4.5 $MW_e$, meaning roughly 6 $MW_e$ is available for export. Heat exports from steam and hot water would be 13 $MW_{th}$ APP also announced a second plant size option of 150,000t/year in March 2009.* | | |
| Time to commercialisation | Has been commercial since the 1980's | | |
| Target applications | EPI produced the first wood fired fluidized bed gasifier power plant in the US and continue to provide innovative gasifier solutions to unique industry applications. They are currently introducing the gasifier approach as an add-on to utility coal fired power plants<br><br>*APP syngas used to power gas engines generating secure, clean, local heat and power* | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | APP plant plasma converter operates at above 1500°C | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | $H_2$ 37.5%, CO 40%, ratio 0.94 | Tars | |
| $CO_2$ (% by vol) | 15% | Hydrocarbons (methane, $C_2H_4$, and higher) | Methane < 1% |
| $H_2O$ (% by vol) | 3.2% | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | 3.3% $N_2$ | Others | |
| Syngas clean up | | | |
| **Feedstock requirements** | | | |
| Main feedstocks | EPI past plants: Wood chips, agricultural waste, bio and industrial waste and sewage sludge<br>*APP plant currently using RDF* | | |
| Other potential feedstocks | | | |
| Ability to accept a mixture of feedstocks | Yes | | |
| Ability to accept feedstocks | Yes | | |

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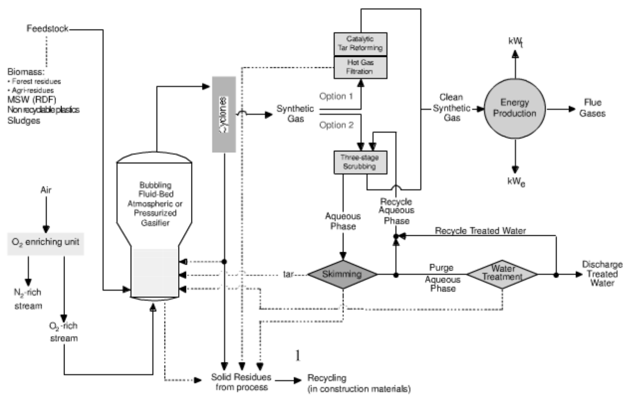
| varying over time | |
| Ability to accept wastes | Yes |
| Pre-treatment required | On-site storage of a day bin, then the fuel is delivered into metering bin(s) and fed into the gasifier through an air lock system.<br>*APP front end recycling facility separates wastes, and then dries material to form RDF* |
| Feedstock properties (energy content, moisture content, size etc) | EPI plants are able to use fuels with up to 55% moisture and high ash contents (in excess of 25% ash). The fuel sizing requirement is typically 3 inches or less |
| **Capital and operating costs** | |
| Costs | *Revenue streams: gate fees, recycling sales, sales of electricity, heat, Plasmarok*<br>*Typically use approximately one-third of the electricity produced to power the process. Two-thirds would be left for export to the grid, and would receive double ROCs*<br><br>*APP have stated that the approx capital cost including all fees for a facility is ~£50m, with opex costs of approx £4.8m including lifecycle costs and the cost of the parasitic load at the renewable power selling price (around £50/MWh). Quoted costs include the equipment for pre-processing, shredding and drying of the waste* |

### 6.2.4 Enerkem

| **Basic information** | |
|---|---|
| Technology provider | Enerkem Technologies Inc |
| Location | Quebec, Canada |
| Information sources | http://www.enerkem.com |
| Background and links | Enerkem is a subsidiary of the Kemestrie Inc. Group, a spin-off company of the Université de Sherbrooke, founded in 1992. It is the sole owner of a technology portfolio resulting from investments begun in 1981 by the Canadian government as part of its National Energy Plan.<br><br>Long history of development and many transfers of the BioSyn technology ownership (Canertech, Nouveler, Biothermica, Centre Quebecois de Valorisation de la Biomasse (CQVB), Université de Sherbrooke) - pilots were built and subsequently discontinued during the 1970's, 80's and 90's<br><br>Novera are the UK license holder, and Environmental International Engineering (EIE) the license holder in Spain, France, Italy, and parts of Latin America |
| **Gasifier type** | |
| Technology type | Bubbling Fluidised Bed |
| Technology name | BIOSYN gasification process<br> |
| Technology Overview | This process utilizes an autothermal bubbling fluidized bed (BFB) gasifier, with air or oxygen operating at pressures up to 16 atmospheres. The process includes proprietary catalysts for cracking tar and other components in the producer gas. The process is capable of operating on biomass, sorted MSW, and plastics |
| Method of heat provision to the gasifier | Direct |
| Oxidant | Usually air, although additional oxygen (40%) can be injected to change syngas composition. The presence of steam at a specific partial pressure is also part of the process |
| **Gasifier operating data** | |
| Temperature | 700°C usual, up to 900°C possible |
| Pressure | 10 bar usual, up to 16 bar possible |
| Scale and output | Demonstration plant in Westbury, Canada, will produce 5 million litres of ethanol from 13,000 tons of waste wood annually (equivalent input of 30odt/day or $8MW_{th}$) |
| Efficiency (%) | Enerkem will provide performance guarantees of minimum energy conversion efficiency (solids to conditioned synthesis gas) of 70% as well as composition of the synthesis gas based on the composition of the feedstock<br>Process produces 360 litres (95 gallons) of ethanol from 1 odt of waste |
| Reliability issues | |
| **Development and commercial status** | |

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| Pilot scale plants | Canadian Industries Limited (CIL) was formed in the early 1970s under ICI. CIL initiated the OMNIFUEL program to develop a versatile fluidized-bed technology to convert its industrial wastes into useful syngas for either energy or chemical synthesis. A 19odt/day RDF pilot plant was constructed in Kingston, Ontario. This was discontinued after CIL restructured.<br>BBC Engineering was formed and installed a 10t/hr (165odt/day) demonstration gasifier coupled to a boiler at the Levesque sawmill in Hearst, Ontario. The economics did not favour the commercialisation of the process despite its technical success<br><br>Canertech was created in the late 1970s by the Canadian government to promote alternate energy sources. Nouveler, a subsidiary of HydroQuebec, formed a joint venture, Biosyn Inc., with Canertech to demonstrate the gasification of biomass and the conversion of the syngas to methanol. A 10 t/h (250odt/day) 16bar gasification plant was operated at St. Juste de la Bretenniere, Quebec from 1984 to 1986, with over 1,600 gasification hours, and over 600 hours coupled to an Alstrom generator. Canertech was dissolved in 1984, and Nouveler became the sole owner of Biosyn.<br><br>Biodev, Inc. was a joint venture between Nouveler and SNC to commercialize the Biosyn technology. A demonstration project was secured in Guyane, France, to produce 7.5 MW of electricity (48odt/day input). The plant was constructed and briefly operated. It was abandoned in the late 1980s, due to costs overruns and higher-than-expected operating costs, and Biodev was dismantled. Biothermica Ltd. was formed as an independent company to continue to pursue the commercialization of the licensed Biosyn technology. The gasification plant and sawmill at St. Juste were sold to a sawmill company, BECESCO, in 1989.<br><br>The intellectual property generated by Biosyn was transferred to Centre Quebecois de Valorisation de la Biomasse (CQVB) in 1989. CQVB, a provincial corporation, launched a program to use the gasification technology to process forest waste, agricultural waste, MSW and RDF, and industrial wastes. A research program was started in 1990 at Université de Sherbrooke. Research was carried out using a 50 kg/h () gasifier that was built by IREQ. It was then transferred to Sherbrooke, and a PDU facility was built around the gasifier in 1993.<br><br>There has been an another ENERKEM pilot plant in operation since 2003 in Sherbrooke, Quebec. This BioSyngas-Estrie project with the City of Sherbrooke has produced syngas, methanol and ethanol – designed for 2.8t/day (1.5odt/day) biomass input, but able to take 5t/day (3.8odt/day) |
| Commercial scale plants | Industrial reactor built in Castellon, Spain in 2003 by Environmental International Engineering, taking in 60odt/day of plastic waste, and produces 7MW of electrical power. Feedstocks advertised to include mainly plastics, but some MSW, wood waste and RDF<br><br>Westbury, Quebec commercial scale demonstration plant (40t/day or 30odt/day wooden poles) was mechanically completed in Dec 2008, commenced start-up in Feb 2009, and is now in commissioning. The next step is to add fuel production modules, to produce 5 million litres (1.3 million gallons) of second-generation ethanol annually |

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| Future plans | Enerkem and GreenField Ethanol have signed a 25-year agreement with the City of Edmonton, Alberta to build and operate a plant that will produce and sell next generation biofuels, including methanol and cellulosic ethanol. The City of Edmonton will supply a minimum of 100,000 tonnes of sorted MSW (228odt/day), and the plant will initially produce 36 million litres of biofuels each year (one ethanol module) from 2010<br><br>Also developing a 4times larger project at Varennes, Quebec with GreenField Ethanol, taking in 400,000 tonnes of RDF/year (1,096odt/day), producing 140 million litres of ethanol (3 phases dependent on feedstock agreements)<br><br>March 2009 announcement that a new plant will also be constructed in Pontotoc, Mississippi. Three Rivers Solid Waste Management Authority of Mississippi (TRSWMA) will supply approximately 189,000 t/year (609t/day) of unsorted MSW to the plant. Timeline not given<br><br>Novera Energy was granted was granted planning permission for an Enerkem plant in Dagenham in September 2006. The 90,000 tonnes/year (247odt/day) plant will take refuse derived fuel from Shank's MBT plant in Frog Island, with the syngas used to generate around 10-12MW of electricity by the end of 2009. However, Novera withdrew from the UK's New Technologies Demonstrator Programme (which would have provided funding if operational for more than 8000hours/year) and at the time, were still looking for additional funding for the plant. The project was sold to Biossence in Apr 2009, who are developing several waste to power projects in the UK, and are partnering with New Earth Energy. However, little information regarding this pyrolysis + gasification technology is available, and although large plants are planned, there do not appear to be any pilot scale plants built to date. | | |
| Time to commercialisation | | | |
| Target applications | Sequential catalytic conversion into methanol and ethanol production – can also convert syngas into other fuels, such as synthetic diesel, synthetic gasoline, and dimethyl ether | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 2-10% $H_2$, 12-30% CO, hence ratio 0.1-0.8 | Tars | |
| $CO_2$ (% by vol) | 16-30% | Hydrocarbons (methane, $C_2H_4$, and higher) | |
| $H_2O$ (% by vol) | | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | 30-55% $N_2$ | Others | |
| Syngas clean up | Cyclone, cooling, washing and filtering | | |
| **Feedstock requirements** | | | |
| Main feedstocks | The EIE Spanish plant takes only plastic waste, and the demonstration plant will be using treated wood electricity poles (negative cost) | | |
| Other potential feedstocks | 20 different feedstocks have been tested in the pilot plant: including MSW, forest residues, construction and demolition wood, and treated wood | | |
| Ability to accept a mixture of feedstocks | Yes in the future | | |
| Ability to accept feedstocks varying over time | | | |
| Ability to accept wastes | Yes | | |
| Pre-treatment required | Drying, sorting and shredding | | |
| Feedstock properties (energy content, moisture content, size etc) | Moisture content of 20-25%, maximum size of 5cm | | |
| **Capital and operating costs** | | | |

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| Costs | Westbury plant construction received financial support from Sustainable Development Technology Canada and the Quebec Natural Resources and Wildlife Ministry<br>The estimated cost of the system when coupled to energy production varies from $1,500 to $2,000/kW<br><br>Edmonton plant will cost £70million |

### 6.2.5 Iowa State University

| **Basic information** | |
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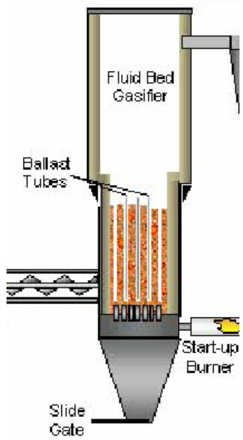
| Technology provider | Iowa State University (ISU) |
| Location | Ames, Iowa, USA |
| Information sources | http://www.cset.iastate.edu/research-projects.html |
| Background and links | The Center for Sustainable Environmental Technologies (CSET) performs research on a variety of thermochemical technologies including Gasification, Fast Pyrolysis, Bio-oil to fuels, Torrefaction of biomass and Biochar production for agronomic applications and carbon sequestration nutrient recycling between production agriculture and biofuels manufacturing |
| **Gasifier type** | |
| Technology type | Bubbling Fluidised Bed |
| Technology name | BECON (Biomass Energy Conservation Facility) - Thermal ballasted latent heat BFB gasifier   |
| Technology Overview | The latent heat gasifier is operated in a discontinued mode; first the heat released during combustion at 850°C is stored as latent heat in the form of vaporized molten salt (e.g. lithium fluoride) sealed in ballast tubes immersed in the fluidized bed. During the pyrolysis phase, which occurs at temperatures between 850 and 600°C, the BFB reactor is fluidized with steam rather than air. Condensation heat stored in the phase change material is released during this phase of the cycle to support the drying and endothermic reactions of the biomass pyrolysis and gasification stages. There is no nitrogen dilution of the product gas, resulting in relatively high concentrations of hydrogen and carbon monoxide. Once the temperature has dropped sufficiently, the fuel feed is stopped and the heat source is directed to the vessel again, and the process repeats.<br>Although the process gives a high heating value syngas, it is complex, non continuous, with variable temperatures and considerable material fatigue and erosion |
| Method of heat provision to the gasifier | Indirect, batch heating |
| Oxidant | Steam |
| **Gasifier operating data** | |
| Temperature | 850°C falling to 600°C as the gasifier cools |
| Pressure | Atmospheric |
| Scale and output | $1MW_{th}$ (uses 5odt/day of biomass) |
| Efficiency (%) | Carbon conversion efficiency of 85% |
| Reliability issues | Feedstock shredding difficulties, hence a small size was needed |
| **Development and commercial status** | |
| Pilot scale plants | $1MW_{th}$ BECON pilot was built in 2002. Currently uses 5odt/day of switch grass. |
| Commercial scale plants | |
| Future plans | Iowa are also investigating bench-scale BTL processes, decentralised pyrolysis technologies, and syngas fermentation.<br>The ultimate goal of Iowa's partnerships with Frontline Bioenergy and Hawkeye Renewables is to develop cost-effective technologies that can be adapted in the existing corn-based ethanol industry within a reasonable payback time. (Frontline BioEnergy, located in Ames, Iowa, has installed its own gasification unit at Chippewa Valley Ethanol Co. LLLP in Benson, Minn., which is using wood chips to displace 90 percent of its natural gas. In production since April, the gasifier uses approximately 380 |

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| | tons of wood waste per day)<br><br>August 2008: ConocoPhillips Co. and Iowa State University are partnering to test an integrated biomass-to-liquids system whose process, as described by the energy department, uses "gas cooling through oil scrubbing rather than water scrubbing in order to minimize wastewater treatment." The intended biomass for gasification is switchgrass. The DOE's description of the ConocoPhilips and Iowa State University process continues: "The gas-oil scrubbing liquid will then be sent to a coker in existing petroleum refining operations to be used as a feedstock." The team was awarded $2 million toward the $3.1 million project | | |
| Time to commercialisation | | | |
| Target applications | One of Iowa's research goals is to optimize performance for producing a hydrogen-rich gas suitable for powering fuel cells. Other projects have looked at replacement of industrial chemicals. Recent funding will now direct research towards catalytic ethanol production and replacement of natural gas burning | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 26% $H_2$, 39% CO (ratio 0.67) | Tars | |
| $CO_2$ (% by vol) | 18% | Hydrocarbons (methane, $C_2H_4$, and higher) | 11% methane |
| $H_2O$ (% by vol) | | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | | Others | |
| Syngas clean up | Slipstream includes: a guard bed designed to remove hydrogen sulfide and hydrogen chloride; a steam reformer designed to crack tar and decompose ammonia and high temperature and low temperature water-gas shift reactors | | |
| **Feedstocks** | | | |
| Main feedstocks | Tested switch grass, discarded seed corn and wood chips | | |
| Other potential feedstocks | Plans include the use of grasses, corn cobs and stover, and other agricultural biomass residues | | |
| Ability to accept a mixture of feedstocks | | | |
| Ability to accept feedstocks varying over time | | | |
| Ability to accept wastes | No | | |
| Pre-treatment required | Shredding | | |
| Feedstock properties (energy content, moisture content, size etc) | Less than 5mm | | |
| **Capital and operating costs** | | | |
| Costs | ConocoPhillips announced in 2007 that they were establishing an eight-year, $22.5 million research program at Iowa State University dedicated to developing technologies that produce bio-renewable fuels, with a particular focus on fast pyrolysis<br><br>Very recent (6th March 2009) funding announcement of a two-year, $2.37 million grant from the Iowa Power Fund for two syngas projects: efficient burning, and catalytic ethanol production. Partners with Frontline BioEnergy LLC and Hawkeye Renewables LLC | | |

### 6.2.6 ThermoChem Recovery International

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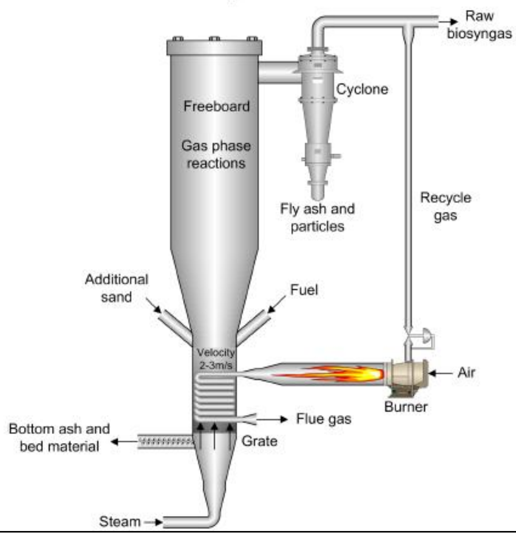
| **Basic information** | |
| Technology provider | ThermoChem Recovery International, Inc (TRI) |
| Location | Baltimore, MD, USA |
| Information sources | http://www.tri-inc.net/company_overview.html |
| Background and links | Manufacturing and Technology Conversion International (MTCI) formed in 1996<br>TRI hold the worldwide licence to commercialise MTCI technologies (except in India, where this is held by ESVIN Advanced Technologies Limited). TRI working with Norampac Inc at the Trenton mill |
| **Gasifier type** | |
| Technology type | Bubbling Fluidised Bed |
| Technology name | “Pulse-enhanced” BFB gasifier<br><br> |
| Technology Overview | Indirectly heated steam reformer gasifier |
| Method of heat provision to the gasifier | Indirect – a small proportion of the produced gas is recycled to a pulse burner to produce heat to gasify the feedstock |
| Oxidant | Steam |
| **Gasifier operating data** | |
| Temperature | 790-815°C |
| Pressure | Atmospheric |
| Scale and output | |
| Efficiency (%) | For the integrated paper mill and gasifier, 71-81% thermal efficiency achievable |
| Reliability issues | Poor specifications lead to failure of the Big Island project |
| **Development and commercial status** | |
| Pilot scale plants | Extensive plant tests were conducted in a 20t/day (12odt/day) pilot unit built in 1992 at MTCI laboratories near Baltimore, Maryland - including using black liquor solids<br>50t/day (30odt/day) black liquor demo built in 1996 at Weyerhauser’s New Bern facility, North Carolina<br><br>ESVIN set up a demonstration unit at the mill premises of Seshasayee Paper and Boards, Erode, India in 1993-94 |
| Commercial scale plants | Georgia Pacific, Fluor Daniels, and Stone Chem (the North American subsidiary of TRI), with 50% support from USDOE, constructed a 200t/day (120odt/day) sodium carbonate black liquor gasification demonstration plant at the Big Island, Virginia GP paper mill. The demo project, started in Feb 2001, cost $87m - however, was not successful due to poor reformer specifications (and the expected cost of modifying the reformers' performance was too high), and hence closed in 2006.<br><br>Other MTCI technology projects have been abandoned in the past, with a 145t/day project started with V.I.A. Biomasse-Heizkraftwerk GmbH & Co. Kirchmöser KG to burn the syngas in an existing waste wood combustion plant running into serious difficulties with the permitting authorities. Two other projects prepared jointly by Biomassezentrum Spreewald GmbH & Co. KG, Dresden, (future |

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| | operator), ECS Energie Consulting und Service GmbH, Dresden, (project developer), EBU GmbH, Ludwigshafen, (engineering) and SPIRIT of TECHNOLOGY AG (financing), Hosenfeld, at Vetschau and a second site in Bavaria were abandoned<br><br>In conjunction with the Norampac board mill in Trenton, Ontario, Canada, another TRI site started up in 2003, completed testing in 2006 and is now fully commercially operational, providing process steam and spent liquor back to the mill. Processes 115t/day (69odt/day) |
| Future plans | Two projects were awarded federal grants of $30m each in 2008:<br>• Flambeau River Biofuels, Park Falls, Wisconsin, USA. Announced in November 2007 their plans to build a demo plant (15% scale) to produce 16,500t/year of FT waxes (for diesel) in a joint venture with Syntroleum, and provide heat and power for the paper mill. The gasifier will take in 580odt/day of residual forest biomass. Construction will start in 2009, and is expected to be complete in 2010. Future plans at Flambeau include construction of a larger scale 1,900odt/day unit producing 40m gallons/year of FT liquids<br>• Project Independence, New Page Corp, Wisconsin Rapids. New Page Corp acquired Stora Enso North America in early 2008. The plant will take in 497odt/day of woody biomass comprised of mill residues and unmerchantable forest biomass to make 370 barrels per day of FT liquids. Estimated to be operational in 2012.<br><br>August 2008: One syngas cleaning project receiving US DOE grant funding includes Southern Research in partnership with Pall Corp., Thermochem Recovery International Inc. and Rentech Inc. The project will test a 1 MW (4.8odt/day) biomass gasifier for syngas generation with ceramic filter technology and a proven sorbent/catalyst system for syngas decontamination. The team is assembled and a group design for a syngas cleanup system is complete, which is part of Phase I. In its entirety, Phase I consists of design, fabrication and testing of the gas cleanup system on TRI's biomass gasifier, installation of which is underway at Southern Research as part of a separate contract. This is a three-year project. By the end of 2008, fabrication of the syngas cleanup system is expected to have begun, with test runs and optimizing strategies to start sometime in 2009, along with Phase II. Phase II will be linking up all the above with a FT line and converting the clean syngas into FT wax. A refinery pilot step will be added to take the FT wax and convert it into clean diesel, and a final step is to evaluate the performance of the clean diesel in a passenger truck[101]<br><br>TRI corporate website also lists rather vague plans:<br>Major Paper Company (2,000t/day biomass-to-biofuels plant)<br>Regional Paper Company (displace natural gas in boiler with bio syngas)<br>Alternative Energy Company (biomass-syngas-combined cycle power gen)<br>Major Paper Company (displace natural gas in kiln with bio syngas) |
| Time to commercialisation | |
| Target applications | Past commercial applications have been dedicated onsite mill process heat - able to close the loop (take useful products, and give back useful products). Move towards biofuels production |

| **Syngas characteristics and cleanup** | | | |
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| Temperature | | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 43.3% $H_2$, 9.2% CO by volume (ratio of 4.7)<br>after cleanup, $H_2$ >65% | Tars | Medium or low (potentially, if proper bed material or fuelmix is used to increase the gasification temperature without aggl. problems) |
| $CO_2$ (% by vol) | 28.1% | Hydrocarbons (methane, $C_2H_4$, and higher) | 4.7% methane, 9% $C_{2+}$ |
| $H_2O$ (% by vol) | 5.6% | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |

[101] Ron Kotrba (2008) "Cleansing and Reforming Syngas " Available online: http://www.biomassmagazine.com/article.jsp?article_id=1856&q=&page=all

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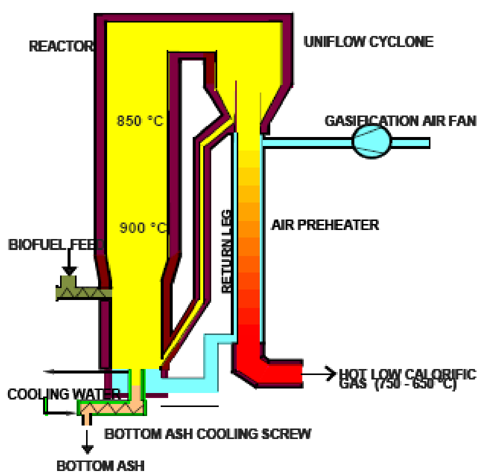
|---|---|---|---|
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | 0% $N_2$ | Others | |
| Syngas clean up | Ash is removed in the combustion chamber, downstream syngas scrubber | | |
| **Feedstocks** | | | |
| Main feedstocks | Past plants have only used black liquor solids<br>New proposed plants will be using woody biomass comprised of mill residues and residual forest biomass (treetops, bark, branches and similar material recovered from the forest floor during harvesting operations) | | |
| Other potential feedstocks | | | |
| Ability to accept a mixture of feedstocks | No | | |
| Ability to accept feedstocks varying over time | No | | |
| Ability to accept wastes | No (only mill process waste) | | |
| Pre-treatment required | No treatment required | | |
| Feedstock properties (energy content, moisture content, size etc) | Gasifier operates with 40% moisture content feedstock (either dried black liquor solids, or fresh woody residues) | | |
| | | | |
| Costs | For a 44t/day (26odt/day) black liquor MTCI gasifier: capital cost $1.1m<br>Flambeau Rivers project will cost $84m (€57m) for the 15%-scale demonstration facility<br>Future scaled up plant expected to have a total cost of approximately $250 m | | |

## 6.3 Circulating fluidised bed gasifiers

### 6.3.1 Foster Wheeler (CFB)

| **Basic information** | |
|---|---|
| Technology provider | Foster Wheeler Energia Oy |
| Location | Espoo, Finland |
| Information sources | http://www.fwc.com/GlobalPowerGroup/EnvironmentalProducts/BiomassGCS.cfm |
| Background and links | Foster Wheeler is an international engineering, construction and project management contractor and power equipment supplier – Foster Wheeler Energia Oy, part of the Global Power Group, is Foster Wheeler's Finnish subsidiary. FW acquired the power generation business of Alhstrom Pyropower Inc (API) in 1995, which included their fluidised bed technology and plants<br><br>The FW CFB gasification technology was developed in the early 1980s, the driver for development being very high oil prices. The first commercial-scale CFB gasifiers, using 17 to 35 MW of dry waste wood as feedstock, were delivered for the pulp and paper industry by Ahlstrom Corp. in the mid 1980s, enabling oil to be substituted in the lime kiln process. During the 1990s, a gasification process producing raw gas from a variety of biomass and recycled fuels to be co-combusted in a pulverized coal boiler was developed. Additionally, three commercial-scale atmospheric CFB gasifiers with fuel inputs from 40 to 70 MW were supplied during the years 1997-2003<br><br>Energie E2, the Danish utility, had previously developed CFB co-firing straw boilers, and then merged with ELSAM, both becoming part of DONG Energy Company. FW then took over their main biomass gasification business at Lahti, Finland – since the takeover, Energie E2 and ELSAM no longer exist as such |
| **Gasifier type** | |
| Technology type | Circulating Fluidised Bed |
| Technology name | Foster Wheeler atmospheric CFB<br> |
| Technology Overview | Consists of a gasification reactor, a cyclone to separate the circulating-bed material from the gas, and a return pipe to return the circulating material to the bottom part of the gasifier. From the cyclone, the hot product gas flows into an air pre-heater located below the cyclone |
| Method of heat provision to the gasifier | Direct<br>The circulating solids contain char that is combusted with the fluidizing air, generating the heat required for the pyrolysis process and subsequent, mostly endothermic, gasification reactions. The circulating material also serves as a heat carrier and stabilizes the process temperatures. |
| Oxidant | Previous plants: Air<br>New NSE plant: Steam/oxygen |
| **Gasifier operating data** | |
| Temperature | 900°C |
| Pressure | Atmospheric |
| Scale and output | Various – see Commercial plant section below. As a conversion guide, the original 3$MW_{th}$ input pilot |

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| | plant took in 14.5t wood/day |
| Efficiency (%) | |
| Reliability issues | Lahti availability has consistently been over 96% |
| **Development and commercial status** | |
| Pilot scale plants | 1981: 3$MW_{th}$ test unit built at the Hans Ahlstrom Lab, Finland, using various fuels (14.4odt/day)<br>1986: 4$MW_{th}$ test facility built for Kemira Oy in Vuorikemia, Finland. Used peat and coal (19.2odt/day)<br><br>Besides pilot plant tests performed at FW's Karhula R&D center with gas cleaning, long-term testing has been carried out with slipstream equipment at the Lahti gasification plant. This development project led by FW has been co-funded by TEKES, and the other partners have been Lahti Energia Oy and Energi E2, a utility from Denmark with a strong CFB straw boiler background.<br><br>In 2001, ENERGI E2 and Foster Wheeler carried out a test program regarding straw gasification in a 3 $MW_{th}$ (14.4odt/day) atmospheric CFB gasifier with gas cleaning. Parallel with this, a design study was conducted with the aim to carry out conditions for a 100$MW_{th}$ (480odt/day) gasifier connected to the coal fired power plant at Amagerveaerket. Economic calculations showed that the cost for the plant would be 38.4M EUR. However, high prices of straw and low prices of the district heating in Copenhagen made the project unviable |
| Commercial scale plants | Four CFB plants were built in the 1980's using A. Ahlstrom Corp. Technology:<br>1983: 35$MW_{th}$ (168odt/day) bark and sawdust, syngas used as lime kiln fuel, built for Oy W. Scheuman at Wisaforest Oy, Pietarsaari, Finland<br>1984: 25$MW_{th}$ (120odt/day) bark input, syngas used as lime kiln fuel, built for Norrsundet Bruks, Sweden. The CFB unit at the Norrsundet mill closed in 2008<br>1984: 27$MW_{th}$ (130odt/day) bark input, syngas used as lime kiln fuel, built for ASSI Karlsborg, Sweden. The Karlsborg unit is still there but not operated presently<br>1985: 15$MW_{th}$ (72odt/day) bark input, syngas used as lime kiln fuel, built for Portucel, in Rodao, Portugal<br><br>*1993: 18$MW_{th}$ (86*odt/day) *pressurised CFB as part of a biomass IGCC built with Sydkraft in Varnamo, Sweden – was mothballed in 2000 –* ***see CHRISGAS project for more information***<br><br>1997: The first CFB gasifier connected to a pulverized coal boiler was constructed in 1997 at the Kymijärvi power plant of Lahden Lämpövoima Oy in Lahti, Finland. In this process, the syngas is fed directly to a pulverized coal boiler without gas cleaning. By co-firing with biomass syngas, the coal fired boiler emissions are decreased. This 40-70$MW_{th}$ (192-336odt/day) biomass input plant has produced an additional 7-23$MW_e$ for the town since 1998<br>2002: A similar plant was built at the Electrabel Ruien pulverized coal power plant, in Belgium – moisture contents can vary between 60-20%, and corresponding fuel inputs are 45-86$MW_{th}$ (216-413odt/day) |
| Future plans | A completely new, 160 $MW_{th}$ (average of 768odt/day) CFB BMG plant at Lahti, Finland is now in the design phase. The design includes 2 gasifiers, hot gas cleaning based on gas filtration, and a new gas fired boiler. Fuel gas and flue gas cleaning facilities have been designed to fulfil all WID regulations. The 685-821t/day of waste used will be a mix of industrial-based RDF and locally sourced and sorted MSW<br><br>*FW, together with Neste Oil and Stora Enso, is participating in a VTT-driven project targeting the development of an advanced process for producing multi-purpose Ultra Clean synthesis Gas (UCG) from solid biofuels –* ***for more information see VTT****. The pressurised oxygen/steam 12$MW_{th}$ (60odt/day) plant is expected to start up in early 2009, with VTT acting as the main R&D partner in this project. After the demonstration phase is completed (48 months), the unit will be converted to an atmospheric, air-blown CFB to make syngas for the lime kiln process.*<br>*As part of this UCG project, NSE Biofuels Oy Ltd., the 50-50 joint venture between Stora Enso Oyj and Neste Oil Corporation is focusing on the production of synthetic diesel from wood residues, and awarded a contract to FW for a CFB biomass gasifier in May 2008. The gasification and syngas cleaning will be part of NSE's new-generation renewable diesel demonstration plant, integrated into Stora Enso's Varkaus Mill in Finland.*<br>*Foster Wheeler and the JV partners have also agreed in principle for further co-operation, aiming for* |

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| | *delivery of a 200-300MW$_{th}$ (1,522odt/day) commercial-scale plant to be located at one of Stora Enso's mills* | | |
| Time to commercialisation | Has been fully commercial since 1980's | | |
| Target applications | Previous applications have either used the syngas to replace oil in lime kiln firing, lower coal use in power station boiler heating, or for standalone IGCC applications. Latest developments plan to produce FT diesel, and longer term involvement in the VTT UCG project will be developing multiple syngas uses, such as FT liquids, methanol, SNH and hydrogen | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | 700°C at gasifier exit | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 15-17% $H_2$, 21-22% CO, hence ratio 0.74 | Tars | |
| $CO_2$ (% by vol) | 10-11% $CO_2$ | Hydrocarbons (methane, $C_2H_4$, and higher) | 5-6% methane |
| $H_2O$ (% by vol) | | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | 46-47% $N_2$ | Others | |
| Syngas clean up | | | |
| **Feedstock requirements** | | | |
| Main feedstocks | Lahti has used fuels such as bark, wood chips, sawdust and uncontaminated wood waste. Other fuels have also been tested subsequently, including RDF, plastics, railway sleepers and tyres<br>Ruien was designed for fresh wood chips, but can also use bark, hard and softwoods, and recycled wood chips | | |
| Other potential feedstocks | | | |
| Ability to accept a mixture of feedstocks | Yes | | |
| Ability to accept feedstocks varying over time | Yes – as a result of availability and price changes, the share of REF fuel has gradually increased at the expense of cleaner biomass fuels | | |
| Ability to accept wastes | Yes | | |
| Pre-treatment required | Drying is not required - some modifications have been necessary to deal with unusual waste impurities such as metal wire, nails | | |
| Feedstock properties (energy content, moisture content, size etc) | Moisture contents can vary between 20-60%, ash content is usually 1-2% | | |
| **Capital and operating costs** | | | |
| Costs | The value of the new Lahti 160MW$_{th}$ project is roughly €100M<br>VTT's Waste to Energy demonstration stage at the new Lahti plant has a budget of €23.5M for 48 months, with a grant from the EC of €8.7M<br><br>Total cost of the original Kymijarvi Lahti plant were 12 million EUR, including fuel preparation plant, civil works, instrumentation and control as well as electrification. The project received 3 million euros support from the THERMIE Program of the European Commission. The estimated payback time of the investment was 5–7 years. | | |

### 6.3.2 Växjö Värnamo Biomass Gasification Center

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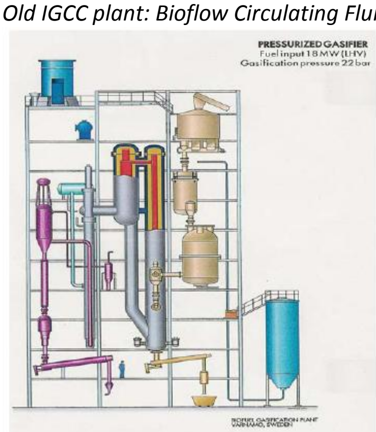
| **Basic information** | |
| Technology provider | Växjö Värnamo Biomass Gasification Center (VVBGC), formerly Sydkraft |
| Location | Värnamo, Sweden |
| Information sources | http://www.chrisgas.com/ http://www.vvbgc.com/ |
| Background and links | Original plant was a joint venture named Bioflow between Sydkraft AB and Foster Wheeler Energy, creating an IGCC gasifier and Typhoon gas turbine. Started construction in 1991, operation from 1993-1999. Transferred ownership to the non-profit organisation VVBGC in 2003. *Old plant data is in italics*<br><br>CHRISGAS partners: Sweden - Växjö University (co-ordinator), Växjö Värnamo Biomass Gasification Centre (VVBGC), AGA-Linde, Catator, KS Ducente, Royal Institute of Technology (KTH), S.E.P. Scandinavian Energy Project, TPS Termiska Processer, (Valutec), and Växjö Energi; Denmark - TK Energi; Finland - Valutec; Germany - FZ Jülich, Linde, and Pall Schumacher; Italy - University of Bologna; Netherlands - Technical University Delft; Spain - CIEMAT. |
| **Gasifier type** | |
| Technology type | Circulating Fluidised Bed |
| Technology name | *Old IGCC plant: Bioflow Circulating Fluidized Bed*, new plant: CHRISGAS CFB conversion<br> |
| Technology Overview | Nothing specific on this technology. Standard CFB:<br>Compared to FB & BFB: higher quality syngas, higher throughput, high yields because residence time means good C conversion. CFB fairly low tar, only EF and Downdraft FB have less. Sand bed allows in-bed catalytic processing, tolerant to particle size and fluctuations in feed quantity and moisture. Flexible fuels<br>However, CFB syngas is rich in particulates. CFB quite advanced, especially pressurized. Significant danger of bed agglomeration using biomass, need intelligent fuel mixing for safe operation at higher temperatures. The size of fuel particles determines the minimum transport velocity; high velocities may result in equipment erosion. The heat exchange is less efficient than BFB, temperature gradients may occur in the direction of the solid flow |
| Method of heat provision to the gasifier | Direct |
| Oxidant | *Old plant: air*<br>Rebuilt plant: oxygen/steam mix |
| **Gasifier operating data** | |
| Temperature | 950-1000°C |
| Pressure | 18-20bar |
| Scale and output | 4t/hr feed (96t/day or 86odt/day), i.e. $18MW_{th}$ input capacity. Outputs 6 $MW_e$ and 9 $MW_{th}$ |
| Efficiency (%) | |
| Reliability issues | *Old IGCC plant: 8500hrs of testing over 6 years from 1993-1999. Did have problems with ceramic filter candles breaking under mechanical fatigue – sintered metal filters were used from 1999* |
| **Development and commercial status** | |
| Pilot scale plants | The old Värnamo IGCC plant was mothballed in 2000 after testing because unviable (Swedish electricity prices were very low, and plant capacity too small). Was reactivated in October 2005, as the Växjö Värnamo Biomass Gasification Center AB, as one of the prominent European center piece |

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| | for R&D of the CHRISGAS project (running Sept2004 - Aug2009). The original plant ran on air, conversion is to oxygen steam mix | | |
| Commercial scale plants | | | |
| Future plans | Primary mission of the project is to produce 3,500 $Nm^3$/hr of clean hydrogen-rich gas from biomass by 2009. Ultimate CHRISGAS goal is to produce price competitive biofuels, and a source of gasification education<br>The R&TD Deliverables for the CHRISGAS project are: Test new drying and feeder systems, conduct BMG tests and obtain operational data at 3-4t/hr (86odt/day), and evaluate catalysts, filters, gas cleaning systems etc. used in the Bioflow process<br>Modifications will include: installing a new steam/oxygen distributor, a new hot gas filter system, and the installation of a catalytic high temperature reformer. Unfortunately, only some of these demo activities happened within the CHRISGAS timeframe, and additional funding for a rebuild (scheduled Apr07-May09) is delayed. The project currently faces an uncertain future | | |
| Time to commercialisation | | | |
| Target applications | *Old IGCC plant: Syngas successfully combusted in a closely integrated Typhoon gas turbine for CHP district heating*<br>CHRISGAS conversion: hoping to produce biofuels | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | *Old IGCC plant: 350-400°C* | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | *Old IGCC plant <0.1ppm* |
| $H_2$, CO (% by vol), ratio | *Old IGCC plant: 11% $H_2$, 16% CO (ratio of 0.69). New conversion will mean both %s higher, and steam reforming and WGS much higher $H_2$ in the final syngas* | Tars | *Old IGCC plant <5g/$Nm^3$* |
| $CO_2$ (% by vol) | *Old IGCC plant: 10.5%* | Hydrocarbons (methane, $C_2H_4$, and higher) | *Old IGCC plant: 6.5%* |
| $H_2O$ (% by vol) | *Old IGCC plant: raw gas 12%* | Particulates (ppm and size, e.g. Ash, soot) | *Old IGCC plant: dust <2ppm by weight* |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | *Old IGCC plant: 44% $N_2$, <700ppm $NH_3$,* but conversion will be $O_2$/ steam blown, so $N_2$ much lower. | Others | |
| Syngas clean up | *Old plant: The raw gases were cooled to 350°C – 400°C, then cleaned for particulates without condensation employing candle filters (a hot-gas ceramic filter)*<br>New plant: Cleaning HT filter (remove particulates), up-grading (steam reforming via catalytic ATR or thermal WGS of tars and light hydrocarbons including methane) | | |
| **Feedstock requirements** | | | |
| Main feedstocks | *Old IGCC plant used Wood chips, pellets, bark, straw* | | |
| Other potential feedstocks | | | |
| Ability to accept a mixture of feedstocks | | | |
| Ability to accept feedstocks varying over time | | | |
| Ability to accept wastes | | | |
| Pre-treatment required | Drying (using a flue gas dryer in a separate fuel prep plant)<br>Crushed, pressurised in a lock-hopper system, and fed to gasifier by screw feeders | | |
| Feedstock properties (energy content, moisture content, size etc) | Moisture content: 5-20% | | |
| **Capital and operating costs** | | | |
| Costs | The CHRISGAS project is financed by € 9.5 million EC grant, € 1.5 million STEM grant, and € 7 million grant from other team members<br>Rebuild & Operation Dec 2006: need 250m SEK. STEM giving 182m SEK with advance 26m SEK. Industrial consortia to be established for remaining 68m SEK. STEM gave extra 4m SEK in Aug2008 to allow extension to find industrial funds (1€=9.2SEK) | | |

### 6.3.3 VTT

| **Basic information** | |
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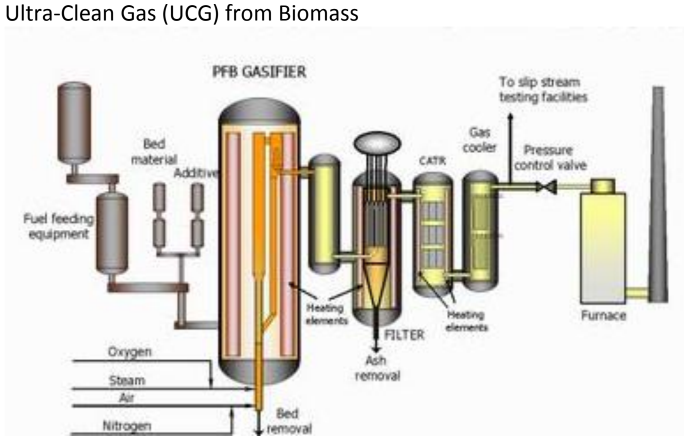
| Technology provider | VTT Technical Research Centre of Finland |
| Location | Otaniemi, Espoo, Finland |
| Information sources | http://www.vtt.fi/palvelut/cluster7/topic7_3/energia__taso3_item5_kaasutus.jsp |
| Background and links | Retaining its focus on resolving the technical hurdles to BMG, VTT has successfully continued biomass gasification R&D since the 1980s, whilst many other countries suffered cut-backs in funding. VTT are now combining their research and lab operations with KCL (Oy Keskuslaboratorio Centrallaboratorium Ab).<br>The UCG project involves the Helsinki University of Technology, Neste Oil, Foster Wheeler Energy, Andritz, Vapo, Pohjolan Voima and the large forest industry companies UPM, Stora Enso, M-Real and MetsäBotnia.<br><br>Other biomass and waste gasification RD&D activities at VTT include:<br>• PDU gasification tests with auto shredder residues<br>• CFB gasification of plastics and fuel gas utilization in industrial kilns<br>• Evaluation of gasification of contaminated (CCA) wood in the NOVEL (1.3MWe + 3.3MWth fixed bed updraft gasifier) process<br>• Catalyst development and design for gas cleaning (e.g. evaluating Zirconia as a substitute for Ni for tar cracking) at the Novel demonstration plant<br>• Integrated process concepts for producing liquid biofuels and/or green electricity at pulp and paper mills<br>• Improvement of economics of BFB BMG processes by advanced ash management involving integrated oxidiser tests with wood derived and waste derived solid recovered fuel (SRF) filter dust<br>VTT has several test rigs, fixed bed, BFB and CFB gasifier and cleaning test facilities<br>The most recent R&D gasification programs also being carried out at VTT include UCGFUNDA from 2008-2010 (studies into supporting industrial development), and Lahti (high efficiency gasification based on Waste To Energy 160 $MW_{th}$ demonstration) |
| **Gasifier type** | |
| Technology type | Circulating Fluidised Bed |
| Technology name | Ultra-Clean Gas (UCG) from Biomass<br> |
| Technology Overview | Pressurised fluidised bed PDU for Biomass Gasification |
| Method of heat provision to the gasifier | Direct |
| Oxidant | Oxygen and Steam for syngas applications, Air-blown for IGCC |
| **Gasifier operating data** | |
| Temperature | 600-1000°C, with 750°C in the target configuration |
| Pressure | 10 bar in the target configuration |
| Scale and output | 12 $MW_{th}$ (60odt/day) biomass input to the second phase NSE Biofuels plant |
| Efficiency (%) | |
| Reliability issues | No ash related problems, simple design and high reliability |
| **Development and commercial status** | |

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| Pilot scale plants | 500kW$_{th}$ (2.5odt/day) input PDU has been operational since 2006<br>A variety of synthesis gas conversion tests are being carried out to evaluate producing liquid biofuels, process optimization, and integration with pulp and paper and refinery industries | | |
| Commercial scale plants | | | |
| Future plans | The UCG project ran from 2004-2007, and set out its future vision for commercialization of the gasification technology in three phases. The input capacity of the first phase PDU is 500 kW$_{th}$.<br><br>The second phase plant was planned to be a 50 MW$_{th}$ input capacity for use in a lime kiln, estimated to be launched in 2008-2010, but is now known to be using a 12 MW$_{th}$ (60odt/day) CFB supplied by Foster Wheeler at the Varkaus mill, Finland. The full BTL chain is being developed by NSE Biofuels, a joint venture between Stora Enso and Neste Oil. The purpose of this phase involves verifying the risk-free operation of the process, viability, gain long-term experience with gas filtering, tar reforming, shifting, final gas cleaning and chemical synthesis. The gasifier is already operational, with additional slipstream and processing equipment under construction. After the 48 month demonstration using oxygen/steam to produce FT liquids is complete, the plant will be converted back to an atmospheric, air-blown CFB, using the syngas in the lime kilns<br><br>The third phase, from 2010 onwards, encompasses the construction of a 200-300MW$_{th}$ (1,522odt/day) demonstration plant which will be able to produce 105,000t/year of FT diesel, enough to cover about 3% of the Finnish transport biofuel demand once commissioned in 2013 | | |
| Time to commercialisation | First fully commercial scale FT plant should be available in by about 2015 | | |
| Target applications | Production of FT diesel for transport | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | 750°C | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | | Tars | |
| $CO_2$ (% by vol) | | Hydrocarbons (methane, $C_2H_4$, and higher) | |
| $H_2O$ (% by vol) | | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | | Others | |
| Syngas clean up | High temperature filtration, catalytic reforming and optimized gas conditioning processes | | |
| **Feedstock requirements** | | | |
| Main feedstocks | The main focus at the moment is on exploiting forest industry residues and by-products without risking the supply of raw-materials to the forest industry | | |
| Other potential feedstocks | Will be able to exploit any carbonaceous feedstock, including forest industry residues, bark, biomass from fields, refuse-derived fuels and peat | | |
| Ability to accept a mixture of feedstocks | Yes – fuel flexible | | |
| Ability to accept feedstocks varying over time | | | |
| Ability to accept wastes | Yes | | |
| Pre-treatment required | | | |
| Feedstock properties (energy content, moisture content, size etc) | | | |
| **Capital and operating costs** | | | |
| Costs | The PDU project overall budget amounts to EUR 4 million<br>The total cost of the development and demonstration phases will amount to approximately EUR 300 million. In the commercial plant, the estimated production costs of synthetic biodiesel will be 0.45-0.60€/litre<br><br>Plant Capacity: 300 MW$_{th}$ of feedstock (LHV basis)<br>Annual operating time: 8000 hrs<br>Interest on capital: 10 % for 20 years | | |

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| | O&M costs: 4 % of investment<br>Base values for purchased/sold energy (other values applied in sensitivity case studies):<br>Feedstock: € 10 /MWth (LHV)<br>Electricity: € 30/MWe<br>HP steam: € 16/MWth of transferred heat<br>MP and LP Steam: € 13/MWth of transferred heat<br>Fuel gas: € 14/MWth (LHV)<br>The estimated investment costs are:<br>Fischer-Tropsch (F-T) primary liquids; once-through synthesis: € 210 million<br>F-T primary liquids with reforming loop: € 230 million<br>Methanol: € 220 million<br>Synthetic (Substitute) Natural Gas (SNG): € 200 million<br>Hydrogen, either via traditional method or via PSA separation: € 195 million |

### 6.3.4 CUTEC Institute

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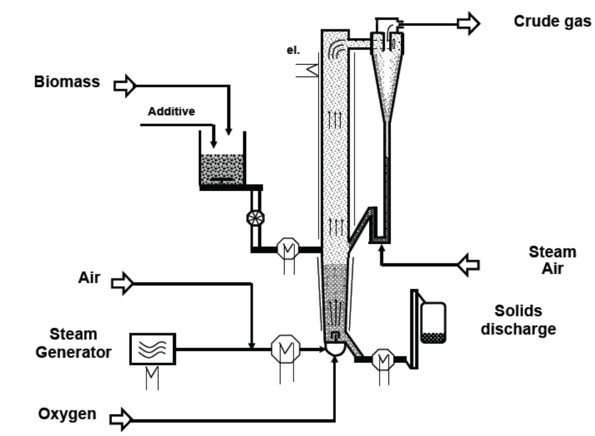
| **Basic information** | |
| Technology provider | Clausthaler Umwelttechnik-Institut GmbH |
| Location | Clausthal-Zellerfeld, Germany |
| Information sources | http://www.cutec.de/en/index.php |
| Background and links | Technology research center, links to either to the Technical University of Clausthal<br>Thermal processes department mission is to experimentally evaluate and optimise whole process chain, develop process model for upscaling, define biomass quality and gas cleaning for small BTL<br>CUTEC part of EU FP6 RENEW project |
| **Gasifier type** | |
| Technology type | Circulating Fluidised Bed |
| Technology name | CUTEC<br> |
| Technology Overview | Standard CFB |
| Method of heat provision to the gasifier | Directly |
| Oxidant | Steam/oxygen, or air |
| **Gasifier operating data** | |
| Temperature | 950°C |
| Pressure | Atmospheric |
| Scale and output | Total thermal input 400kW$_{th}$ (2.7odt/day) |
| Efficiency (%) | Cold gas efficiency 78%, carbon conversion rate of 94% |
| Reliability issues | |
| **Development and commercial status** | |
| Pilot scale plants | 400kWth Biomass gasification to FT pilot plant constructed, takes in 171.3kg/hr biomass (i.e. 4.1t/day or 2.7odt/day). 350hrs of gasifier and gas cleaning operation in 2008, with 100hours operation of full process chain for FT production |
| Commercial scale plants | |
| Future plans | Plan to upscale to demonstration level (4-10 MW$_{th}$ input, or 27-68odt/day) |
| Time to commercialisation | |
| Target applications | FT synthesis |

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| **Syngas characteristics and cleanup** | | | |
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 31.6% $H_2$, 22% CO, hence ratio 1.44 | Tars | 9.5g/Nm3 |
| $CO_2$ (% by vol) | 33.6% | Hydrocarbons (methane, $C_2H_4$, and higher) | 0.6% $C_2H_2$, 1.2% $C_2H_4$, 7.9% methane |
| $H_2O$ (% by vol) | | Particulates (ppm and size, e.g. Ash, soot) | Dust in crude gas 12g/Nm$^3$ |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, | 3% $N_2$ | Others | |

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| $NO_x$) | | | |
| Syngas clean up | Hot gas filtration, $H_2O$ scrubber, RME scrubber, activated carbon filters, compressor | | |
| **Feedstock requirements** | | | |
| Main feedstocks | Successfully tested sawdust, wood pellets, wood chips, and chipboard residues | | |
| Other potential feedstocks | Plan to test straw pellets, and sunflower seed residue. Will also look at energy crops | | |
| Ability to accept a mixture of feedstocks | | | |
| Ability to accept feedstocks varying over time | | | |
| Ability to accept wastes | | | |
| Pre-treatment required | | | |
| Feedstock properties (energy content, moisture content, size etc) | A variety of feedstock sizes can be handled | | |
| **Capital and operating costs** | | | |
| Costs | | | |

### 6.3.5 Fraunhofer Umsicht

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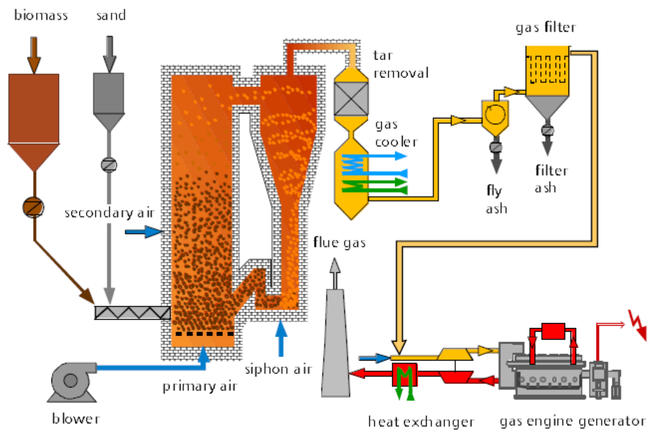
| **Basic information** | |
| Technology provider | Fraunhofer UMSICHT |
| Location | Oberhausen, Germany |
| Information sources | http://www.umsicht.fraunhofer.de/englisch/ |
| Background and links | Founded as a non-profit technical-scientific institution in June 1990, now 273 staff. Turnover of more than 17,9 million EUR in 2007, more than 50 % of this from industrial orders for its various other technologies |
| **Gasifier type** | |
| Technology type | Circulating Fluidised Bed |
| Technology name | Biomass Heat and Power Plant (BHPP)<br> |
| Technology Overview | CFB gasifier with catalytic gas treatment and block heat & power plant (BHPP) with IC engine |
| Method of heat provision to the gasifier | Direct |
| Oxidant | Air |
| **Gasifier operating data** | |
| Temperature | 915°C |
| Pressure | Atmospheric |
| Scale and output | 0.5 $MW_{th}$ fuel capacity input (2.4odt/day) |
| Efficiency (%) | 30-33% (or net 26-29%) electrical efficiency |
| Reliability issues | No indication for any problems arising at longer operational periods. Tar reduction was one of the key technical challenges during the project |
| **Development and commercial status** | |
| Pilot scale plants | The pilot plant was commissioned on the Institute's premises in Oberhausen in 1996. Process development and optimisation were undertaken on this plant, the size of which approximately corresponds to the smallest commercial installations, with a thermal capacity of approximately 0.5 MW (2.4odt/day biomass). The work was concluded successfully at the end of 2002. The pilot plant ran for about 1,600 hours in gasification mode with the BHPP in uninterrupted operation for about 340 hours. An almost tar-free gas was formed by combining the fluidised bed method, the selection of the fluidised bed material and the use of a new downstream catalytic cracking stage, in which tarry hydrocarbons were reformed by special honeycomb catalytic converters. |
| Commercial scale plants | As a first step towards commercial use, Fraunhofer Umsicht endeavoured to establish demonstration plant with a thermal output of 5 MW. The intended thermal capacity of a plant for typical commercial use was between 10 and 15 MW, corresponding to a requirement for (dry) wood fuel of 15,000 to 22,000 tonnes/year (46-61odt/day). 3 to 4.5 MW electricity can be generated from this input with simultaneous extraction of useful heat.<br>It has not yet been possible to identify a specific site with acceptable conditions for the plant - construction was planned to start at the end of 2002 (with further commercialisation beginning in 2004) – but did not go ahead |
| Future plans | Fraunhofer UMSICHT have been looking into syngas tar reforming:<br>Fraunhofer developed and demonstrated catalytic tar reforming up to application readiness in their own pilot plant for biomass gasification in the past (was capable of meeting 50mg/Nm3 requirement |

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| | continuously). Original catalytic reforming experiments were on a lab scale, and developed for autothermal gasification in air-blown CFB gasifiers. A 100scm/h slip stream reactor at the biomass CHP in Güssing, Austria using FICFB, was built in summer 2006, with commissioning finished in April 2007. The producer gas contaminated with tar is sucked off from the freeboard of the gasifier, fed into the catalytic reactor, and discharged back to the product gas line between the gasifier and gas cooler. Despite the low operating temperature of the reformer (840 instead of 910°C) tar conversion rates of more than 80% were found, whereas tar composition was hardly influenced. In operation continuously for 36 hours.<br><br>Brief mention back in 2003 of combining CFB technology with another Fraunhofer research area: MARS® – Modular Incineration Plant with Reduced Flue Gas Cleaning Residues, whereby the scientists around Ising were planning to develop a process for integrated energetic utilization of sewage sludge and used wood through pre-gasification of sewage sludge and feeding-in of fuel gas into a used wood power station | | |
| Time to commercialisation | | | |
| Target applications | Syngas can be burnt in a combustion chamber with a natural gas incinerator, or be fed into an IC engine | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 18% CO, 14% $H_2$, ratio 0.78 | Tars | engine specifies <50mg/$Nm^3$ after cleaning |
| $CO_2$ (% by vol) | 16% | Hydrocarbons (methane, $C_2H_4$, and higher) | 3% methane |
| $H_2O$ (% by vol) | 10% | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | 39% $N_2$ | Others | |
| Syngas clean up | Hot gas catalytic tar reforming, fabric filtering | | |
| **Feedstock requirements** | | | |
| Main feedstocks | Pilot: Non-contaminated forest wood chips | | |
| Other potential feedstocks | Demo would have taken unpolluted biomass such as wood chips, bark, coarse lumber shavings or sawdust | | |
| Ability to accept a mixture of feedstocks | | | |
| Ability to accept feedstocks varying over time | | | |
| Ability to accept wastes | No | | |
| Pre-treatment required | Belt drying | | |
| Feedstock properties (energy content, moisture content, size etc) | Input fuel modelled at 12% moisture | | |
| **Capital and operating costs** | | | |
| Costs | Investment costs of 3,900 EUR/kWe are anticipated for a demo plant, falling to 2,750 EUR/kWel in the future (public funding certainly needed) | | |

### 6.3.6 Uhde

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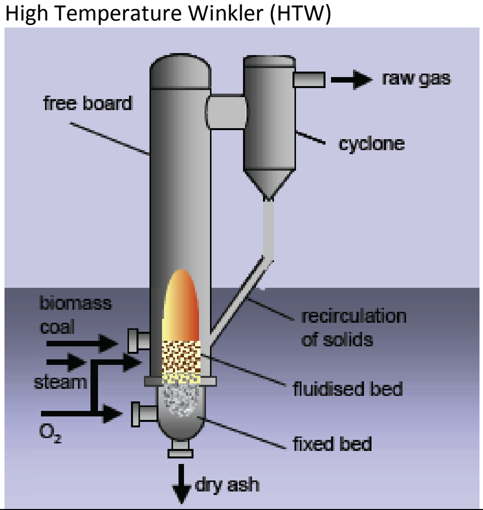
| **Basic information** | |
| Technology provider | Uhde |
| Location | Dortmund, Germany |
| Information sources | http://www.uhde.eu/competence/technologies/gas/index.en.html |
| Background and links | In the mid 1970's, Rheinbraun (now RWE) embarked on the development of the High-Temperature Winkler (FTW) coal gasification process – a further development of the atmospheric pressure Winkler fluidised bed. The first focus was on syngas production from lignite, but in the 1980's use for electricity production within an IGCC also became important<br><br>Uhde holds the exclusive license for the High-Temperature Winkler gasification technology, although the HTW is jointly marketed by RWE, Uhde and Envirotherm. The Uhde company markets the HTW process for gasification of wastes under the name of Uhde PreCon.<br><br>Latest biomass to liquids project being developed at the Institute for Energy Process Technology and Chemical Engineering (IEC) at the Technische Universitat Bergakademie Freiberg (TUB-F)<br>Financial support being provided by Agency Renewable Resources, RWE, Vattenfall, TOTAL, Uhde, Lurgi, DaimlerChrysler, VW |
| **Gasifier type** | |
| Technology type | Circulating Fluidised Bed |
| Technology name | High Temperature Winkler (HTW)<br> |
| Technology Overview | This new process for producing fuel using synthesis gas was developed by Prof. Bernd Meyer at the Institute for Energy Process Technology and Chemical Engineering IEC) at the TU Bergakademie Freiberg. It is based on fluidised bed gasification with subsequent fuel synthesis. A HTW CFB gasifier has been modified for biomass conversion by adding the bottom of a Sasol-British Gas Lurgi slagging, moving bed gasifier onto the HTW CFB. Ash is collected from the bottom, after the material falling from the fluidised bed is oxidised in an after-treatment in the fixed bed |
| Method of heat provision to the gasifier | Direct |
| Oxidant | Air or Oxygen, and steam |
| **Gasifier operating data** | |
| Temperature | 900-950°C |
| Pressure | 10 or 25 bar |
| Scale and output | 10 $MW_{th}$ input capacity, equivalent to 2t wood/hr (48t/day) |
| Efficiency (%) | Carbon conversion >98%, cold gas efficiency 81% |
| Reliability issues | Plants have demonstrated high availability >85% |
| **Development and commercial status** | |
| Pilot scale plants | Pilot plant investigations were carried out from 1974-1985 in Frechen, Germany, using 24t/day of lignite (22odt/day)<br>Rheinbraun then started the HTW oxygen/steam demonstration at Berrenrath, Cologne in 1986 to demonstrate industrial-scale maturity. The 10bar oxygen blown, 130 $MW_{th}$ capacity plant took in |

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| | 30t/hr of dry lignite (720t/day or 648odt/day), with the syngas produced being piped to a methanol synthesis plant at nearby Wesseling, producing 300t/day methanol. The plant underwent several measuring programmes and continuous optimising efforts. In order to demonstrate further application potential of HTW, plastics waste, MSW and sewage sludge were also tested in the plant, at up to 50% co-gasification. After 67,000 operating hours, the plant was shut down in 1997 after all testing complete, since economic operation was not viable.<br><br>A demonstration ammonia plant based on peat was built for Kemira Oy in Oulu, Finland in 1988. The existing oil-based ammonia plant was modified to use peat additionally in production. HTW Peat gasification was in production use with partial capacity for thousands of hours together with oil gasification. The 13bar plant was also tested with wood, lignite, hard coal and wastes, taking in 720t/day (576odt/day) producing 300t/day $NH_3$. The problems encountered were due to the heterogeneous quality of peat. Difficulties were also caused by the high naphthalene content of gas and by blockages in the cyclone-recycle pipe of the gasification. Technical solutions for these problems were available, which proves that the production of synthesis gas and ammonia from peat on a commercial scale is technically possible<br><br>1989-1992 also saw higher pressure investigations carried out at the Wesseling pilot plant. During the 10,000 operating hours, at pressures up to 25bar and feed of up to 7t/hour (168t/day or 151odt/day), both oxygen/steam and air blown operation modes were tested. The work culminated in the design of an IGCC based around an air-blown HTW gasifier and termed KoBRA (KOmbikraftwerk mit Integrietier BRAunkohlvergasung - combined cycle with lignite gasification). The initial KoBRA plant was due to be built at the Goldenberg power station near Cologne; however, economic considerations intervened and the project has now been dropped. High-efficiency conventional pulverised fuel boilers are now favoured for the next generation of lignite-fired plants<br><br>The emphasis then switched to wastes: The Krupp Uhde PreCon process applies the HTW with gasification of pre-treated solid wastes, e.g. MSW, sewage sludge, auto shredder residue (ASR) or residues from plastic recycling. In 1998, the PreCon process was licensed to Sumitomo Heavy Industries Ltd, who constructed a 1.5bar, 20t/day (15odt/day) MSW demonstration plant at Niihama, Japan. A 100t/day (75odt/day) commercial plant is planned |
| Commercial scale plants | Coal plant concepts: Uhde advertise a 30bar HTW gasifier for IGCC applications, either $600MW_e$ (gross) IGCC plants using oxygen/steam, or $400MW_e$ using air. Alternatively, 10bar HTW plants are available for producing 2,400t methanol/day from $260{,}000Nm^3$/hr of syngas.<br>$400MW_e$ HTW plant was built in Vresova, Czech Republic in 2002, using ~2,000odt/day of dried coal |
| Future plans | In the Technische Universitat Bergakademie Freiberg (TUB-F) BTL process, syngas generation will be demonstrated using a modified $10MW_{th}$ HTW gasifier combined with a Lurgi unit for gas cleaning and methanol synthesis. The gasification unit will be tested for different feedstocks, such as such as wood chips, wood pellets, straw pellets and lignite, taking up to 48odt/day. The main aims of the plant are to optimise the operation parameters, and test the gas cleaning unit for several raw gas qualities.<br>A feasibility study was conducted in 2004, basic engineering and cost determination end of 2006, and a decision of funding and start of realisation was scheduled to be at the start of 2007<br><br>However, both the gasification and the synthesis are still in the planning stages. At the moment, the operational plans are being drawn up as part of one of the FNR-sponsored projects (Agency of Renewable Resources, associated with the German Federal Ministry of Consumer Protection, Food and Agriculture)<br><br>The full BTL concept (for a $300MW_{th}$ or 1440odt/day biomass input plant) is envisioned to include:<br>Biomass collection: 500k odt/year of waste wood and straw<br>Biomass conditioning: 10 pelletising and chipping plants processing 50k odt/year each<br>Gasification: pressurized fluidised bed gasification, 2 units of $150MW_{th}$ each<br>Gas conditioning: CO shift, Rectisol, methanol synthesis<br>Methanol distillation, synthesis: olefins and middle distillates output of 160 $MW_{th}$, equivalent to 110 kt/year of diesel or gasoline, with transportation to a refinery site or customer location |
| Time to commercialisation | |
| Target applications | Gas generation for methanol production – using the MtSynfuel® process developed by Lurgi |
| **Syngas characteristics and cleanup** | |

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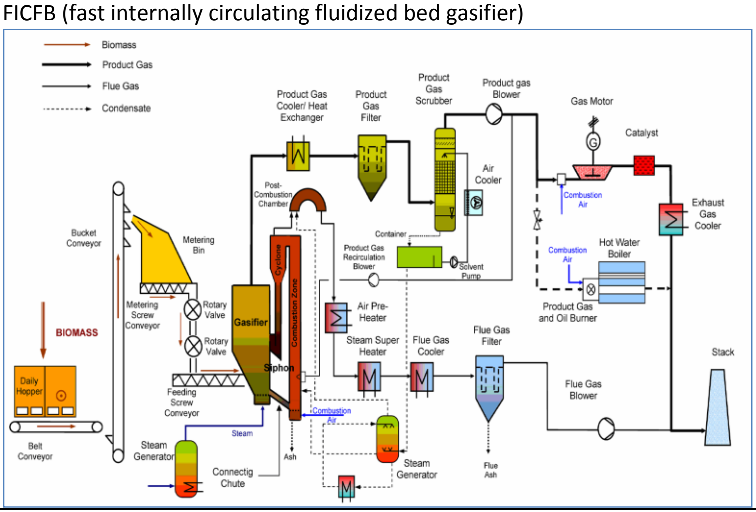
| Temperature | 900°C at gasifier exit | Halides (HCl, Br, F) | 0ppm HCl |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 30.1% $H_2$, 33.1% CO, hence ratio 0.91 | Tars | $C_6H_6$, 770ppm |
| $CO_2$ (% by vol) | 30.6% | Hydrocarbons (methane, $C_2H_4$, and higher) | 5.7% methane |
| $H_2O$ (% by vol) | Dry volumes | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | 0.03% $H_2S$ | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | 0.4% $N_2$, 90ppm $NH_3$ | Others | |
| Syngas clean up | Warm gas filter operating at about 285°C | | |
| **Feedstock requirements** | | | |
| Main feedstocks | Past HTW plants have used lignite, or peat for main production, although wood has been tested in Oulu | | |
| Other potential feedstocks | TUB-F plan to use wood chips, straw pellets, and lignite for future plants | | |
| Ability to accept a mixture of feedstocks | Yes | | |
| Ability to accept feedstocks varying over time | | | |
| Ability to accept wastes | Yes | | |
| Pre-treatment required | Drying and sizing before fed to lock hopper system | | |
| Feedstock properties (energy content, moisture content, size etc) | Lignite is used in the form of grains, whereas MSW was standard dried pellets sized 15-20mm | | |
| **Capital and operating costs** | | | |
| Costs | The cost of the Oulu 576odt/day peat project amounted to FIM 230 million | | |

## 6.4 Dual fluidised bed gasifiers

### 6.4.1 REPOTEC/TUV

| **Basic information** | |
|---|---|
| Technology provider | Renewable Power Technologies Umwelttechnik GmbH (REPOTEC)<br>Vienna University of Technology (TUV) |
| Location | Güssing, Austria<br>Vienna, Austria |
| Information sources | http://www.repotec.at/en/index.php<br>http://www.vt.tuwien.ac.at/ |
| Background and links | REPOTEC founded in 1991. RENET Austria collaboration with Biomassekraftwerk Güssing GmbH, AE-Energietechnik, Jenbacher AG, Gussinger Fernwarme GmbH, Vienna University of Technology (TUV) |
| **Gasifier type** | |
| Technology type | Dual Fluidised Bed |
| Technology name | FICFB (fast internally circulating fluidized bed gasifier)<br><br> |
| Technology Overview | Technology originally developed by TUV, partnership with REPOTEC<br>Comprises two separate chambers: steam and biomass enters the BFB gasification chamber, and the resulting charcoal and sand mix is fed into a CFB combustion chamber, with the heated sand being fed back into the gasification chamber. A nitrogen free syngas leaves the gasifier chamber |
| Method of heat provision to the gasifier | Indirect |
| Oxidant | Steam gasification, air for combustion |
| **Gasifier operating data** | |
| Temperature | Gasification 900°C, combustion 1000°C |
| Pressure | Atmospheric |
| Scale and output | Rated at 2MWe, 4.5MWth output, with 8MW fuel input, taking in 1.76t/hr biomass<br>Now up to 2.3t/hr (i.e. 40odt/day) |
| Efficiency (%) | 25% electrical efficiency + 56.3% thermal efficiency = 81.3% total |
| Reliability issues | Availability has greatly improved, in the past there were some syngas cooler fouling and corrosion, and scrubber ammonia and condensate issues |
| **Development and commercial status** | |
| Pilot scale plants | Previous 100kW (0.5odt/day) pilot started in 1997, and 10kW (0.05odt/day) testrig in 1993 |
| Commercial scale plants | 8MWth input plant (40odt/day) with outputs of 2MWe, 4.5MWth, operating at Güssing, Austria. Startup was Nov 2001, commissioning in 2002. A very impressive 32,500 hours of operation by April 2008.<br><br>The biomass gasification CHP plant at Oberwart, Austria is a 2.7MWe, 1.5-6 MWth output plant, was built for Energie Oberwart. The plant is similar in design to the Güssing plant, taking in 53odt/day of wood. However, in 2004 when REPOTEC and the utility BEGAS were negotiating the hours guaranteed in the contract, BEGAS ended up giving the contract to Ortner (a combustion installer), |

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| | but without requesting a co-operation with REPOTEC. Ortner went on to build the plant, with heavy cooperation from TUV. Construction finished in 2007, commissioning was ongoing in Nov 2008. The plant uses gas cooling and gas clean-up in a bag filter followed by a tar scrubber. The cooled and cleaned producer gas is fed into two gas engines for power generation. In addition there is a biomass drying unit and an organic rankine cycle (ORC) integrated, to increase electric efficiency by recovering waste heat. | | |
| Future plans | The Güssing gasifier already supplies whole town – have also been carrying out testing for syngas uses: FT, methanation, SOFC – along with further R&D for optimisation, and tar cleanup<br><br>Carried at feasibility study on 100MW (495odt/day) plant in Gothenburg with Conzepte Technik Umwelt (CTU) under management from M+W Zander FE GmbH | | |
| Time to commercialisation | Currently only economic with Feed In Tariff, national and EU grants | | |
| Target applications | Local town CHP (FT is only being currently tested on a bypass flow of $10Nm^3/hr$) | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | Gasifier 900°C, after filter 150°C, after scrubber 40°C | Halides (HCl, Br, F) | 3ppm |
| Pressure | Atmospheric | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 38-45% $H_2$, 22-25% CO, ratio approx 1.6-1.8 | Tars | Dry gas output 2.3g/Nm3, after filter and scrubber 0.02-0.03g/Nm3 |
| $CO_2$ (% by vol) | 20-23% | Hydrocarbons (methane, $C_2H_4$, and higher) | Methane 9-12%, $C_2H_4$ 2-3%, $C_2H_6$ 0.5%, $C_2H_2$ 0.4%, $C_6H_6$ 8g/m$^3$, $C_7H_8$ 0.5g/m$^3$, $C_{10}H_8$ 2g/m$^3$ |
| $H_2O$ (% by vol) | none | Particulates (ppm and size, e.g. Ash, soot) | 5-10g/Nm$^3$, after cleaning <0.005g/Nm$^3$. Ash only from combustion |
| Sulphur (COS, $H_2S$, $CS_2$) | $H_2S$ 40-70ppm, other organic S 30ppm | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | 2-3% vol $N_2$, raw syngas has 1000-2000ppm $NH_3$, after cleaning <400 | Others | |
| Syngas clean up | Cooler, filter, scrubber | | |
| **Feedstock requirements** | | | |
| Main feedstocks | Wood chips. 60% from local farmers (costing 0.016 EUR/kWh), 40% wood working residues (costing 0.007 EUR/kWh). 10yr contracts | | |
| Other potential feedstocks | | | |
| Ability to accept a mixture of feedstocks | No | | |
| Ability to accept feedstocks varying over time | Remain fixed | | |
| Ability to accept wastes | No | | |
| Pre-treatment required | None: stored in hopper, screws take metered amount up into gasifier | | |
| Feedstock properties (energy content, moisture content, size etc) | Moisture content must be less than approx 20% | | |
| **Capital and operating costs** | | | |
| Costs | Total investment EUR 10m (EU and national grants 6m). Construction time 14-18 months. Operating costs are 10 to 15%/yr of investment costs<br><br>Expected product price for grid heat EUR 0.02/kWh$_{th}$, consumer heat EUR 0.039/kWh$_{th}$, electricity EUR 0.16/kWh$_e$ | | |

### 6.4.2 SilvaGas

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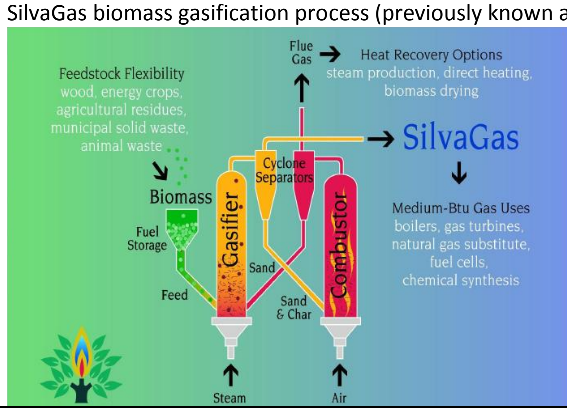
| **Basic information** | |
| Technology provider | SilvaGas Corporation (previously FERCO) |
| Location | Atlanta, Georgia, USA |
| Information sources | http://www.silvagas.com<br>http://www.biggreenenergy.com |
| Background and links | Patent process developed at Battelle's Columbus Laboratories (BCL). FERCO Enterprises bought the rights in 1992. Partners in the McNeil site were Burlington Electric, Battelle, US DOE, and NREL. SilvaGas license now held by Biomass Gas & Electric, who were set up in 2001 to commercialise the SilvaGas technology |
| **Gasifier type** | |
| Technology type | Dual Fluidised Bed |
| Technology name | SilvaGas biomass gasification process (previously known as the Batelle process)<br><br> |
| Technology Overview | Biomass fed into hopper, with nitrogen used to purge any remaining air<br>CFB gasification chamber uses steam, and cyclone separates syngas from sand and char<br>Air burning of this char in a CFB combustion chamber heats the suspended sand, which is fed back into the gasifier |
| Method of heat provision to the gasifier | Indirect, hot sand from char combustion chamber |
| Oxidant | Gasification steam (combustion air) |
| **Gasifier operating data** | |
| Temperature | 800-850°C (although heat loss from Vermont robust linings meant nearer 700°C was usual) |
| Pressure | Atmospheric |
| Scale and output | Original design was for 200odt/day (40MWth biomass input), but McNeil site eventually used over 350odt/day (500t/day as received) of wood with no syngas changes or efficiency reduction |
| Efficiency (%) | 35-40% combined cycle electrical efficiency |
| Reliability issues | Numerous design and operational changes to the plant were necessary to improve the performance of process auxiliary systems at startup, but core process OK. Testing campaigns smooth and reliable |
| **Development and commercial status** | |
| Pilot scale plants | 10-12odt/day pilot plant was operated for more than 20,000hrs from 1980 in West Jefferson, Ohio at Battlelle Columbus |
| Commercial scale plants | Commercial scale demonstration plant (350odt/day) operated in Burlington, Vermont, at the McNeil wood burning station. Constructed in 1997, first full steam operation Aug 1999. Continuous syngas output was successfully tested for gas co-firing in the solid woodfuel boiler.<br>Decommissioned in 2002 after end of US DOE program, because was uneconomic – the electricity price from the inefficient steam turbine was above that of natural gas generation on the grid. Federal funding in support of full IGCC implementation (installing a more efficient syngas gas turbine) did not occur. FERCO failed to raise further capital with disputes between investors, and went bankrupt in 2002. |
| Future plans | Winkleigh, Devon, UK: 300odt/day EC & wood res, Siemens Cyclone 23MWe turbine, partnered with Peninsula Power - failed planning in 2004 |

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| | Forsyth County, Georgia: 30 MWe plant (540odt/day wood wastes) developed by Biomass Gas&Electric is thought to be still be in planning – status unclear, as construction was due to be complete in 2009, but delays were experienced with the environmental permits<br><br>Tallahassee, FL: 42 $MW_e$ plant (730odt/day, or 1043t/day) was planned to also provide 60 million Btu's of synthetic gas to a natural gas distribution system by 2011. However, BG&E withdrew their permit application in Feb 2009, and are no longer pursuing the project – there was strong local NIMBY opposition<br><br>BG&E has also signed a contract with Progress Energy of Florida, to build two 75MWe (~940odt/day) biomass electric power plants.<br><br>An announcement made by Rentech in May 2009 is their intention to build a large BTL plant in Rialto, California. This will be using a SilvasGas gasifier to convert urban waste wood into 600barrels of FT liquids/day, and export 35MWe of power, with operation starting in 2012 [102]. A biomass input scale is not given, but for the outputs given should be approximately 800odt/day. | | |
| Time to commercialisation | | | |
| Target applications | Integrated heat and power production (IGCC), future developments would have distributed syngas as well, but now FT synthesis looks the most likely application | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | Atmospheric | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 22% $H_2$, 44.4% CO, hence ratio 0.49 | Tars | |
| $CO_2$ (% by vol) | 12.2% | Hydrocarbons (methane, $C_2H_4$, and higher) | Methane 15.6%, ethylene 5.1%, ethane 0.7% |
| $H_2O$ (% by vol) | | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | | Others | |
| Syngas clean up | A novel hot-gas conditioning catalyst (DN34) has been developed that converts about 90% of condensable tars to lower molecular weight, and therefore, essentially non-condensable forms | | |
| **Feedstocks** | | | |
| Main feedstocks | Have tested woody biomass, herbaceous crops, hybrid willow, reconstituted wood pellets, and whole-tree chips (i.e. mainly clean woodchips) | | |
| Other potential feedstocks | Traditional biomass (Wood, Wood residues, Straw, Switch grass), MSW, Energy Crops, Agricultural residues, Poultry litter, Residue fuels (Urban waste wood, Paper mill residues/sludges) | | |
| Ability to accept a mixture of feedstocks | Yes | | |
| Ability to accept feedstocks varying over time | Yes | | |
| Ability to accept wastes | Yes, only if sorted | | |
| Pre-treatment required | No extensive preparation required (only drying, and removal of air) | | |
| Feedstock properties (energy content, moisture content, size etc) | Able to accept 10-50% feedstock moisture content – average moisture content of received material is 30%, and anything less than 3" in size | | |
| **Capital and operating costs** | | | |
| Costs | \$14m capital cost for Burlington McNeil plant<br>\$12m for 400odt/day brownfield existing site (\$530/kW for gasifier island, or \$1500/kW IGCC)<br>For a 740-900odt/day site, capital costs of \$18-26m<br><br>Electricity price: between \$0.04-0.05/kWh in theory (still more expensive than gas generation back in | | |

[102] Rentech, In F2Q09 Earnings Call Transcript (2009) Available online: http://seekingalpha.com/article/137259-rentech-inc-f2q09-qtr-end-03-31-09-earnings-call-transcript?page=-1

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| | 2002), however, reality was \$0.08/kWh<br>12% ROI can be realised with syngas Btu selling price of \$3/MM Btu without any tax credits/support schemes<br><br>Estimated cost of Forsyth County, Georgia plant is \$40m (400odt/day wood wastes)<br>Estimated cost of Tallahassee, FL plant was \$85m (750odt/day MSW) |

### 6.4.3 Taylor Biomass Energy

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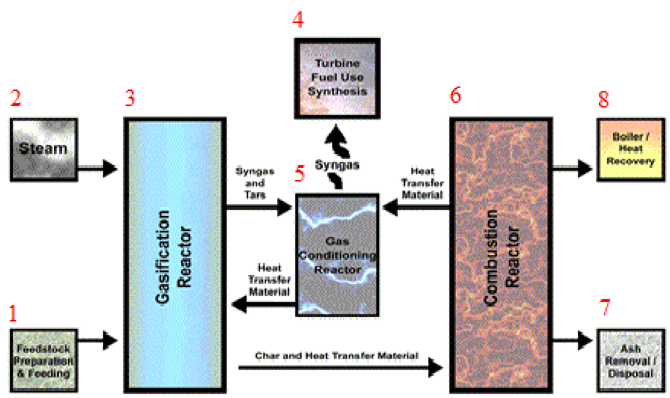
| **Basic information** | |
| Technology provider | Taylor Biomass Energy LLC |
| Location | Montgomery, New York |
| Information sources | http://www.taylorbiomassenergy.com |
| Background and links | Taylor originally a recycling company for construction and demolition wastes<br>Mark Paisley joined Taylor Biomass after the SilvaGas Burlington site closure, which led to a trade secrets dispute in 2007, since Taylor Biomass Energy now have an identical FICFB design to SilvaGas, at even the same plant size. *Data below which applies to SilvaGas is in italics*<br><br>The program partners in the NY plant are Taylor Biomass Energy, LLC (Taylor Sorting and Separating Process (recycling process) and Taylor Gasification Process), Abengoa Bioenergy (ethanol production), Süd Chemie (commercial catalyst preparation), O' Neal, Inc., (detailed engineering), and Sanders Brothers (modular construction). |
| **Gasifier type** | |
| Technology type | Dual Fluidised Bed |
| Technology name | Taylor Gasification process<br> |
| Technology Overview | *Biomass fed into hopper, with nitrogen used to purge any remaining air*<br>*CFB gasification chamber uses steam, and cyclone separates syngas from sand and char*<br>*Air burning of this char in a CFB combustion chamber heats the suspended sand, which is fed back into the gasifier* |
| Method of heat provision to the gasifier | *Indirect, hot sand from char combustion chamber* |
| Oxidant | *Gasification steam (combustion air)* |
| **Gasifier operating data** | |
| Temperature | *800-850°C (although heat loss from Vermont robust linings meant nearer 700°C was usual)* |
| Pressure | *Atmospheric* |
| Scale and output | *Original design was for 200odt/day (40MWth biomass input), but McNeil site eventually used over 350odt/day (500t/day as received) with no syngas changes or efficiency reduction*<br>Taylor Biomass plant will also use 300-400odt/day |
| Efficiency (%) | *35-40% combined cycle electrical efficiency* |
| Reliability issues | *Numerous design and operational changes to the plant were necessary to improve the performance of process auxiliary systems at startup, but core process OK.*<br>In September 2007, whilst processing some wastes, fireworks didn't get culled out of the waste stream and exploded in the grinder. Pyrotechnic debris injured two of Taylor's employees and caused significant damage to the equipment |
| **Development and commercial status** | |
| Pilot scale plants | *SilvaGas 10ton/day pilot plant has been operated for more than 20,000hrs since 1980.* |
| Commercial scale plants | *SilvaGas successful commercial scale demonstration plant operated in Burlington, Vermont, at the McNeil wood burning site. Constructed in 1997, first full steam operation Aug 1999. Decommissioned in 2002 after end of DOE program (became uneconomic)* |
| Future plans | Taylor Biomass Energy is receiving funding and support from NY State Energy RDA; plans are to build |

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| | a 370odt/day waste gasification to power facility in Montgomery, NY in 2009/2010. Mention of future biorefinery possibility, although project still in planning<br><br>TBE will also be providing the gasifier in a 11.5Mt/yr ethanol plant project in Colwich, Kansas, proposed by Abengoa Bioenergy in 2007 (with DOE funding). Biomass input is expected to be 700odt/day, and Abengoa will use the syngas for steam generation, to provide heat requirements for the entire biomass plant, including the biomass enzymatic hydrolysis to ethanol part, and for an adjacent starch to ethanol plant. Abengoa's longer term goal is to use syngas for catalytic synthesis of ethanol[103] | | |
| Time to commercialisation | | | |
| Target applications | Integrated heat and power production (IGCC), future developments may produce ethanol | | |
| **Syngas characteristics and cleanup (SilvaGas)** | | | |
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | *Atmospheric* | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | *22% $H_2$, 44.4% CO, hence ratio 0.49* | Tars | |
| $CO_2$ (% by vol) | *12.2%* | Hydrocarbons (methane, $C_2H_4$, and higher) | *Methane 15.6%, ethylene 5.1%, ethane 0.7%* |
| $H_2O$ (% by vol) | | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | | Others | |
| Syngas clean up | *A novel hot-gas conditioning catalyst (DN34) has been developed that converts about 90% of condensable tars to lower molecular weight, and therefore, essentially non-condensable forms* | | |
| **Feedstocks** | | | |
| Main feedstocks | *SilvaGas have tested woody biomass, herbaceous crops, hybrid willow, reconstituted wood pellets, and whole-tree chips (i.e. mainly clean woodchips)* | | |
| Other potential feedstocks | Taylor Biomass Energy will be using biodegradable wastes (from MSW, C&I and C&D), and waste wood | | |
| Ability to accept a mixture of feedstocks | *Yes* | | |
| Ability to accept feedstocks varying over time | *Yes (heating value remains the same)* | | |
| Ability to accept wastes | Yes | | |
| Pre-treatment required | *No extensive preparation required (only drying, and removal of air)* | | |
| Feedstock properties (energy content, moisture content, size etc) | *Able to accept 10-50% feedstock moisture content, and anything less than 3" in size* | | |
| **Capital and operating costs** | | | |
| Costs | Abengoa and its partners (including Taylor Biomass Energy) will be recieving up to $76m for their Kansas cellulosic ethanol plant as part of US DOE funding program over 4 years<br><br>*SilvaGas data:*<br>*$12m for 400odt/day brownfield existing site ($530/kW for gasifier island, or $1500/kW IGCC)*<br>*For a 740-900odt/day site, capital costs of $18-26m*<br>*Electricity price: less than $0.05/kWh in theory, however, reality was $0.08/kWh*<br>*12% ROI can be realised with syngas Btu selling price of $3/MM Btu without any tax credits/support schemes*<br>*Estimated cost of Forsyth County, Georgia plant is $40m (400odt/day wood wastes)*<br>*Estimated cost of Tallahassee, FL plant is $85m (750odt/day MSW)* | | |

[103] Bryan Sims (2008) "Taylor Biomass Energy to install Abengoa's biogasification unit" Available online: http://www.biomassmagazine.com/article.jsp?article_id=1426

### 6.4.4 ECN

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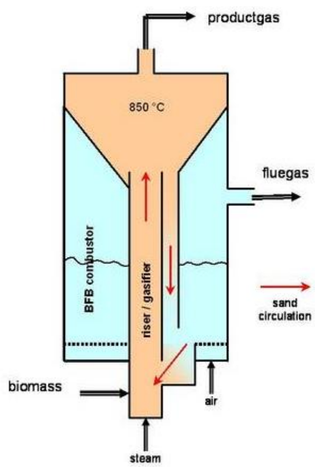
| **Basic information** | |
| Technology provider | Netherlands Energy Research Foundation (ECN) |
| Location | Petten, Netherlands |
| Information sources | http://www.milenatechnology.com |
| Background and links | Development of the MILENA gasifier started close to the finishing date of the BIVKIN gasifier (air blown CFB attached to 500kWe ICE), with the goal of realising an installation which could be used to do experiments under realistic 'commercial' conditions<br>Partners with HVC (owner of demo plants and first commercial plants), Dahlman (supplier of OLGA tar removal) and EPC (supplier of "further gas cleaning" and methanation, contractor) |
| **Gasifier type** | |
| Technology type | Dual Fluidised Bed |
| Technology name | MILENA<br><br> |
| Technology Overview | Dual-bed gasifier with a CFB gasifier and BFB combustor. Biomass is heated and gasified in a rising, circulating flow of hot sand and the less reactive char is directed to the combustor when the circulating sand is heated. This is an indirectly heated (allothermal) air-blown gasification concept, designed to produce a $N_2$ free syngas with high amounts of hydrocarbons. MILENA is simpler than SilvaGas or REPOTEC/TUV designs, more compact and better suited for elevated pressures |
| Method of heat provision to the gasifier | Indirect |
| Oxidant | Gasification steam (Combustion air) |
| **Gasifier operating data** | |
| Temperature | Gasifier 850°C, combustor 925°C |
| Pressure | Unknown, presumed atmospheric |
| Scale and output | Pilot 3.8odt/day biomass (800$kW_{th}$ input) |
| Efficiency (%) | Cold gas efficiencies of 80% possible for large-scale systems |
| Reliability issues | Some construction delays, and some minor adjustments to the installation (flue gas cooler) and start up procedure are required. |
| **Development and commercial status** | |
| Pilot scale plants | The first design of the MILENA gasifier was made in 1999.<br>Lab scale 25kW (5 kg/h, i.e. 0.12odt/day) built in 2004, has undergone several duration tests and fully automated operation with gas cleaning and methanation<br><br>Pilot plant 800kW (taking in 160kg/h, i.e. 3.8odt/day biomass) started operation on 4th September 2008, currently in the process of initial testing |
| Commercial scale plants | |
| Future plans | ECN plans to license the MILENA gasification technology after the successful operation of the 800 kW pilot – with the next step as a demo plant of 10 MW (48odt/day). This demo facility will not be constructed on ECN ground, because the site in Petten is not suitable for this kind of size plants, and will start with gas production for a boiler (for validation). In the next phase the 10 MW MILENA will be coupled to OLGA for removal of tars and the gas used in a gas engine. The last phase will be a |

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| | complete gas cleaning section with gas upgrading, resulting in SNG at gas grid specifications.<br>ECN plan to have 100MW (480odt/day) plant operational by 2014, and 1GW (4,800odt/day) by 2018<br><br>The scale foreseen for a commercial single-train Bio-SNG production facility is between 50 and 500 $MW_{th}$ (240 and 2,400odt/day biomass input) | | |
| Time to commercialisation | | | |
| Target applications | Production of bio-SNG is ultimate target, or intermediate generation of power with gas engines or turbines. These applications fit the syngas because of its high HV (high % of methane produced directly, and high %s of hydrocarbons), and the complete biomass gasifier conversion | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 18% $H_2$, 44% CO, hence ratio 0.41 | Tars | 40g/$Nm^3$ |
| $CO_2$ (% by vol) | 11% | Hydrocarbons (methane, $C_2H_4$, and higher) | methane 15%, $C_2H_6$ 1%, higher HCs 5% |
| $H_2O$ (% by vol) | 25% on wet basis | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | $H_2S$ 40-100ppmv | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | $N_2$ 4%, $NH_4$ 500-1000ppmv | Others | |
| Syngas clean up | Tar removal using a special scrubber technique called OLGA (OiL based GAs washer) developed by ECN, further gas cleaning ($CO_2$ removal unit and gas compressor), and methanation | | |
| **Feedstocks** | | | |
| Main feedstocks | Testing of dry beech wood, grass and sewage sludge in the 25kW testrig<br>Newly constructed pilot feed system works well with wood pellets | | |
| Other potential feedstocks | | | |
| Ability to accept a mixture of feedstocks | Yes | | |
| Ability to accept feedstocks varying over time | | | |
| Ability to accept wastes | Yes | | |
| Pre-treatment required | $CO_2$ used to purge the feeding system of air | | |
| Feedstock properties (energy content, moisture content, size etc) | Able to cope with 10-25% moisture content (25% likely for commercial applications)<br>Increase in allowable fuel particle size from 1 – 3mm for the lab scale installation to <15mm for the pilot plant | | |
| **Capital and operating costs** | | | |
| Costs | | | |

## 6.5 Plasma gasifiers

### 6.5.1 Westinghouse Plasma

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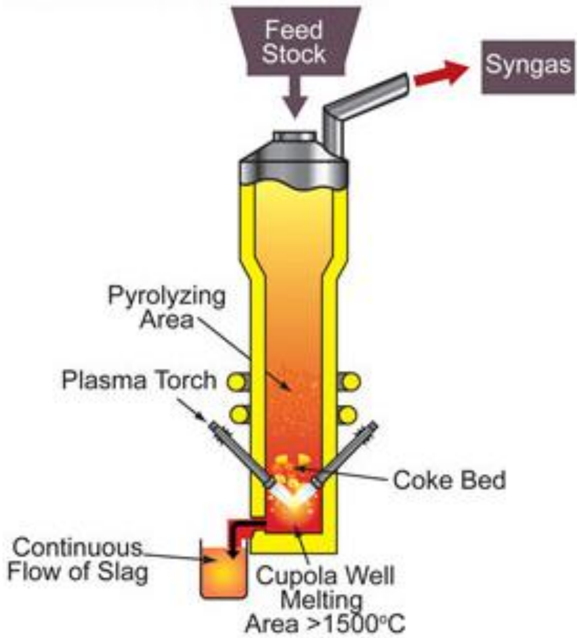
| **Basic information** | |
| Technology provider | Westinghouse Plasma Corp, a division of Alter NRG |
| Location | Madison, Pennsylvania |
| Information sources | http://www.westinghouse-plasma.com/<br>http://alternrg.ca/gasification/commercial.html |
| Background and links | WPC technology was initially developed in collaboration with NASA for use in the Apollo space program for high temperature re-entry testing. R&D from 1970-1990. In 2003, WPC formed as a subsidiary of engineering and construction firm, Alter NRG |
| **Gasifier type** | |
| Technology type | Plasma |
| Technology name | Plasma Gasification Vitrification Reactor (PGVR)<br> |
| Technology Overview | WPC's Plasma Gasification Vitrification Reactor (PGVR) is a combination of moving bed gasifier with WPC plasma torches. Westinghouse Plasma torches located in the bottom of the gasifier, firing into a bed of carbon to melt inorganics in the MSW, forming glass aggregate and metal nodules that emerge from the bottom of the unit. Westinghouse Plasma has designed a donut-shaped chamber in the upper half of the gasifier, above the moving bed, where tars and other hard-to-gasify molecules reside for 0.5 to 1 minutes and are cracked. Any material may be gasified – simply placed without preparation into the top of the gasifier |
| Method of heat provision to the gasifier | Electrically generated plasma from the torches, and direct |
| Oxidant | Air, and the plasma torches can run on air, oxygen, nitrogen, noble gases |
| **Gasifier operating data** | |
| Temperature | 1,500-5,500˚C |
| Pressure | Atmospheric |
| Scale and output | |
| Efficiency (%) | 100% carbon conversion |
| Reliability issues | No moving parts, high reliability. Hitachi have been pleased with the gasifier availability, although some problems with the downstream equipment |
| **Development and commercial status** | |
| Pilot scale plants | WPC Pilot Facility: testing, modifying and/or validating modelling assumptions using their pilot plant located at the Westinghouse Plasma Centre (Waltz Mill site) in Madison County, PA. To date, over 100 pilot tests have been completed on a wide range of feedstocks |

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| | In 1999, WPC built a Waste Treatment & Energy Processing Demo Facility at Hitachi Metals, Ltd in Yoshii, Japan, taking in 24t/day of unprocessed MSW (18odt/day assuming average MSW moisture content of 25%) |
| Commercial scale plants | Japan's Hitachi Metals, Ltd. uses WPC technology in two Japanese facilities to produce steam and electricity - both built in 2002:<br>• Utashinai plant, with two parallel gasifier chains, can process 200-280 t/day of MSW (up to 210odt/day) or a combination of MSW and auto shredder residue (ASR) at a rate of 165-190 t/day. The Utashinai facility uses 4MW internally and provides 3.9 MW of net electricity output to the grid. Maximizing power output isn't the primary objective of the Utashinai facility, and if the plant was optimized, it could produce close to 7.0 MW of net electricity. If the facility was configured in combined cycle mode, it could produce as much as 12.0 MW net. However, the plant has struggled to make ends meet, due to the lack of available MSW. On average, the plant only processes 60% of the expected trash volume, and has also suffered operational problems (though not with the plasma torch itself), with one of the two lines often down for maintenance<br>• The Mihama-Mikata facility processes 22 t/day of waste (16.5odt/day), including 4.8 t (3.6odt/day) partially dewatered sewage sludge delivered from the local wastewater treatment plant. Since sewage sludge has less organic material than MSW, the sewage sludge is mixed with the MSW to maintain sufficient energy density in the feed material for stable and consistent thermal energy production |
| Future plans | WPC have several projects either under construction or planned:<br>• SMS Infrastructure, Ltd is constructing two 72 t/day (54odt/day) hazardous waste disposal plants (both 5MW), in Nagpur, India. Were due to be completed by the end of 2008<br>• Kiplasma Industries and Trade Inc. of Istanbul, Turkey has ordered four plasma torch systems and reactors. These will be used to process 144 tons/day (108odt/day) of common hazardous waste materials for the production of electricity. WPC is expecting to ship the plasma torch systems for this order in the second half of 2008 and the facility is expected to begin commercial operation in the fourth quarter of 2009<br>• Geoplasma's St Lucie WTE project: on a landfill site, would have processed 3000t/day (2,250odt/day) MSW and waste water treatment sludge in six 500t/day gasifier modules, producing 120MWe (1st phase half capacity). Steam from St. Lucie plant to be sold to Tropicana Products for conversion to electricity in Tropicana's existing steam turbines. This plant was due to be constructed in 2010 at a total cost of $450million, however, October 2008 announcement that the plant is now likely to only be a lower risk 200 (or possibly 600) t/day demo (likely 150odt/day) to provide comfort with the technology before scaling up. It proved to be no longer economically viable to "mine the landfill", with a lack of project finance and difficulties in selling the produced energy, hence the currently preferred plant design is only to take incoming wastes<br>• Geoplasma, with Georgia Tech Research Institute, also have plans to build a 300t/day (225odt/day) plant on Hawaii, and secured $100million in special purpose revenue bonds from the state in June 2008. Once built, the plant should produce 10.6 MWe of which 4.1 MWe will be consumed by plasma torches and other parasitic loads, with 6.5 MWe to be sold to the Hawaiian Electric Company. Previous plans had failed due to no guarantee for a steady trash supply, and the preferred expansion of existing incineration plants<br>• In 2007, Green Power Systems obtained agreements to acquire waste from the City of Tallahassee, and for the City to purchase the produced electricity. The proposed Leon County facility is being designed for 1000 t/day (750odt/day) using a Westinghouse PVR, with an expected electrical output of 40 MWe. Completion was scheduled for October 2010, with project funding from a Brazilian investment group, Controlsud International for an estimated cost of $182 million. However, Controlsud walked away from the deal in Feb 2009 after Green Power had paid them $140,000 for a risk assessment. Green Power are still searching for funds<br>• Sun Energy, New Orleans 2500t/day (1,875odt/day) garbage to electricity, close to end of planning application, project not finalised yet<br>• US Science & Technology's 300t/day (225t/day) Sacramento project was rejected by the local council in late 2008, and has been delayed indefinitely<br>• Koochiching Development Authority (KDA) – Coronal WTE Project, International Falls, Minnesota. 100 t/day of MSW (75odt/day), making syngas for a neighboring paper mill, reducing the mill's usage of natural gas<br>• Other upgrading in coal to liquids plants<br>• Waste2Tricity hold exclusive UK license, looking to develop 136t/day MSW sites (114odt/day) |

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| | • Coskata, in partnership with General Motors, is building its 40,000gallons/year ethanol pilot plant in Madison, Pennsylvania, next to the Westinghouse Plasma Centre - using a Westinghouse Plasma gasifier to produce its syngas for fermentation. Pilot plant will use Marc-3 plasma torches, whilst commercial scale plants will use larger Marc-11 torches. Coskata claim they can get 100gallons of ethanol from 1 odt of organic feedstock, and will be using wood, agricultural residues (e.g. sugarcane bagasse) and MSW. Pilot operational in Q1 2009 will take in 1.2odt/day, with two commercial plants planned for 2011, producing 50 or 100Mgallons of ethanol/year from 1,600 or 3,200t/day of feedstock – although 1,500odt/day has been quoted as the most likely size | | |
| Time to commercialisation | Commercial applications of WPC's plasma gasification have been in operation since 2002 | | |
| Target applications | Heat and power generation | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 40.37% CO, 15.88% $H_2$, hence ratio 0.39 | Tars | |
| $CO_2$ (% by vol) | 3.55% | Hydrocarbons (methane, $C_2H_4$, and higher) | |
| $H_2O$ (% by vol) | 37.33% | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | $N_2$ free | Others | |
| Syngas clean up | Particulate removal and water quenching | | |
| **Feedstock requirements** | | | |
| Main feedstocks | WPC gasification has almost exclusively focused on waste feedstocks, as these provide a gate fee, with existing plants gasifying MSW, auto-shredder residue and hazardous wastes. | | |
| Other potential feedstocks | However, plasma gasifiers can accept almost any material – testing has been conducted on sewage sludge, oil, coal/water slurry, emulsions, run-of-mine coal and parting refuse, MSW, coal and petroleum coke, biomass, paper, plastics and metals unsuitable for recycling | | |
| Ability to accept a mixture of feedstocks | Yes | | |
| Ability to accept feedstocks varying over time | Yes | | |
| Ability to accept wastes | Yes | | |
| Pre-treatment required | Virtually no need for feed preparation | | |
| Feedstock properties (energy content, moisture content, size etc) | Size reduction is not usually required (can accept feedstocks of variable particle size, containing coarse lumps and fine powders, with no grinding/milling), moisture is not an issue (no drying) and heterogeneous feedstocks are acceptable (no sorting/separation). The flexible operation of the plasma torches also allows variations in the feedstock quantity | | |
| **Capital and operating costs** | | | |
| Costs | Utashinai commercial 265t/day (210odt/day) MSW/ASR plant had a capital cost of $65million<br>Geoplasma's St Lucie 3000t/day (2,250odt/day) MSW/sludge plant would have had a capital cost of $425million<br>Coskata's full BTL pilot plant (1.2odt/day input) will cost $25million<br>It is claimed that a full scale Coskata plant producing 100Mgallon/year (150odt/day) would have capital costs of $3-4/gallon, but production costs of less than $1/gallon | | |

### 6.5.2 Plasco

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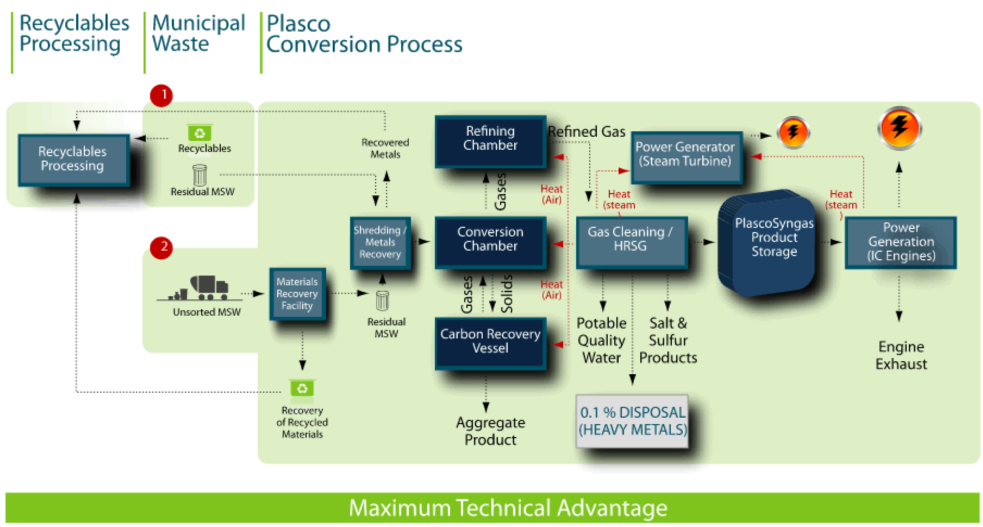
| **Basic information** | |
| Technology provider | Plasco Energy Group Inc |
| Location | Ottawa, Canada |
| Information sources | www.plascoenergygroup.com |
| Background and links | Plasco (formerly Resorption Canada Ltd-RCL Plasma Ltd)) is a privately held Canadian waste conversion and energy generation company that builds, owns and operates Plasco Conversion System facilities using municipal household, commercial or industrial wastes. The Plasco waste conversion technology was developed by Resorption Canada Ltd with significant participation from the National Research Council of Canada (NRC)<br>The Castellgali pilot plant is operated in partnership with Hera Holdings, Spain's second largest waste management company |
| **Gasifier type** | |
| Technology type | Plasma |
| Technology name | Plasco Conversion System<br> |
| Technology Overview | The Plasco system has two primary components; waste conversion/refinement and power generation.<br>The waste conversion process begins with any materials with high reclamation value being removed from the waste stream and collected for recycling. Once these high value products are removed, the MSW is shredded and any remaining materials are removed and sent for recycling.<br>The MSW stream enters the conversion chamber where the waste is converted into a crude syngas using recycled heat (low temperature gasification).<br>The crude syngas flows to the refinement chamber where plasma torches are used to refine the gas into a cleaner syngas, known as PlascoSyngas. Now refined, the PlascoSyngas is sent through a Gas Quality Control Suite to recover sulphur, remove particulates, acid gases and segregate heavy metals found in the waste stream.<br>The solid residue from the conversion chamber is sent to a separate high temperature Carbon Recovery Vessel (CRV) equipped with a plasma torch where the solids are melted. Plasma heat is used to stabilize the solids and convert any remaining volatile compounds and fixed carbon into crude syngas. This additional crude syngas is fed back into the conversion chamber. Any remaining solids are then melted into a liquid slag and cooled into small slag pellets. The slag pellets are an inert vitrified residue sold as construction aggregate |
| Method of heat provision to the gasifier | Electricity, via plasma torches, and direct |
| Oxidant | The reactor vessel is a refractory lined structure with a means for injecting solid waste material into the reactor with a minimum of included air. Some air is injected at the torch to provide the gas for forming the plasma though inert or burned exhaust gas can be used instead, which will contain little or no oxygen |

| **Gasifier operating data** | |
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| Temperature | First stage 700°C, plasma refinement 1200°C |
| Pressure | Unknown, presumed atmospheric |
| Scale and output | Plasco facilities are built in identical 100 t/day modules. This eliminates any scale-up risk associated with our technology and allows a facility to be constructed and commissioned in 15 months. Gross electrical output is 5.2MWe, net 4.2MWe. |
| Efficiency (%) | Inputs: 10.3 BTU of MSW along with 2.1 BTU of electricity for the plasma torch<br>Outputs: Non-recoverable losses total 1.7 BTU, syngas chemical energy 9.5 BTU and sensible heat 1.2 BTU. Hence waste-to-syngas efficiency of 76%<br><br>Every one tonne of waste converted gives rise to 1.2MWh electricity, 300litres of potable water, 5-10kg of salt, 150kg of construction aggregate and 5kg of sulphur agricultural fertiliser. Based on MSW containing 16.5 GJ/t and 30% moisture |
| Reliability issues | |
| **Development and commercial status** | |
| Pilot scale plants | 5 t/day (3.5odt/day) research and development facility in Castellgali, Spain has been operational since 1986 |
| Commercial scale plants | 100 t/day (70odt/day) commercial demonstration plant completed construction and began testing in late 2007 in Ottawa, Canada. The company indicates that extensive third-party emission testing has been done on the demonstration plant in Ottawa under the auspices of the Ontario ministry of Energy and the<br>Environment.<br>Additionally, more funding was provided to the facility by First Reserve Corporation of Greenwich, Connecticut. First Reserve Corporation purchased C$35 million in common shares of Plasco and allocated CAN$115 million for investment in 2008<br>From June to December 2007, Plasco tested the performance of the plant using shredded feedstock and delivering energy to Hydro Ottawa. Converting MSW to energy is the final step in the plant's commissioning, which was completed in 2008. Electricity was first produced in Feb 2008 |
| Future plans | Advertises only 100t/day (70odt/day) modules, avoiding "scale-up risks"<br><br>In June 2008, the City of Ottawa, Canada, signed a letter of intent to bring a 400 tonne per day (280odt/day) Plasco facility, using 4 parallel gasifiers, to the community, providing 21MWe of power. The City of Ottawa will provide the site, the waste and a CAN$40 per tonne tipping fee<br><br>In Sept 2008, the Central Waste Management Commission in Red Deer, Canada also signed a contract for a 200 tonne per day Plasco facility (140odt/day) using 2 parallel gasifiers<br><br>Also looking into a 400t/day (280odt/day) site at the City of Port Moody (near Vancouver), have signed a non-binding letter of intent<br><br>Plasco were possible partners in the EnviroParks Ltd project to establish organic waste and mixed waste treatment facilities next to the Tower Colliery at Hirwaun, Wales, but EuroPlasma were selected due to understanding of UK law and EU regulations |
| Time to commercialisation | |
| Target applications | Heat and power (internal combustion engines) |

| **Syngas characteristics and cleanup** | | | |
|---|---|---|---|
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | | Tars | |
| $CO_2$ (% by vol) | | Hydrocarbons (methane, $C_2H_4$, and higher) | |
| $H_2O$ (% by vol) | | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | | Others | |
| Syngas clean up | | | |
| **Feedstock requirements** | | | |

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| Main feedstocks | Requires residual MSW (sorted and of high enough calorific value) with additional plastic wastes |
| Other potential feedstocks | Post-MRF residue would be an acceptable feedstock for MSW plasma conversion applications (complete removal of glass, metals and inert mineral material before input to the plasma reactor is preferred). |
| Ability to accept a mixture of feedstocks | Yes |
| Ability to accept feedstocks varying over time | Yes |
| Ability to accept wastes | Yes |
| Pre-treatment required | Yes, sorting to remove metals. Shredding of feedstock will be necessary to provide a homogeneous mix to the feed handling system and a moisture content of 25% is preferred (mixtures that include green and food wastes would be acceptable). |
| Feedstock properties (energy content, moisture content, size etc) | Calculations based on an average 30% moisture, 16.5 GJ/t |
| **Capital and operating costs** | |
| Costs | Private investment in Plasco in the last three years has totalled CAN$90 million. The company received CAN$9.5 million in funding from Sustainable Development Technologies Canada and a CAN$4 million loan from the Ontario Ministry of Research and Innovation<br><br>In an article in Waste Management World, Plasco claims the capital cost of their system to be 'less than' US$530 per tonne of annual throughput capacity. Therefore their 2+1 module (at 68,000 t/yr) would cost around $36M |

### 6.5.3 Startech

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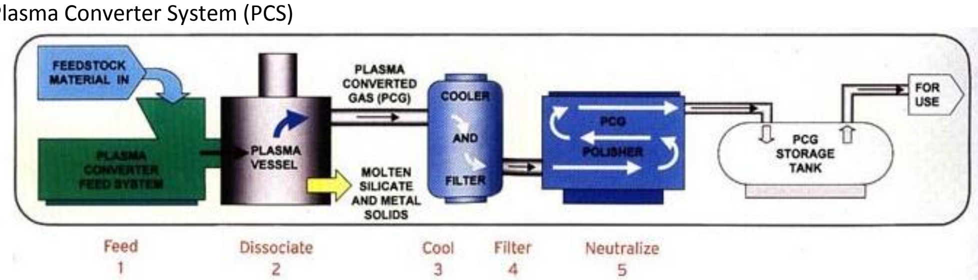
| **Basic information** | |
| Technology provider | Startech Environmental Corporation |
| Location | Wilton, Colorada, USA |
| Information sources | [www.startech.net](http://www.startech.net) |
| Background and links | Startech was incorporated in 1993 in Colorado to tackle waste remediation. In November 1995, Kapalua Acquisitions, Inc., completed the acquisition of Startech Corporation<br>In 2000, recognizing the increasing importance of alternative energy and power sources in general, and hydrogen in particular, Startech expanded their product line to include a hydrogen separation technology named StarCell™. Working in conjunction with their core product, the Plasma Converter™, StarCell provides a green and renewable source of hydrogen to accelerate the hydrogen economy. In addition, Startech offers its customers the opportunity to produce methanol from the Plasma Converted Gas (PCG™) produced in the Plasma Converter<br><br>Startech has formed a strategic alliance with Hydro-Chem, a division of Linde<br>waste2greenenergy Limited is its technology distributor in the UK and Poland<br>GlobalTech Environmental Inc are Startech's Asian distributors (Australia and China) |
| **Gasifier type** | |
| Technology type | Plasma |
| Technology name | Plasma Converter System (PCS)<br> |
| Technology Overview | Startech's plasma converter system is shown above. First, the trash is fed into an auger that shreds it into small pieces. Then the mulch is delivered into the plasma chamber, where the superheated plasma converts it into two products (The plasma torch at the top of the containment vessel is directed by an operator to break down whatever material is fed into it. It acts much like contained, continuous lightning, and everything that is fed into the system is broken down into its constituent atoms. The system is called a closed-loop elemental recycling system). One product is a plasma-converted gas (PCG), or syngas, which after acid gases, volatile metals and particulate matter are removed, is fed into the adjacent Starcell patented system for conversion into fuel (hydrogen or methanol). The other product is molten glass, which can be sold for use in household tiles or road asphalt |
| Method of heat provision to the gasifier | Electricity for the plasma torch, and direct |
| Oxidant | None, only for the plasma torch |
| **Gasifier operating data** | |
| Temperature | Startech's plasma gasification uses extremely high energy plasma (at a temperature of 16,649°C, which is three times as hot as the surface of the Sun). |
| Pressure | Slightly below atmospheric |
| Scale and output | Startech advertise 5, 10, 20, 50 and 100 t/day systems (3.8, 7.5, 15, 37.5 and 75odt/day). Modular 500t/day plants are under proposal with central gas cleanup (375odt/day) |
| Efficiency (%) | Inputs: 9.3 million BTU (inherent content of solid waste), and 1.8 million BTU electricity<br>Outputs: 8.1 million BTU of syngas, and 3 BTU of heat – hence waste-to-syngas conversion efficiency of 73% |
| Reliability issues | |
| **Development and commercial status** | |

| | | | |
|---|---|---|---|
| Pilot scale plants | Startech opened its demonstration and training centre located in Bristol, Connecticut in Jan 2001. The facility houses a 10,000 pound (5t) per day (3.8odt/day) Startech Plasma Converter closed-loop elemental recycling system. The facility is used for testing and analysis, and third party validation services<br><br>There is a 10 t/day (7.5odt/day) Startech PCS operational in Sydney since 2006, processing hazardous wastes.<br><br>In May 2006, the Company announced it had successfully completed Phase One of a two-phase DOE Program focusing on the production of syngas ("Plasma Converted Gas") from processing coal and municipal solid waste in its Plasma Converter. Phase Two, now in progress, is focused on the separation of hydrogen from the PCG synthesis gas mixture using the Company's StarCell system | | |
| Commercial scale plants | Installation of the industrial waste system in Hiemji, Japan was completed back in January 2006, using 5 t/day (3.8odt/day) of hazardous incinerator ash. PCB (polychlorinated byphenyls) testing was completed in October 2006. Preliminary results indicated complete destruction of the PCB's in the Plasma Converter System. Pending the final test report, Mihama can apply for its operator certification. Ideally, as the Company's Japan distributor, Mihama can then use this system to support its Startech sales and marketing operations and be able to demonstrate a workable Plasma Converter System in a commercial operation to its other customers<br><br>2006: $15 million joint venture contract with the Liaoning Academy of Environmental Sciences for the establishment of the Liaoning GlobalTech Hazardous Waste Processing Facility Co. Ltd. using the Startech Plasma Converter System. The 10t/day (7.5odt/day) Startech System that will be the first in China to process industrial hazardous waste including PCBs.<br>Startech reports a commissioning date in 2008 for the sale of three PCS units, totalling 25t/day (7.5, 7.5 and 3.8odt/day), to convert waste to methanol in Puerto Rico. Most of the plants are reported to be operational in 2008. | | |
| Future plans | In 2007, Startech announced a planned 200 t/day (150odt/day) facility in the City of David, Panama. This follows another planned 200 t/day (150odt/day) facility in Center of Las Tablas, Panama.<br><br>A joint project with ViTech Enterprises to manufacture and install a 10 t/day (7.5odt/day) plasma converter facility to destroy out-of-date pharmaceutical products is in progress in South Carolina, USA<br><br>In Dec 2008, formal contract was signed with with one of Poland's largest chemical companies, Zaklady Azotowe Kedzierzyn SA ("ZAK"), for the sale to ZAK of PCG syngas (Plasma Converted Gas (TM)) and steam from the Startech Plasma Converter System(TM) to be installed, owned and operated by SG Silesia within the grounds of ZAK's existing production facilities located in Kedzierzyn-Kozle in the southern Silesian region of Poland. This new facility will initially process 10t/day (7.5odt/day) of high value industrial waste feedstocks in 2010, before being increased to 100t/day (75odt/day)<br><br>Startech entered into a Joint Venture Agreement with FFI (Future Fuels Inc.) in 2006 to produce several of a kind "Spent Tyres to ethanol" plants utilising Startech's Plasma Converter System as the "Front End" to Produce Syngas to feed FFI's proprietary Gas to Liquid Technology for the production of ethanol – but no projects or plant sizes have been announced<br><br>Startech also announced in 2006: "Just on Waste-to-Alternative Fuels alone, we have a 100 t/day Tyres and Refinery Tank Bottoms project in Northern China, an initial 100 t/day project for Black Coal in Mongolia, 250 t/day for Tyres in Hunan Province, and 500 t/day for Tyres in Nanjing. We also have waste-to-hydrogen projects in South Korea and hazardous waste projects in the Philippines" However, none of these projects are using biomass | | |
| Time to commercialisation | | | |
| Target applications | Mainly electricity generation, although new addition of hydrogen, methanol or ethanol generation possible | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |

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| $H_2$, CO (% by vol), ratio | 52% $H_2$, 26% CO, ratio of 2 | Tars | |
| $CO_2$ (% by vol) | 3% | Hydrocarbons (methane, $C_2H_4$, and higher) | <1% methane, <0.5% others |
| $H_2O$ (% by vol) | | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | 16% $N_2$ | Others | |
| Syngas clean up | Removal of acid gases, volatile metals and particulate matter from the syngas | | |
| **Feedstock requirements** | | | |
| Main feedstocks | MSW, industrial, hazardous wastes, incinerator ash and coal | | |
| Other potential feedstocks | Able to take:<br>PCBs or Chlorinated Organics;<br>Medical/Pharmaceutical Wastes;<br>Scrap Tires & Mixed nonrecyclable Plastics;<br>Household Hazardous & NonHazardous Waste;<br>Industrial Hazardous Waste;<br>Refinery & Petrochemical Wastes;<br>Used Mineral & Vegetable Oils | | |
| Ability to accept a mixture of feedstocks | Yes | | |
| Ability to accept feedstocks varying over time | Yes | | |
| Ability to accept wastes | Yes | | |
| Pre-treatment required | None. The converter processes all materials without sorting. In some cases it may be desirable to volume reduce waste materials through the use of a shredder to achieve optimal processing efficiencies | | |
| Feedstock properties (energy content, moisture content, size etc) | | | |
| **Capital and operating costs** | | | |
| Costs | Capital cost: A Startech plasma converter that could handle 2000 tonnes of waste daily (~1500odt/day) costs roughly $250 million.<br>Operating cost: The electrical power requirement for conversion of one tonne of municipal solid waste into vitrified solids and syngas averages around 670 kWh. Might be possible to reduce operational cost by 75% with sale of by-products | | |

### 6.5.4 Solena

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| **Basic information** | |
| Technology provider | Solena Group |
| Location | Washington DC, USA |
| Information sources | www.solenagroup.com |
| Background and links | Dr. Robert Do founded Global Plasma Systems in 1995, and Soleno was formed from this company in 2001. One of Solena's co-founders, Dr. S.L. Camacho, worked with plasma technology as the lead scientist at NASA, when it was used for space flight re-entry testing. Solena Group's objective is to build, own and operate Bio-Energy production facilities worldwide using its patented "SPGV" technology and Integrated Plasma Gasification and Combined Cycle (IPGCC).<br><br>Acciona, Spain's largest supplier to renewable energy, are the exclusive developer of Solena's projects throughout Spain and a co-investor/shareholder with Solena in projects worldwide<br>Envirosol, a Honolulu company, is Solena's exclusive local representative in Hawaii<br>Deutsche Bank AG provides structure financing, equity and debt financing for all of Solena's projects<br>Solena used to be a strategic partner of Westinghouse Plasma, who provided the actual plasma torches for Solena's gasification reactor and balance of plant patented designs - but that arrangement was severed and Solena is working on their own plasma torch designs |
| **Gasifier type** | |
| Technology type | Plasma |
| Technology name | Solena Plasma Gasification and Vitrification (SPGV) technology, used within its Integrated plasma gasification combined cycle (IPGCC) process<br><br> |

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| Technology Overview | The IPGCC system generally consists of four separate processes:<br>• Feedstock handling (in the case of waste, according to physical and chemical characteristics, metal and glass contents are removed for recycling, and the remaining material is sized, dried, and baled)<br>• Plasma gasification and vitrification (PGV). In each PGV reactor, 3 plasma torches are located in the bottom of the gasifier. Less energy is injected through the torches than in the Westinghouse system, and a carbon-based catalyst and oxygen-enriched air are also used to enhance gasification in the bed above the torches. Hydrocarbon material forms syngas, and all inorganic materials in the feedstock are simultaneously vitrified into an inert glassy slag, suitable for use as construction materials including aggregates, tiles or bricks<br>• Gas cooling and clean-up (Acid gases, volatile metals and particulate matter are removed from the cooled gasifier effluent)<br>• Gas turbine combined cycle generation (GE LCV gas turbines + steam turbines) for combustion of the low heating value syngas |
| Method of heat provision to the gasifier | Electricity via the plasma torches, and direct |
| Oxidant | Oxygen enriched air. Supplying oxygen to the reaction allows internal heat generation, which reduces required torch power (compared to plasma torch systems heating a pyrolysis reaction) but also reduces the chemical energy content of the produced gas (because it's been partially oxidized) |
| **Gasifier operating data** | |
| Temperature | 4,000°C to 5,000°C |
| Pressure | Atmospheric |
| Scale and output | There are two standard modules of IPGC facilities. Our large 40 $MW_e$ facility (based on GE MS5001 Combined Cycle power systems) typically gasifies 20 tons of biomass per hour (480t/day or 360odt/day) and the smaller 15 $MW_e$ gross facility (based on GE GT10 Combined Cycle Power system) gasifies between 5 to 10 tons per hour (120-240t/day, or 90-180odt/day) of biomass, depending on the feedstock composition |
| Efficiency (%) | Claim biomass to syngas efficiency of up to 90%, with 1 tonne of waste giving 1 MWh of net power output, and an electrical efficiency of 36% |
| Reliability issues | Solena claim that operating at atmospheric pressure, the PGV system can achieve an 85% availability |
| **Development and commercial status** | |
| Pilot scale plants | |
| Commercial scale plants | • Solena state that plants based on their IPGCC technology are operational in North America, the Caribbean, Europe and South America – but no details provided. The company members have been involved in many projects and ventures that utilize plasma arc technology, related to hazardous or low-level nuclear waste volume reduction or in metals production. There have been some test programs on MSW or generic waste disposal.<br>• ENEL, the major Italian utility, made a $3m equity investment in Solena in March 2000 and a commitment to a plant. A facility in Rome, Italy was said to be under construction in 2002, and due to be commissioned in 2004 with a capacity of 336 t/day MSW (252odt/day). Plasma torches were to be supplied by Westinghouse, the gas cleanup system by LGL, and a combustion turbine from General Electric. The electricity generated was due to be subsidised<br>• 2003: Solena announced plans for a $15m, Plasma R&D Center, located at an existing facility on the "Universidad del Turabo" campus, AGMUS, in Puerto Rico. After facility retrofitting, Solena will build a prototype shipboard PGV plant. This 24t/day (18oodt/day) compact reactor will be capable of treating all ship-board waste streams, and its Europlasma torch uses 300kW<br>• Jan 2008: announcement of an $18m dollar contract to integrate a 135odt/day MSW Solena system into a $90m facility, with construction set to begin in March 2008. The facility will produce 15 $MW_e$ in the Galicia region of Spain in partnership with ECOTEK – although is currently still in the permitting stage<br>• Solena state that they have a number of units representing different generations of their technology, but they appear mainly for waste destruction, not energy production. A demonstration plant was built in Bordeaux, France in 1998 using a Europlasma torch. There are about 7 plants in Japan. One was built for GM. Two more are under construction in Spain and others are in various stages of development in France, the UK, the US, and Malaysia.<br><br>As of late 2008, none of the above energy projects appear to have been built, and no IPGCC systems appear to exist – information on physical deployment and project completion is not available |

<table>
<tr><td>Future plans</td><td colspan="3">Solena claim to have numerous projects planned:<br>• A 20-28 MW (216odt/day) plant in the Czech Republic is at an uncertain stage of planning<br>• 5th March 2008: announced their plans to convert waste into liquid fuel for military and commercial aircraft, in partnership with Rentech, Inc., a pioneering coal-to-liquid production company that will use Solena's bio-syngas as a replacement for synthesis gas generated from coal or natural gas. Construction of the $250m facility in Gilroy, California is due to start in 2009, for operation in 2011. Rentech Standard FT module system will produce 1,800 barrels of bio-fuel a day (equating to 17 million gallons/year), with 70% Jet A-1 fuel (also known as SJ-8 for military uses) and 30% Naptha. The plant will use 1,500t/day (1,125odt/day) of raw material from municipal, agricultural and forestry waste supplied by Norcal Waste Systems. As of the end of 2008, discussions with Rentech are still ongoing, but Solena was still at the stage of agreeing terms with its feedstock suppliers[104]<br>• 2009: Solena has also signed an agreement to build a similar 40MW, 480t/day (360odt/day) plant in the City of Santiago del Estero, Argentina and is also in talks to build another plant in Mississippi, USA<br>• Among Solena's other initiatives are to build five 40 MW plants in California (360odt/day)<br>• Invesco Group conduced a feasibility study for a 40 MW plant in Niarobi, Nigeria (360odt/day)<br>• 10th March 2009: proposing a 42$MW_e$ (360odt/day) WTE gasification plant for Manatí in the Caribbean. After a preliminary evaluation, the Puerto Rico Electric Power Authority referred the project to the Solid Waste Management Authority, which now has to make a decision<br>• A $80m, 10 $MW_e$ plant in Malaysia, using 90odt/day padi husks.<br>• A number of 130$MW_e$ Integrated Plasma Gasification Combined Cycle plants in the eastern U.S. to use waste coal and coal fines. Solena Group's principal partner is Stone and Webster<br>• Solena, in cooperation with its partner Bio Fuel Systems, is developing the use of micro-algae as feedstock for the gasification process, for production of FT liquids. The micro-algae employed use solar (or artificial) light to photosynthesize $CO_2$ within a special electromagnetic bio-reactor. The most readily available source for this $CO_2$ are the emissions from combusting some of the syngas in the IPGCC Plant's combined cycle, thus creating a closed-loop process in terms of $CO_2$ emissions.<br>• 23rd March 2009: the Port Authority of Venice plan to build an $273m algae power plant. The project is a collaboration between Enalg Srl and l'Autorita Portuale di Venezia, using the technology from Solena Group, to generate 40$MW_e$, about half of the Old Town's power needs, from the plasma gasification of algae grown in 11hectares of ponds (360odt/day)<br>• Solena is also working with fuel cell companies to develop a small integrated plasma to fuel cell system that can process 1-5t/hour (24 to 125t/day, or 18-94odt/day) of solid wastes, generating 1$MW_e$</td></tr>
<tr><td>Time to commercialisation</td><td colspan="3"></td></tr>
<tr><td>Target applications</td><td colspan="3">Syngas is currently to designed for converted into renewable power in the IPGCC process, but future applications will see syngas used in chemical synthesis processes to produce products such as methanol, or bio-diesel and other liquid fuels via FT</td></tr>
<tr><td colspan="4">Syngas characteristics and cleanup</td></tr>
<tr><td>Temperature</td><td>1,250°C</td><td>Halides (HCl, Br, F)</td><td>0.05% HCl</td></tr>
<tr><td>Pressure</td><td></td><td>Alkalines (Na, K)</td><td></td></tr>
<tr><td>$H_2$, CO (% by vol), ratio</td><td>42.53% $H_2$, 45.29% CO, ratio of 0.94</td><td>Tars</td><td></td></tr>
<tr><td>$CO_2$ (% by vol)</td><td>4.25%</td><td>Hydrocarbons (methane, $C_2H_4$, and higher)</td><td>2.56% $C_2H_4$</td></tr>
<tr><td>$H_2O$ (% by vol)</td><td>0.01%</td><td>Particulates (ppm and size, e.g. Ash, soot)</td><td></td></tr>
<tr><td>Sulphur (COS, $H_2S$, $CS_2$)</td><td>0.11% $H_2S$</td><td>Other inerts (e.g. Bed material)</td><td></td></tr>
<tr><td>Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$)</td><td>5.2% $N_2$</td><td>Others</td><td></td></tr>
<tr><td>Syngas clean up</td><td colspan="3">In general, the syngas will be conditioned to a certain temperature and moisture content, cleaned by scrubbing out any acid gases or particulates and then compressed to the required pressure of the turbine system</td></tr>
</table>

[104] Rentech F4Q08 earnings call transcript (2008), Available at: http://seekingalpha.com/article/111030-rentech-inc-f4q08-quarter-end-9-30-08-earnings-call-transcript?page=-1 [Accessed 14th May 2008]

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| **Feedstock requirements** | |
| Main feedstocks | Power is produced by the gasification of low value or opportunity waste streams, such as biomass, MSW or industrial and hospital wastes, and tyres. In addition in a non-renewable mode, the SPGV reactor can cleanly and safely use coal and coal and oil wastes as feedstock |
| Other potential feedstocks | Advertise that they are able to use all biomass including woods, shrubs, grasses and other agricultural products as well as municipal and industrial waste |
| Ability to accept a mixture of feedstocks | Yes. The feedstock for the IPGCC can be very heterogeneous (MSW) or homogeneous (coal) or a combination allowing it the plant to continue operations even if the fuel feedstock are inconsistent or changed |
| Ability to accept feedstocks varying over time | Yes |
| Ability to accept wastes | Yes |
| Pre-treatment required | |
| Feedstock properties (energy content, moisture content, size etc) | |
| **Capital and operating costs** | |
| Costs | Estimated cost of $250 million for the 1500t/day (1,125odt/day) MSW to aviation FT plant in Gilroy, California, with production costs of $ 130/Barrel ($3/gallon) + $1/gallon Excise Tax<br>Estimated cost of $273 million for the Port of Venice algae to 40MWe project (360odt/day)<br><br>Other estimated costs for proposed projects include:<br>• Valencia, Spain: 130,000 t/yr (~300odt/day) $75m<br>• Kualiti Alam, Malaysia: 50,000 t/yr (~114odt/day) $45m<br>• Vicenza, Italy: 130,000 t/yr (~300odt/day) $75m<br>• Rome/Malagrotta: 24,000 t/yr (~55odt/day) $12m<br>• CFF, France: 150,000 t/yr (~342odt/day) $75m<br>• Ibie, Spain: 150,000 t/yr (~342odt/day) $75m<br><br>Solena will likely sell electricity to the grid at 8 to 12 cents per kWh, possibly competitive with the 2006 U.S. average of 8.9 cents per kWh |

### 6.5.5 InEnTec

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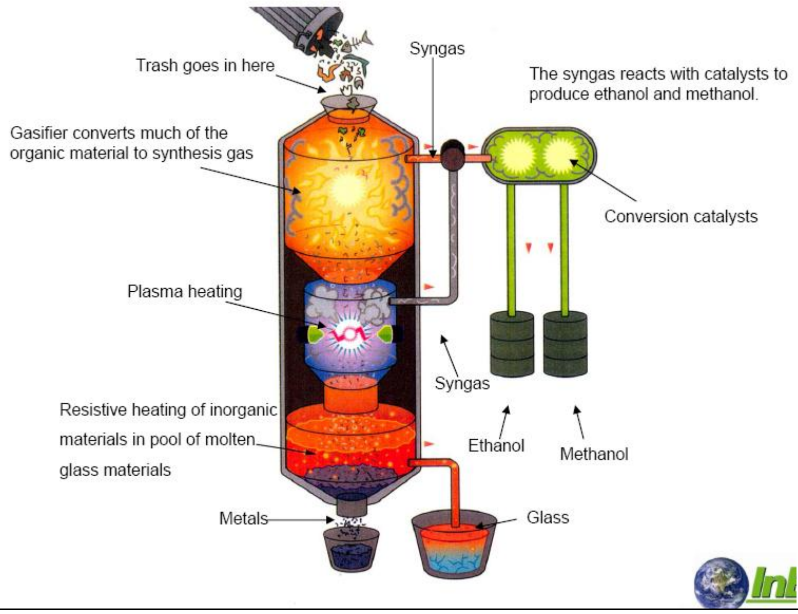
| **Basic information** | |
| Technology provider | InEnTec LLC (previously Integrated Environmental Technologies, LLC) |
| Location | Bend, Oregon, USA |
| Information sources | http://www.inentec.com |
| Background and links | Dr. Cohn, Messrs. Titus, Surma and Dinkin founded Integrated Environmental Technologies (IET) in July 1995. IET has exclusive rights to the Plasma Enhanced Melter (PEM) technology. The IET technology builds upon extensive U.S. Department of Energy sponsored research at Massachusetts Institute of Technology (MIT) and Battelle Pacific Northwest National Laboratory (PNNL)<br><br>InEnTec has an agreement with Battelle Memorial Institute ("BMI"), pursuant to which BMI will act as an important supplier of technical support and potential customer contacts. BMI is a world leader in waste glassification technology (immobilising waste within glass), and is also an InEnTec shareholder. Joint marketing agreements with Kawasaki Heavy Industries & Hitachi (Japan) |
| **Gasifier type** | |
| Technology type | Plasma |
| Technology name | Plasma Enhanced Melter (PEM)<br> |
| Technology Overview | During the first gasification process, waste is mixed with oxygen and superheated steam, thereby being heated to more than 700°C. Some of the feedstock breaks down into syngas, and the remaining material falls into the molten glass pool in the bottom chamber. Further syngas is created and extracted. Metals in the waste are recovered, after they sink to the base of the liquid glass pool. The highly-stable glassy aggregate is also recovered and may be recycled as road building, blasting grit or construction material. Volume reductions are up to 98% depending on how the process is run and the composition of the waste.<br><br>The PEM technology is unique in that it combines three processes, the combination of which results in a highly controllable waste treatment system:<br>• plasma arc using multiple graphite electrodes<br>• joule (resistance) heating using glass melter technology<br>• superheated steam |
| Method of heat provision to the gasifier | The PEM system has two energy sources. DC power is used for the plasma arc and AC power is used in the joule-heating zone in the process chamber. The DC plasma arc is formed between two carbon electrodes and then extended to the molten glass bath inside the process chamber. This molten glass bath is further heated using electrodes connected to an AC power source |
| Oxidant | Oxygen and superheated steam |
| **Gasifier operating data** | |

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| Temperature | First gasification chamber operates at around 700°C, whereas the plasma operates at temperatures from 3,000°C to 10,000°C |
| Pressure | Atmospheric |
| Scale and output | Modular facilities, usually 10 or 25odt/day input waste |
| Efficiency (%) | |
| Reliability issues | |
| **Development and commercial status** | |
| Pilot scale plants | In 1996, IET opened its Technology Center in Richland, Washington for treating 25odt/day hazardous and radioactive wastes. The Allied Technology Group Inc (ATG) plant used a G200 PEM. However, the facility ATG plasma arc facility had chronic operational problems, including with its emissions equipment. ATG filed for bankruptcy, and closed the facility in 2001. InEnTec state the plant is still in cold standby<br><br>Kawasaki Heavy Industries PCB Demonstration Unit: This G100 (10odt/day) system was installed at Ryukyus University on the Japanese island of Okinawa by Kawasaki Heavy Industries (one of IET's representatives in Japan) in 2003. It was used to demonstrate to the Japanese Regulatory Authorities that the PEM could safely process PCBs and meet Japanese destruction requirements. The demonstration program was executed in mid 2003 and lasted for two months. Following the test and receipt of approval from the Japanese authorities for processing of PCB contaminated materials, the system was dismantled and shipped to another location near Kobe. In 2006, Kawasaki moved and installed the G100 system in Harima, Japan, for a demonstration of asbestos destruction. This very successful test was completed in June 2006. The system will now be moved to the KHI facility near Osaka, Japan, and reinstalled for PCB destruction on an ongoing basis. KHI is looking into large-scale commercial projects using the PEM technology<br><br>A 1 odt/day PEM system was due to be installed by IET's Malaysian representative BioPure Systems in Kuala Lumpur, Malaysia, for use as a testing and demonstration facility for the Malaysian market. However, this plant was never built, and InEnTec cancelled the project on 13$^{th}$ June 2008<br><br>InEnTec Chemical LLC (IET) completed demonstration of its mobile PEM system for four of the world's largest chemical companies to produce ultra clean, $H_2$-rich syngas from chemical residuals that would normally be incinerated as hazardous waste. IET showcased the new $H_2$ production process on 6$^{th}$ June 2008 at the Veolia Environmental Services incineration plant near Port Arthur, Texas. Air Liquide Large Industries US LP are interested in using InEnTec PEM technology as a result.<br>This mobile facility was also demonstrated to the US Air Force at Fort Riley, Kansas in September 2005. |
| Commercial scale plants | Asia Pacific Environmental Technology's (APET) Hawaii Medical Vitrification (HMV) facility in Honolulu, HI uses a G100 PEM system to treat 10odt/day of hospital and other medical waste from the Honolulu area, destroying all pathogens and biohazards and generating electricity from the syngas. However, the plant never underwent air emissions testing, which led to the State Department of Health taking legal action against InEnTec, plus the plant had numerous problems leading to a shut down between August 2004 and April 2005 due to damage to the refractory plasma arc equipment.<br><br>The G300 PEM system was installed at Fuji Kaihatsu's facility in Iizuka, Japan (near Fukuoka). The system is designed to process up to 10 odt/day of plastics and industrial waste into electricity in a low pollution process.<br><br>Global Plasma of Taipei, Taiwan installed a G100 (10odt/day) system for treating medical waste and batteries. Commissioning of the plant was completed in March of 2005. The system easily passed the Taiwan EPA performance test for environmental emissions. This is the first system using a dual-fuelled diesel engine for combustion of the syngas.<br><br>Permits to build a plasma arc facility in Red Bluff, California were rescinded in December 2005. Some of InEnTec's documents claimed their technology was "pollution-free" and did not produce dioxin despite their own test results from a research project that showed emissions of dioxin and other pollutants |

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| Future plans | 1st October 2007: InEnTec announced contracts with Dow Corning Corporation and Veolia Environmental Services for the US's first plasma-based gasification process to recycle hazardous waste. IET will install its patented PEM technology at Dow Corning's plant in Midland, Michigan, to be operated by Veolia. The plant will take in 6600 t/year (15 odt/day) of liquid hazardous waste and produce 12 million pounds per year (5500t/year) of HCl and 10.5 million BTU per hour of syngas. Design and procurement of the facility began in the summer of 2007 and it was expected to be online in mid 2008. Lakeside Energy is providing the equity to be used for working capital and financing of the Dow Corning project, and formed a joint venture, InEnTec Chemical in Oct 2008 with InEnTec to further commercialise the PEM technology<br><br>InEnTec Chemical has previously announced plans to build a second plant in the southeast region of the U.S. that will serve some of the world's leading chemical manufacturers. That plant will also be operated by Veolia ES Technical Solutions with construction expected to begin in late 2009.<br><br>22nd July 2008: InEnTec announced that its PEM will be used to convert MSW into ethanol for cars and trucks, as one of the first commercial-scale production facilities of its kind in the U.S. The project, located in Storey Country, Nevada, is named Sierra BioFuels, and will be owned by Fulcrum BioEnergy Inc. InEnTec's new subsidiary, InEnTec Energy Solutions, LLC, will retain a minority stake in the project. When it begins operations in early 2010, the Sierra BioFuels plant is expected to produce approximately 10.5 million gallons of ethanol per year, and to process nearly 90,000 tons per year of MSW (290t/day or 218odt/day) that would otherwise have been disposed in landfills. A novel ethanol catalyst, jointly developed by the Saskatchewan Research Council and the Nipawan Biomass Ethanol New Generation Co-operative, will be used. | | |
| Time to commercialisation | | | |
| Target applications | A portion of the syngas may be recycled to provide power to the PEM, and the other portion used to generate electricity, although the syngas can be used for solely for heat and power, hydrogen, or catalytic methanol and ethanol production | | |
| **Syngas characteristics and cleanup** | | | |
| Temperature | | Halides (HCl, Br, F) | |
| Pressure | | Alkalines (Na, K) | |
| $H_2$, CO (% by vol), ratio | 36.5% $H_2$, 46.8% CO, ratio of 0.78 | Tars | |
| $CO_2$ (% by vol) | 11.8% | Hydrocarbons (methane, $C_2H_4$, and higher) | |
| $H_2O$ (% by vol) | 1.5% | Particulates (ppm and size, e.g. Ash, soot) | |
| Sulphur (COS, $H_2S$, $CS_2$) | | Other inerts (e.g. Bed material) | |
| Nitrogen ($N_2$, HCN, $NH_3$, $NO_x$) | 3.3% $N_2$ | Others | |
| Syngas clean up | A high-efficiency scrubber is used to remove volatile metals and other pollutants from the syngas, and particles are also removed | | |
| **Feedstock requirements** | | | |
| Main feedstocks | IET is most interested in treating radioactive, hazardous, industrial, municipal, tyre, incinerator ash and medical waste streams, and have also tested PCBs and asbestos | | |
| Other potential feedstocks | Other wastes such as MSW, provided high enough calorific content | | |
| Ability to accept a mixture of feedstocks | Yes | | |
| Ability to accept feedstocks varying over time | Yes | | |
| Ability to accept wastes | Yes | | |
| Pre-treatment required | | | |
| Feedstock properties (energy content, moisture content, size etc) | Shredded into small pieces of 2 inches to 4 inches | | |
| **Costs** | | | |
| Costs | The Fulcrum Bioenergy project (290t/day) is expected to cost approximately $120 million | | |

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