Programme Area: Bioenergy

Project: Energy From Waste

Title: CARE - Pyrolysis and Gasification of Waste Review

Abstract:

This document is Appendix C of the Energy from Waste UK Benefits Case (Deliverable 2 of 2 in Work Package 4).The ETI commissioned C.A.R.E. Ltd. to provide an assessment of the current pyrolysis and gasification technology status (at system level including the process technology itself and gas clean-up), with detailed justification based on real site/project operational data and experience.

Context:

The Energy from Waste project was instrumental in identifying the potential near-term value of demonstrating integrated advanced thermal (gasification) systems for energy from waste at the community scale. Coupled with our analysis of the wider energy system, which identified gasification of wastes and biomass as a scenario-resilient technology, the ETI decided to commission the Waste Gasification Demonstration project. Phase 1 of the Waste Gasification project commissioned three companies to produce FEED Studies and business plans for a waste gasification with gas clean up to power plant. The ETI is taking forward one of these designs to the demonstration stage - investing in a 1.5MWe plant near Wednesbury. More information on the project is available on the ETI website. The ETI is publishing the outputs from the Energy from Waste projects as background to the Waste Gasification project. However, these reports were written in 2011 and shouldn't be interpreted as the latest view of the energy from waste sector. Readers are encouraged to review the more recent insight papers published by the ETI, available here: http://www.eti.co.uk/insights

PYROLYSIS AND GASIFICATION OF WASTES:
UK AND IRELAND REVIEW

Report to:

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CARE
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The authors accept no responsibility for opinions or conclusions based upon the report, which were not expressed by the report authors.

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1. INTRODUCTION

The ETI have commissioned C.A.R.E. Ltd. to provide the following:

- Assessment of the current pyrolysis and gasification technology status (at system level including the process technology itself and gas clean-up), with detailed justification based on real site/project operational data and experience as evidence, to include technical and/or commercial evidence as appropriate.
- Focus on mixed waste as a feedstock but with biomass based data if insufficient waste based projects available.
- UK focus with as much detail and breadth as can be provided with evidence from global sites as possible

To this end, Conversion And Resource Evaluation Ltd. has looked at the range of technology companies in the UK who have delivered projects with a track record and included accessible information where possible. The report has the following structure:

1. Technology introduction and terminology
2. UK Gasification companies profiled - projects and issues
3. UK Pyrolysis companies - projects and issues
4. Non-UK projects/companies in waste gasification and pyrolysis - key examples with data
5. Process emissions data, solid leachate data and gas compositional data - waste gasification and pyrolysis
6. Gas cleaning in pyrolysis and gasification - unit operations and collection/recovery efficiencies
7. Technology costs - published and company data from UK and worldwide
8. Engine Specifications for syngas and producer gas
9. Conclusions

Appendices:

A Summary of non-profile commercial waste pyrolysis companies with engine experience and references.

B Overall assessment of the 250 kWe Biomass Engineering Ltd. gasification process operating on wood – contains mass balance data, LCA assessment and overall gas cleaning system performance based on detailed tars and particulates measurement.

1.1 Terminology

Alternative energy is of growing importance in satisfying environmental concerns over fossil fuel usage. Wood and other forms of biomass and wastes are one of the main sustainable energy resources available and provide the only source of liquid, solid and gaseous fuels. Wood and biomass can be used in a variety of ways to provide energy as summarised in Figure 1:

- by direct combustion to provide heat for use in heating, for steam production and hence electricity generation
- by gasification to provide a fuel gas for combustion for heat, or in an engine or turbine for electricity generation,
- by fast pyrolysis to provide a liquid fuel that can substitute for fuel oil in any static heating or electricity generation application.

Thus only fast pyrolysis can directly produce a liquid fuel from biomass which is important when biomass resources are remote from where the energy is required as liquid can be readily stored and transported.

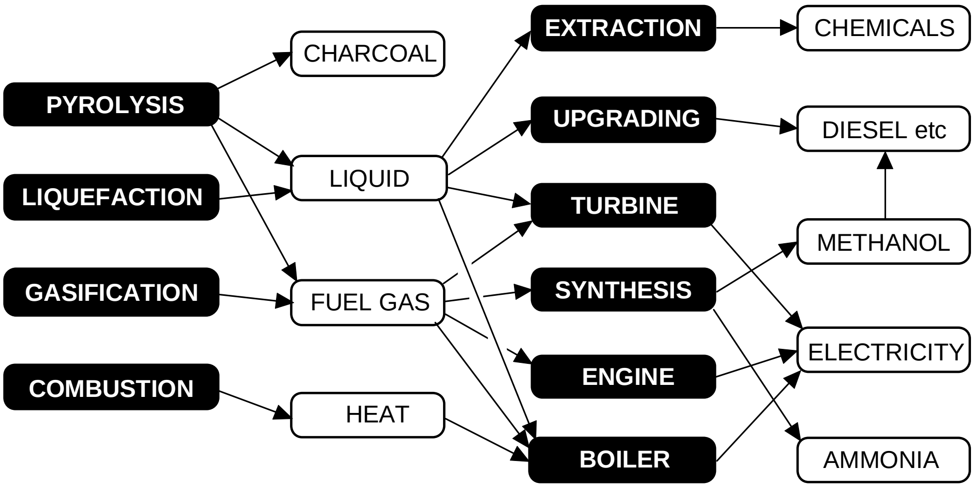

Figure 1. Thermochemical biomass processes and products

1.2 Terminology; Pyrolysis, Gasification and Combustion

When biomass is burnt completely (combusted) sufficient air is added to oxidise all of the combustible components. Thus:

> Combustion is the reaction of a material with air/O_2 with the intent of completely oxidising it (λ typically > 1).
>
> λ (lambda) is defined as the exact air (O_2)/fuel ratio required to completely oxidise the fuel. This is also known as the stoichiometric ratio.
>
> Gasification is the sub-stoichiometric conversion of a material into a gas, commonly referred to as "producer gas" if the reaction is with air and “syngas” if the reaction is with O_2. Steam is also sometimes added along with the oxidant to promote gasification. The "ideal" stoichiometric air/fuel ratio is in the 0.3-0.4 to assure complete gasification of the solid fuel and obtain the highest heating value in the gas product.

Pyrolysis is defined as the thermal degradation of biomass in the absence of oxygen to produce condensable vapours, gases, and charcoal; in some instance a small amount of air may be admitted to promote this endothermic process (where $\lambda < 0.1\text{-}0.2$, typically 0 for fast pyrolysis or very high temperature pyrolysis).

Liquefaction is low temperature (250-350°C), high pressure [50 – 200 atm] thermo-chemical conversion in the liquid phase, usually with a high hydrogen partial pressure and also a catalyst to enhance the rate of reaction and / or improve the selectivity of the process.

1.3 Terminology: other

Biomass is defined as a sustainable source of fixed carbon in the short term, i.e. less than 10-20 years. This includes wood, grasses and agricultural crops.

Bio-char is char derived from the thermal conversion of biomass which is used for non-energy purposes. It may however have an alternative use as an energy carrier and in this case is called charcoal or activated carbon if further treated.

Syngas or pyrolysis gas is the non-condensable product of pyrolysis containing CO, CO_2, H_2, CH_4, and higher hydrocarbons.

Tar is the generic (unspecific) term for entity of all organic compounds present in the gasification product gas excluding gaseous hydrocarbons [C_1 through C_6] (1). In gasification, tar does have a specific definition:

> generic (unspecific) term for entity of all organic compounds present in the gasification product gas excluding gaseous hydrocarbons (C_1 through C_6)

Producer gas is the primary non-condensable product of gasification containing CO, CO_2, H_2, CH_4, and higher hydrocarbons. Water and N_2 may also be present as diluents depending on the oxidant/gasification agent used.

Pyrolysis liquid [also know as "bio-crude-oil", "bio-oil", "pyroligneous acid", "pyrolysis tar" and biofuel-oil"] is the condensable organic liquid product of pyrolysis containing a wide range of oxygenated chemicals. Pyrolysis liquids also inherently contain water, formed during the pyrolysis process.

Pyrolytic lignin is the fraction recovered from pyrolysis liquids by the addition of water to the pyrolysis liquids causing precipitation of the lignin-derived components.

1.4 Pyrolysis

1.4.1 Slow pyrolysis

Slow pyrolysis has been used for centuries to produce charcoal, tars, alcohols such as ethanol and methanol and other solvents. This is usually carried out in batch processes using kilns or retort furnaces (e.g. 2, 3, 4). Conventional pyrolysis is characterised by:

- long solids and volatiles residence times [typically greater than 5 s for volatiles; solids residence times can be minutes, hours or days],
- relatively low reactor temperatures [< 400°C],
- atmospheric pressure,
- very low heating rates ranging from 0.01°C/s to up to 2°C/s,
- very low rate of thermal quenching of the products [minutes to hours].

Char, viscous tarry liquid and gases are formed in approximately equal mass proportions due to the slow degradation of the biomass and extensive secondary intraparticle and gas/vapour phase reactions.

1.4.2 Conventional pyrolysis

Conventional pyrolysis is similarly characterised by:

- long solids and volatiles residence times [typically less than 5 s for volatiles; solids residence times can be longer] up to one minute,
- relatively low reactor temperatures [< 450°C],
- slow heating rates of about 2-10°C/s,
- atmospheric pressure,
- low rate of thermal quenching of the products (5, 6).

Yields of organic liquids products from conventional pyrolysis are typically low, e.g. 20 % with char yields of typically 20-25 wt%, 20 wt% water and the balance non-condensable gases comprised mainly of carbon dioxide (7).

1.4.3 Fast pyrolysis

Fast pyrolysis gives higher reaction rates due to the higher temperatures. Over the past ten years, the distinction between flash and fast pyrolysis has largely disappeared and now the term "flash" has largely disappeared and is gradually being replaced by a more generalised definition for fast pyrolysis of:

- high heating rates [> 1000°C/s],
- reactor temperatures greater than 450°C,
- short vapour product residence times [< 2 s for liquid fuels, < 1 s for speciality chemicals],
- rapid product quenching [< 40 ms] (8).

The fast pyrolysis process can be operated from ~450-550°C to optimise liquid yields and above 600°C to increase or optimise the gas yield, commonly referred to as "syngas". This may also be referred to as high temperature pyrolysis.

In order to clarify the different regimes in which pyrolysis occurs, to maximise the yields of different products, the principal variants are summarised in Table 1.

Table 1 Characteristics of key pyrolysis processes (9)

Variant	Residence Time)[1]	Heating Rate	Temperature (ºC)	Major product
Carbonisation	hrs-days	very low	<400	charcoal
Conventional	5-30 min	low	<600	liquids, charcoal & gas
Slow	0.5-5 s	fairly high	550	liquids
Fast (liquid)	<1 s	high	400-600	liquids
Fast (gas)	<1 s	high	>650	chemicals & fuel gas
Ultra[2]	<0.5 s	very high	1000	chemicals & fuel gas
Vacuum	2-30 s	medium	400-450	liquids

Note: 1 of the reacting material in the reactor 2 terminology no longer in common use

While a wide range of reactor configurations have been operated, fluid beds and circulating fluid beds are the most popular configurations due to their ease of operation and ready scale-up respectively. Vacuum pyrolysis utilises indirect heating of a solid surface in contact with the biomass, typically on a horizontal-moving hearth. Key reactor types are summarised in Table 2.

Table 2 Pyrolysis Reactor Types

Reactor type	Mode of contact	Description	Main product(s)
Fixed bed	Beehive kiln	wood is stacked in a retort and heated either with combusting wood or externally	charcoal
Fluid bed	Single reactor	low gas velocity, inert solid stays in reactor, products removed by gas.	liquid at moderate temperature, gas at high temperature
	Fast fluid bed	inert solid is elutriated with product char and gas and inert solid is recycled.	liquid at moderate temperature, gas at high temperature
	Circulating bed	inert solid is elutriated, separated and recirculated. This sometimes also refers to fast fluid bed or twin reactor systems.	liquid at moderate temperature, gas at high temperature
	Entrained bed	usually no inert solid, biomass contacted with hot gas to effect pyrolysis	liquid at moderate temperature, gas at high temperature
	Twin reactor	steam gasification and/or pyrolysis occurs in the first reactor; char is combusted in the second reactor to heat the fluidising medium for recirculation. Either can be any type of fluid bed, although the combustor is often a bubbling fluid bed.	gas at high temperature
Moving bed	Various	Mechanical transport of solid; usually lower temperature processes; Includes: Multiple hearth; Horizontal moving bed; Sloping hearth; augur kiln.	Charcoal and/or gas

Reactor type	Mode of contact	Description	Main product(s)
Other		Rotary kiln, cyclonic and vortex reactors, ablative reactors where biomass pressed and moved on heated reactor surface	Charcoal, or liquid, and/or gas

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Wood charcoal is one of the earliest forms of "concentrated" energy, compared to that of the original wood, having a heating value up to around 30-40 MJ/kg. Slow pyrolysis, which is used to make charcoal, also produces a highly viscous tar, which has limited use (chemical source and/or crude wood preservative). Fast pyrolysis, however, produces a pyrolysis liquid that can be used as a fuel and upgraded to a liquid transport fuel.

The pyrolysis liquids can be burned in a wide range of applications including boilers, dual fuel diesel engines and turbines. Char present in the liquid is due to inefficiencies in the product collection systems. Pyrolysis liquids are not miscible with hydrocarbons and can only adsorb a limited amount of water before the liquid separates into two phases – a viscous tar and an aqueous phase. Typically, the pyrolysis gas is vented, due to the low concentration of the combustible gases. In some processes, the gas is recycled and used as the fluidising medium.

High temperature pyrolysis is used to give a fuel gas, typically with a heating value over 14 MJ/nm^3 that could be used in an engine or turbine, which is discussed below.

1.5 Gasification

1.5.1 Steam Gasification

Steam gasification is the gasification of biomass using steam > 800°C to yield a producer gas. Heat is added indirectly to the biomass via a solid heat carrier or the steam to effect reaction.

1.5.2 Oxygen Gasification

Oxygen gasification is the gasification of a material using either oxygen-enriched air or pure oxygen to yield a producer gas. Heat may be added indirectly to the biomass via a solid heat carrier to effect reaction.

2. UK AND IRELAND GASIFICATION

2.1 Introduction

In the UK, the majority of gasification technologies are focused on clean wood. There have been very limited developments in wastes, only some work by Biomass Engineering Ltd. has been noted using a variety of leather wastes (10), some details of which are provided alter to show likely emissions. Gasification companies in UK and Ireland are summarised in Table 3 overleaf. 19 companies active in the technology or developing projects are reviewed.

It can be seen that of the companies offering a gasification technology, very few have processed wastes. The main reasons for this are:

- Variability in waste composition
- Slagging behaviour of MSW and other derived wastes in the gasification process
- Unsuitability of the technology to wastes [e.g. downdraft not suitable for unsorted wastes or low ahs melting paoint wastes]
- Significant gas cleanup required to meet WID requirements
- Low power prices for the electricity generated
- Lower cost alternatives – landfill and mass burn incineration are more commercially attractive.

Based on the terminology noted above, gasification processes are only those which take the primary product and use it in a prime mover for power or a dedicated boiler application and not those which burn the raw producer gas for heat (which may be used for steam raising).

If the products of pyrolysis or gasification are simply combusted without their further use, this calls into question whether the process is truly a gasification or pyrolysis process. To this end, those processes which combust the products prior to use as classed as combustion plants. Only those which burn cleaned syngas or producer gas for heat or power use are not eligible. Some key examples are Energos and Waste2Energy Ltd., CompactPower/Ethos and Entech which are staged combustors and not true gasification technologies.

Table 3 UK and Ireland Gasification Companies (recent and current)

Company	Feed	Technology and size	Status	Comments
Advanced Plasma Power	RDF	Plasma gasification 75kg/h pre-prepared RDF	Operational Demo plant, Farringdon Oxfordshire relocated to Marston Gate, Swindon	Using technology of Energy Products of Idaho (EPI) Commissioned 2008 Plans to scale up to 164odt/day
ARBRE Energy Ltd	Biomass Energy crops and/or organic waste	Air blown fluidised bed gasifier, 8MW$_e$ Eggborough, North Yorkshire	Project failed. Plant started up in 2001 but full commissioning of plant not completed £26M capital cost	Joint venture including TPS, Kelda, First Renewables (FRL) May 2002 FRL sold to Energy Power Resources (EPR). Later in the year ARBRE put into liquidation
Bioflame	Wood waste	Downdraft gasification Demonstration plant 250 kWe	Demonstrator – problems, but now claim to be commercial.	
Biomass CHP Ltd.	Wood chip	Downdraft gasification Benburb 136 kW$_e$	Dormant	Originally B9 Energy Biomass Ltd., then called Exus Energy [licensee of Gengas/SMP technology] Went into receivership in 2006 – now back as Biomass CHP
		Downdraft gasification BEDZED 126 kW$_e$	BEDZED closed down in 2007	
		Downdraft gasification Kilwaughter Lime Works 300 kW$_e$	Only the Kilwaughter Lime Works plant is under development in Northern Ireland	

Company	Feed	Technology and size	Status	Comments
Biossence East London Ltd	MSW	Fluid bed gasification Dagenham 100,000 household waste 98kt SRF (long term contract from Shanks) £80M capital cost $19MW_e$, $10MW_{th}$	Construction started February 2010 Expected operational 2013	Technology partner is Canadian firm Enerkem Dagenham site bought from Novera in 2009
		Hooton Park, Eastham 200ktonnes SRF 40MW	Planning granted. Construction due to start early 2011	
		Polegate, East Sussex Recovered wood and SRF 95ktonnes/year 16MW	Planning withdrawn August 2010	
Biomass Engineering Ltd.	Wood chip, waste wood, leather wastes	Downdraft gasification Ballymena 75 kWe unit in 2001	Closed down in May 2006	Leading developer of downdraft gasification systems in the UK. Has now expanded into Germany and Italy.
		Downdraft gasification Leeds 50kg/h/230 kWth leather waste gasifier at Pittards	Demonstrator only	
		Downdraft gasification Mossborough Hall Farm, Rainford 250 kg/h wood gasifier	Closed down [Not used by site owner]	
		Downdraft gasification Banbury 250 kWe	Operational	

Company	Feed	Technology and size	Status	Comments
		Downdraft gasification Low Plains, Penrith, UK 1 MWe	Operational	
		Downdraft gasification OGEN – Stoke-on-Trent 3 MWe	Operational	
		Merthyr Tydfil 1 MWe	Operational	
Enviroparks Ltd	MSW and light industrial waste	South Wales 250kWe Pyrolysis followed by plasma gasification	Planning accepted December 2010	Technology from French company EuroPlasma
Innovation Technologies (Ireland) Ltd.	Wood, MDF, sewage sludge	Downdraft gasification [Fluidyne] 30 kWe	Available for testwork	No commercial developments
ITI Energy Ltd	Wood, MSW	1-2 MW_e modular gasification system. Wick 2 MW_e	Closed down.	Problems with first major project in Wick, which has closed down
		Teesside 6.86 MW_e planned	Permits and grid connections in place	
		Nottingham 11.4MW_e planned in (6*ITI gasifiers plus IC engines)	Full planning secured. Full IPPC permits and grid connections in place	
		North Derbyshire 3.2MW_e (2*ITI gasifiers plus IC engines) planned	IPPC permits in preparation. Grid connection in place	

Company	Feed	Technology and size	Status	Comments
		South West 11.4MW$_e$ (6*ITI gasifiers plus IC engines) planned	IPPC permits in preparation. Draft contracts finalized with utility company for grid connection	
Novera Energy Ltd.	RDF	Dagenham East London Sustainable Energy facility (ELSEF)	Carried out planning activities. No longer involved	Originally involved in Dagenham development. Project taken over by Biossence in 2009 (11) Reason stated: Novera to focus on wind energy only
Raynesway Resource Park Limited	Waste	Gasification [not specified] Raynesway Resource Park	Planning refused March 2010. Cyclamax appealed but then withdrew application Dec 2010 but plan a revised application 2011 (12)	Part of Cyclamax
Refgas	Wood waste	Downdraft gasification UEA (University of East Anglia) 2 MWe	Project status is uncertain	
Rural Generation Ltd.	SRC Willow	Downdraft gasification Londonderry 100kWe	Over 18,000 hours operation on SRC willow	Plant shut down since 2009 purely due to RGL diversifying into other activities
Sustainable Energy Ltd., Wales	Biomass	Entrained flow gasification Merthyr Tydfil in Wales 250 kWe plant	Possibly operational. Carbon Trust supported project	
Thompson Spaven	Biomass	Downdraft gasification Surrey demo site 10kWe	No commercial installations in UK	Supplied plant to Intervate for Yorkshire Water Esholt site

Company	Feed	Technology and size	Status	Comments
Waste-to-Energy Ltd.	Sewage sludge Wood Leather wastes	Downdraft gasification Anglian Water 1100 t/h BLC 50 kg/h	Neither operational Leather wastes gasifier incurred severe operational difficulties	Company not actively selling systems. No plants in operation
Wellman Process Engineering Ltd./Wellman Group	Wood	Updraft gasification, 2..5 MWe modules	Dormant	No plants in operation
Ze-gen	Waste C&D	Liquid metal gasification technology	Plant to build 2nd commercial plant in UK	US based firm
ZeroPoint / Kedco	Biomass and wastes	Staged downdraft gasification Newry, Northern Ireland 4MWe	Expected on stream 2011 £15M capital cost	Licensed by Kedco, Ireland – from CPC, Colorado, USA
		Enfield, London 12 MW_e	Planning approved £45M capital cost	

2.2 Advanced Plasma Power (APP)

APP was founded in November 2005 to commercialise the Gasplasma technology developed by Tetronics Ltd and to utilize the gasification technology of Energy Products of Idaho (EPI). Tetronics has been in operation for over 40 years using plasma solutions, mostly in vitrifying incinerator bottom ash and hazardous waste. EPI's main business is in the design and manufacture of fluidised bed combustion and gasification systems and boilers.

2.2.1 Technology

The test facility uses RDF to produce syngas for engines to generate heat and power. The gasification takes place in a bubbling fluidized bed (BFB). The fuel is fed above or directly into the bed, depending on the characteristics of the feed material. The feed undergoes extreme abrasion in the bed which tends to remove and surface deposits (ash and tar) from the particles exposing a clean surface for reaction. The heat for gasification is provided directly by the oxidation of char within the bed. The bed is usually fluidized with air, although oxygen and/or steam are also used. The APP demo-plant operates at 900^{o}C and 19-31bar pressure.

A Tetronics plasma convertor is used to crack the tar, soot and other impurities in the syngas. This process polishes the gas whilst simultaneously vitrifying the ash and organic fraction to form 'rocks'.

The electrical generating efficiency of the APP plant is stated as 35-40%. The APP plants will typically use one-third of the electricity generated to power the process, the rest would be exported to the grid.

It is stated by APP (13) that a plant treating 150,000tonnes of MSW per year would provide enough power for around 15,000 homes and enough heat for around 700. It is stated by APP that the process has a negative overall carbon footprint of -341kgCO_2/MWh compared to 430kgCO_2/MWh as the average carbon emitted from UK power generators at present.

2.2.2 Marston Gate, Swindon

Advanced Plasma Power's 1.6 t/day demo plant was relocated to Marston Gate, Swindon in 2008 in order to upgrade the plasma convertor and to install gas engines (14). It is stated in the NNFCC report on gasification of waste that APP has plans for a heat and power plant in the UK converting 137odt/day of MSW. This plant would incorporate EPI's gasification technology (bubbling fluidised bed) followed by plasma reforming to clean the syngas. No other plants are currently in operation and no details on the Marston Gate plant are available. A commercial scale plant is assumed to be ~100kt/y of MSW input. Gases are filtered in a hot gas filer after the plasma converter and then scrubbed to remove acid contaminants in the gas. Clean gases are burnt in a gas engine.

Wardell-Armstrong conducted an independent analysis of the CO_2 emissions of the Gasplasma® process; it has an overall negative carbon footprint of -341kg

CO2/MWh. Incineration produces 230 kg CO_2/MWh, and as the average carbon emitted from UK power generators at present is 430 kg CO_2/MWh.

No data on the overall plant performance is available.

2.3 Bioflame

2.3.1 Technology

The Bioflame process is a downdraft gasification system. A 250 kWe system has been built and operated, but the status of this is unclear. There appears to be a move from gasification to offering a standard combustion product.

Bioflame have more recently moved into staged combustion with power generation.

2.4 Biomass CHP Ltd. (formerly B9 Energy Biomass and Exus Energy)

This company originally operated under the name of Exus Energy, prior to that they were B9 Energy Biomass Ltd. They went into receivership in 2006 but are now back as Biomass CHP Ltd.. There have been 3 projects with varying degrees of success.

2.4.1 Technology

The technology is licensed from Gengas, Sweden and is a modular downdraft gasification technology of ~135 kWe.

2.4.2 Blackwater Valley Museum Project (BENBURB)

B9 Energy Biomass Ltd originally built this project in 1995 (15). The plant was built in Northern Ireland at a cost of £250,000 and used a downdraft, moving bed gasifier linked to a dual fuelled diesel engine to produce 400kWth and 200kWe at 415 volts from wood waste. Only a 100 kWe was installed with plans to then double the plant capacity with Blackwater II – which never happened.

In November 2006 the Carbon Trust contributed £50,000 towards a project to evaluate and improve gas cleaning and engine management (16). Funding has also been received from the DTI to develop engine catalysts, but no further information on this project has ever been published. There is very limited operational experience on this unit and numerous site visits have shown the unit to be out of use or in a state of disrepair until 2009.

The aim of the plant was to export heat to the museum and sell electricity to the grid. The plant has been rebuilt, but is not operational.

2.4.3 BEDZED

Based on early research and development at the Backwater Valley Museum plant Biomass CHP was awarded a contract to supply a 130kW_e unit to the BEDZED site in Croydon. The plant started in March 2003 (17). A gas engine was installed to be powered by the gas from the biomass gasifier. However the gas cleaning and engine control were inadequate for the engine. The tar content in the gas, although satisfactory for the Blackwater engine was not clean enough for the gas engine at BEDZED (17). The turbo charging and intercooling led to major reliability problems (17). This resulted in poor reliability and high manpower requirements. Over 5,000 hours of operating experience were achieved before the gasifier ceased operating (17). The unit was not run as full power and required a very precise wood chip to ensure reliable operation. The plant has been permanently closed down.

2.4.4 Kilwaughter Chemical Works

This was the second commercial project operated by Exus Energy – a 250kW$_e$, wood fuelled downdraft gasifier (17). In 2006 commissioning and status was unclear after Exus Energy went into receivership. The plant has now been taken over by Biomass CHP is in re-commissioning.

2.5 Biossence East London Ltd

Biossence was established in 2006 and is majority owned by Network Economy AG, a Swiss based investment company (18). Biossence has the rights to use the gasification technology of Canadian company Enerkem in the UK and Ireland.

2.5.1 Process

Biossence’s technology is the fluidized bed gasification technology developed by Enerkem in Canada with catalytic gas cleaning (19). Enerkem has 3 plants in operation in the USA and Canada.

2.5.2 Dagenham

This £80M facility began construction in February 2011 (20) and will process approximately 98,000 tonnes per annum of SRF (21). The feedstock will be supplied from the nearby Frog Island and Jenkins Lane Mechanical Biological Treatment plants operated by Shanks East London as part of a long term fuel supply contract (21).

The plant is designed to generate 18-20MW$_e$ and 10MW$_{th}$. The electrical power will be exported to the National Grid via a connection to the local EDF distribution network and Biossence is currently looking at the opportunity to sell the heat to the proposed London Thames Gateway Heat Network in Dagenham. A small amount of the power will be consumed by the facility itself. The electrical power generated from the non-fossil fuel derived fraction of the SRF will qualify for two Renewable Obligation Certificates per megawatt hour of generation as the plant will use an Advanced Thermal Conversion technology as defined in the Renewable Obligation Order (2009). Power generated from renewable sources will also benefit from Exemption Certificates under the Climate Charge Levy (21).

The plant has been part funded by and £8.9M loan from the London Waste and Recycling Board (LWARB) who also helped acquire the site from Ford (21).It is expected to create 25 permanent jobs and a further 100 jobs during the construction phase.

2.5.3 Hooton Park, Eastham

This plant was first granted planning permission in January 2008 and is expected to process 400,000 tonnes per annum of SRF (22,23). The solid refuse fuel (SRF) will be generated by commercial waste processing and treatment facilities in the region and will consist of a mixture of commercial waste from which all recyclable materials such as glass, metals, aluminium, plastics and inert materials have been removed (22). The plant will generate up to $80MW_e$ which will be exported to the National Grid.

As for the Dagenham site, the electrical power generated from the waste will qualify for Renewable Obligation Certificates per megawatt hour of generation as the plant will use an Advanced Thermal Conversion technology as defined in the Renewable Obligation Order (2009) (22).

2.5.4 Polegate, East Sussex

Biossence Polegate was a partnership between two local businessmen, Resource Rehandling Partnership Biossence, to provide a solution to East Sussex's serious landfill problem and energy supply challenges (24). The plant was to be fuelled by recovered wood and SRF. The proposed site for the facility was adjacent to the existing Cophall Wood Recycling Centre in Polegate, which already had permission for recovery operations (24). The gasification plant was to process 95,000 tonnes per annum to supply green electricity ($16MW_e$) to around 24,000 local homes (24).

Biossence Polegate undertook a full consultation process with residents, local community groups and businesses of Polegate and Hailsham prior to submission of the planning application. They conducted public exhibitions, advertised through the distribution of 14,000 fliers, in July 2009 for local residents and businesses. The planning application was submitted in August 2009 with a view to the facility being operational by 2011 but subsequently planning was withdrawn due to unknown reasons.

2.6 Biomass Engineering Ltd

2.6.1 Technology

The technology is a modular 250 kWe downdraft gasification technology with hot gas filtration. The filtered producer gas is then cooled, demisted and then aerosols removed in a wet walled electrostatic precipitator prior to use in a gas engine.

2.6.2 Technology development

Biomass Engineering Ltd. started work in downdraft gasification in 1996, following on from work initiated by its parent company Shawton Engineering Ltd. in 1995. Limited but significant funding support for the project was obtained from the DTI and the two downdraft gasifiers were constructed in 1996 and operated from 1997 onwards at Shawton Engineering Ltd. At Biomass Engineering Ltd. premises, a specific building and engine room was constructed to allow for testing of the gasifier and gas cleaning systems, with an external engine room housing the gas engines as required. The design capacities of the two gasifiers were 35 and 75 kWe and these were further developed to give reliable performance and a low tar gas. Since that time, Biomass Engineering Ltd. has been involved in several R&D projects to achieve a commercial product:

- 75 kWe commercial unit for Ballymena Borough Council [2000] (25).
- Testing of a ceramic hot gas filtration system [DTI supported project B/U1/00677/00/00] (26).
- Development of a 250 kWe downdraft gasifier for combined heat and power [DTI supported project B/TI/00800/00/00] [2003-2005] (27).
- Testing of renewable fuels in an 80 kWe downdraft gasifier [DTI supported project B/W3/00806].

These projects helped BEL develop a standard 250 kWe modular gasification system with hot gas filtration, cooling and demisting of the gas followed by a wet walled electrostatic precipitator to minimise condensable tars and aerosols in the producer gas prior to power generation. A summary of plants and operational experience is given in Table 4 below. Some of the projects are then summarised.

Table 4. BEL Gasification Plants

Plant Size, location	**Feedstock**	**Status**	**Hours operation & power generation**
55-65 kWe/60 kWth, Ballymena, NI	Wood chip	Started 2000 Centre closed 2008	> 2500 hours > 800 hours
50 kg/h/ 230 kWth unit, Leeds, England	Leather wastes	Test unit since 2002. Dormant	> 200 hours - -
250 kg/h/500 kWth unit, Rainford, England	Pine, spruce, poplar, fir	Started 2003 Dismantled 2009	> 4000 hours > 3000 hours
80 kWe test unit at Newton-le-Willows, England	Wood wastes, willow, spruce, pine, RBEF	Test unit since 1998	> 3000 hours > 500 hours
150 kWe, Culcheth, England	Mixed wood	Started 2005 Ceased 2008	> 1000 hours
250 kWe, Manor Farm, Rainford, UK	Waste woods	Started 2006	> 2500 hours
250 kWe/500 kWe, Wildhausen, Germany	Mixed hardwoods	Started 2007	> 10000 hours > 5000 hours
1000 kWe Low Plains, Cumbria,UK	Mixed wood wastes	Started 2007	> 3750 hours
500kWe/500 kWth, Dortmund, Germany	Mixed wood	Started 2008	> 2000 hours
3000 kWe O-GEN, Stoke-on-Trent, UK	Mixed wood wastes	Started 2009	> 2000 > 500 hours
1000 kWe Merthyr, Wales	Mixed wood wastes	Started 2009	> 1000 hours

2.6.3 Ballymena ECOS Centre, Northern Ireland

This was the first commercial gasification project for BEL and their only one to use a wet gas cleaning system which also cooled the gases. During testing of the gasification system on SRC willow, analyses of the product gases, wastewater and chars were made. Measurement of organics and particulates in the producer gas was performed independently by CRE, with organics content less than 15 mg/Nm^3 [15 ppm] measured in the raw gas. Several hundred hours operation on willow and poplar have been obtained, with continuous test runs of up to 8 hours coupled to a spark ignition engine.

The gas cleaning system was been developed and continually improved prior to delivery, leading to simplification mainly. The gasifier worked fully as a turnkey plant. The Centre closed down in 2008 and the unit was removed. An extensive paper on the operation and performance of the unit is available (28).

2.6.4 Mossborough Hall, Merseyside

This plant uses clean wood waste and is capable of generation 250kWe of electricity. It was connected to the grid in 2005 (27). A very detailed report on the performance of this plant, including all product analyses, tar measurements and producer gas compositions is available and is appended [Appendix B]. This project was very successful with the main limitations relating to lengthy grid connection time and changes required to the air/gas mixing system on the Iveco gas engines. The plant ceased operation in 2008 due to other BEL commitments on other projects.

2.6.5 British Leather Corporation

In April 2003, Biomass Engineering Ltd. was contracted by BLC to test leather wastes in their 80 kg/h test gasifier with the primary aim of assessing Cr (III) levels in the char and ash recovered from the process. The use of the producer gas as a fuel gas was a secondary objective. Work was undertaken in early 2003 which demonstrated that recovered ash had 5-6wt% Cr(III) content and no Cr(VI). Following these trials, Biomass Engineering Ltd. was contracted to build a new 50 kg/h gasifier for BLC to be used in a mobile facility for further work at test sites in the UK. Results are presented for onsite work at Pittards in Leeds during operation from February 2004 to May 2004 in an extensive summary (29).

The typical gas LHV was measured at 4.1 MJ/Nm^3 using wet blue buffing dust and 2 MJ/Nm3 for sludge cake. Volatile Cr(III) and Cr(VI) emissions were < 0.229 mg/Nm^3 and < 0.01 µg/Nm3respectively in the flare stack gases. Cr(III) values of 3.5wt% were measured in the ash from the work at Pittards. No further work has been carried out.

2.6.6 Culcheth, UK

The Culcheth project was an 85 kWe unit, utilising the same system as Rainford, however the gasifier design is the same as the Ballymena unit. The engine was an Iveco engine, which was previously operated at Biomass Engineering Ltd. own site and therefore was ready for operation on producer gas.

The Culcheth system was commissioned in 2005, however due to lengthy delays in the grid connection being completed and approved; the system only started exporting electricity in March 2006. The unit stopped operation in 2007 due to a change in aims by the owners.

2.6.7 Wildhausen, Germany

In 2005 Biomass Engineering Ltd. was approached by Dusseldorf Stadtwerke [DSW] with an interest in using their gasification technology in Germany for bio-energy projects with a rated net thermal input of less than 1 MWth. DSW viewed the Biomass Engineering Ltd. technology as one of the small-scale gasification systems closest to commercial realisation. As noted above, DSW employed UITA to conduct a series of tests at Rainford in 2005 including gas quality, emission analysis, operational capability, reliability and detail mass-energy balances. UITA positive findings satisfied DSW that the plant was ready for commercial introduction into their market. DSW/BEL formed a joint venture and the first plant was installed in Wildhausen, Germany and started operating in July 2006. From early April 2007 the unit has been running continuously from 100-250 kWe output, 24 hours a day. Electricity is exported to the grid. The unit has over 10000 hours with power generation.

Figure 2. Wildhausen Fuel dryer and gasification system

2.6.8 Banbury, UK

The Manor Farm project is a 250 kWe system using chipped mixed woods as the fuel. The unit was delivered on site in September 2006 and was commissioned on the waste wood. The fuel specification has not met the requirements of Biomass Engineering Ltd. and an alternative source of wood had to be obtained as used of the waste wood lead to excessive tar production and the level of debris in the material meant that the gasifier grate became blocked with tramp metal, stones, concrete and other materials.

The use of waste wood was stopped and clean chipped wood used. The unit has been running intermittently for the past 4 years with few issues.

2.6.9 Low Plains, UK

Biomass Engineering Ltd. installed a 4 x 250 kWe gasification systems for a project to generate 1 MWe near Penrith in 2006, with commissioning in 2007. The plant uses mixed woods and the electricity is exported to the grid. Heat from the system is used to dry the fuel as required.

The fuel used in the process did not meet the required specification and changes were made to the feed handling systems to improve wood distribution to the 4 gasifiers.

Also, to meet engine specifications, a venturi scrubber and prototype electrostatic precipitator was added to the gas cleaning system. This proved extremely effective in removing all aerosols, however in cold weather, condensate formation in the gas line prior to the engines became a problem – mixing the gas with cold air caused water aerosols to form, causing engine problems. The trace heating of the pipework and fitting of an additional filter have solved this issue. The unit is now run on a regular basis, exporting power to the grid.

2.6.10 Kb Oerkoenergie, Germany

A 270 kWe system, which is a replica of the Wildhausen plant, is being shipped to Germany in May 2007. This is a CHP unit using local mixed woods. The heat from the system will be used to supply hot water to a spa hotel and the power exported to grid and used on site as required. This unit started operation in June 2007 and uses local wood. The unit has over 10,000 hours operational experience and recently had a filter upgrade to reduce an issue with fine particles not dropping out of the gas in the hot gas filter. This has improved the dust removal and improved the operability of the system.

2.6.11 Stoke on Trent, UK [O-GEN]

This was the first commercial project to utilise wood waste recovered from a local amenity site and operates at 3 MWe, which is 12 x 250 downdraft gasifiers. O-GEN is the site owner and takes local wood waste and gasifies for power using GE Jenbacher engines.

The plant started operation in late 2009, however it soon became clear that the fuel handling and the quality of the fuel would be an issue. Extensive efforts have been made by O-GEN to ensure that only wood meeting the required specification is used in the process. Minor process improvements in terms of ease of removal of char and ash have been made. The process is now in regular operation.

2.6.12 Methyr Tydfil, Wales [MIS]

This a 1 MWe facility using 4 x 250kWe gasification units delivering gas to 2 GE Jenbacher engines. The feedstock is a mixed wood waste feedstock. The plant started operation in 2010 and has been operated intermittently.

Additional wood fuel drying had to be installed as the wood onsite has an unacceptably high moisture content. There have been local issues with MIS not meeting legislative requirements leading to a suspension of plant operations in 2010, including needs for adequate risk assessment compliance (30).

2.7 Enviroparks Ltd.

Enviroparks Ltd, an energy company based in South Wales, have announced plans to build a number of waste treatment centres in the UK, each incorporating a plasma gasifier. Plasma gasification is the gasification of matter in an oxygen-free environment to decompose waste material into its basic molecular structure. It does not rely on incineration but converts organic waste into a fuel gas and inorganic waste into an inert vitrified glass.

2.7.1 Technology

The technology to be used by Enviroparks is a plasma gasification process from France, for which few details are available.

2.7.2 Hirwaun, Wales

The first identified site is to be at Hirwaun in Wales, and will incorporate six separate processes including recycling, material recovery and AD to treat the majority of the waste, with plasma gasification used for the residual components. It is intended that the site will process municipal and light industrial waste, converting the residual waste to an estimated 120,000MWh of electricity through generation of a BioSynGas, refined through the use of plasma torches, which will then be used to drive a gas turbine potentially achieving efficiencies of electricity generation of 40%. This site intends to use the GHO-Power technology.

The first of four announced sites to use GHO-Power technology from French company EuroPlasma, is at Morcenx in France, a 12MW power plant that will use 55,000 tonnes of general industrial waste per annum. Planning for the plant was granted in December 2010.

2.8 First Renewables [Project ARBRE]

2.8.1 Technology

The gasification technology involves two air-blown circulating fluidised-beds (CFB) in series. The gasifier (1st CFB) employs sand as the bed material and the 2nd CFB uses dolomite as a catalyst to crack the heavy tars. Both operate at 850-900℃ and near atmospheric pressure. The product gas has a tar content of 0.5-2%vol of dry gas with a heating value of 4-5 MJ/Nm^3 (120-134 Btu/scf). The system is favourable for fuel capacities greater than 10 MWth.

The air acts as both gasification/fluidizing agent. Part of the air is injected at the bottom of the gasifier and the remainder is injected part way up the vessel. This pattern of air distribution creates a high-density bed in the lower part of the vessel, which allows the gasifier to handle relatively large-sized fuel particles. The CFB of sand particles are maintained by a superficial gas velocity of about 3-10 m/s. The pellets are gasified within the 2-2.2 seconds' residence time producing a raw gas that passes through two stages of solids separation.

The gas stream leaving the secondary cyclone of the cracker consist primarily of methane, hydrogen, carbon monoxide, carbon dioxide, nitrogen, water vapour and trace levels of heavier hydrocarbons along with particulates not arrested within the cyclones.

After the first stage of gas cooling, the gas is cleaned of residual dust in a number of parallel filters, passed through a second cooler and then to a wet scrubber to condense the significant quantities of water vapour contained within the gas. This removes ammonia and other traces of alkali compounds and the small fraction of hydrocarbons which otherwise could condense out in the gas compressor.

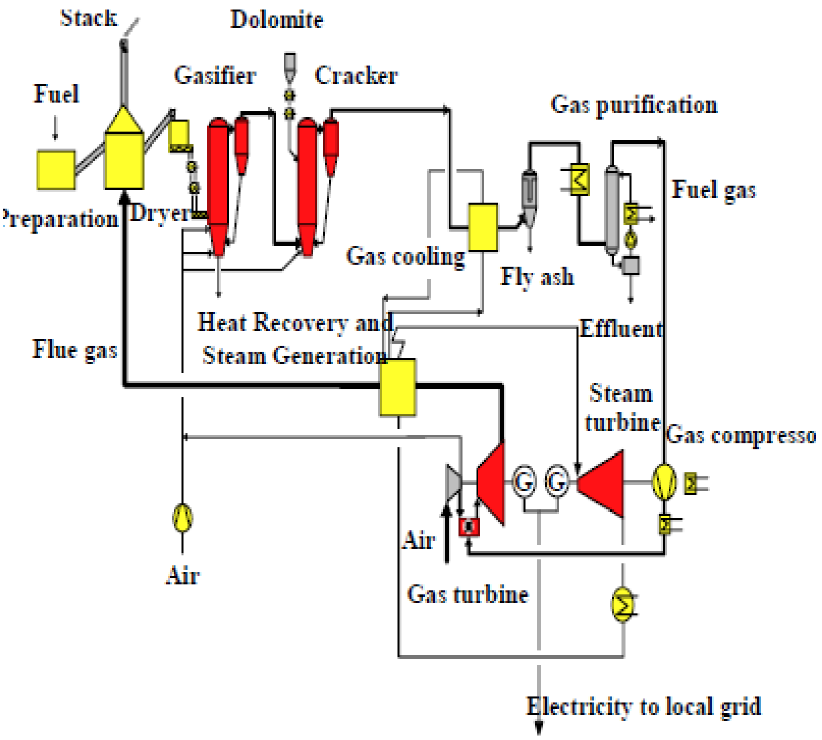

Figure 3. Schematic of TPS gasification process in BIGCC mode

Ash is removed from the bottom of the gasifier and from the filters and is directed to silos for discharge into sealed ash containers for disposal off site.

2.8.2 Gas composition

The biomass fuel used has ranged bagasse, wood chips, wastes and the gas composition is not changed significantly. The specific gas composition from wood shown in Table 5 below is taken from the ARBRE project, with the measured and the design compositions.

Table 5. Measured and design gas compositions for TPS CFB gasification at the ARBRE plant with wood chips at low pressure

Compound	**Wood (measured)**	**Wood (design)**
Carbon monoxide	13-14 %v	20 %v
Hydrogen	11-12 %v	12 %v
Methane	4-4.5 %v	4 %v
Higher hydrocarbons	3-4.7 g/Nm^3	5 g/Nm^3
Carbon dioxide	14-15 %v	15 %v
Nitrogen	50-52 %v	48 %v
Water vapour	As dry	As dry

Heating value	**Value**	**Value**
LHV, kJ/Nm^3	4500-5000	4500-5000
HHV, kJ/Nm^3		
LHV, Btu/scf	120-135	120-135
HHV, Btu/scf		

This was a large BIGCC project funded by the European Commission and called ARBRE (Arable Biomass Renewable Energy. The plant was located in Eggborough next to a power station in North Yorkshire. It was to generate 8MW$_e$ with an efficiency of 30%, utilising air blown fluidised bed technology.

The 25 MWth plant was supplied by SEC from the Netherlands with TPS as technology supplier and featured a Typhoon gas turbine (now termed SGT-100) at total installed plant cost of £30-35 million with European Commission support of 35% of the investment cost or £10 million and £3 million from THE DTI (4.8).

The plant was partially completed by the end of 1999 and starting with plant commissioning in October 2001: several design and operational problems were encountered. Due to certain design inadequacies in detailed engineering and related operational issues, the primary raw gas heat exchanger overheated and promoted plugging with carry-over solids. Hence, the plant could not be operated at design load or for extended periods.

The problems were compounded when financial pressures resulting from change of ownership, etc., did not provide the support needed to remedy the design and operational issues. As it was the original owner Kelda (formerly known as Yorkshire Water) faced economical problems and sold the project for £1 to Energy Power Resources Ltd (EPRL) in April 2002. However because of a contractual dispute (Kelda was committed to commission the plant to operation status) this led to ARBRE Energy Ltd (AEL) going into liquidation in August 2002 by EPRL and TPS.

2.9 Innovation Technologies (Ireland) Ltd., UK

2.9.1 Technology

ITI use downdraft gasification technology provided by Fluidyne, New Zealand. Two small gasifiers are available for fuels testing (31). The largest output is 30 kWe.

2.9.2 Brook Hall Estate

ITI (Ireland) had significant involvement in the early development of the gasification system operated by Rural Generation Ltd. at their Brook Hall Estate facility prior to replacement of the unit with a Fluidyen gasifier.

2.10 ITI Energy Ltd.

ITI Energy Limited is a private limited company funded by the shareholders and venture capital ((32, 33). ITI Energy Limited owns the exclusive worldwide rights to a proprietary intensified gasification system for the thermal conversion of conventional biomass and other more problematic feedstocks such as municipal solid waste, into a synthetic gas clean enough to directly fuel an internal combustion engine (33).

2.10.1 Technology

ITI have developed a patented gasification system that incorporates elements of up, down and crossdraft technology to produce syngas which is low in tars and oils. ITI Energy has also undertaken a significant amount of work on systems to clean and polish the syngas to make it suitable for use in internal combustion engines and has received performance guarantees from several major suppliers of gas engine powered electricity generation equipment.

The conversion efficiency of the engine and generator sets producing electricity from syngas is approximately 45%. ITI has made a conscious decision not to attempt to recover heat from the gas clean-up train; however heat is available from the engine water jackets and the exhaust stacks which can increase the conversion efficiency to 85%. Heat may be exported from site as hot water or steam and used for district heating as part of a Combined Heat and Power (CHP) scheme, for industrial processes or to enable further power generation from an Organic Rankine Cycle process.

ITI sell modular gasification systems. Each system has an output of ~1MW$_e$. These gasifiers are combined with an internal combustion (IC) engines to generate power. The gasification technology was developed at Newcastle University. Each module converts 1.5tonnes of RDF into 1.7MW$_e$ and 2MW$_{th}$ per hour (33).It is stated that for a plant designed to export 10MW of electricity to the grid will require a site footprint of between 0.5 and 0.75 hectares.

2.10.2 Wick

This 2MW$_e$ plant was originally part of the Caithness Heat and Power Scheme (CHAP) and was scrapped in early 2009 by the Highland Council (34). It was funded under the Bio-Energy Capital Grants scheme. The CHaP scheme was set up in 2004 to provide heat and power to 500 local homes and to generate additional income from the sale of electricity to the grid (35) The council stated that the technology was unlikely to deliver the power needed for the community scheme. The plant could not reliably and economically fulfil its objectives. The problem was the electricity generation component of the plant which was not fit for purpose (34).

Initially the company was community-owned which had three directors representing the neighbouring distillery, the local community and the Council (35). In August 2008 CHaP became a single member company. The Council took over running of the company to ensure a future for the operation. The Council made a number of efforts to improve the operation of the company from a technical, operational and economical viewpoint. The Council commissioned a full load gasification trial to confirm the gasifier's capability to run the engine at 1,500kW electrical output (35). The trial encountered a number of technical problems and the trial failed. The CHaP board concluded that given the failure of the trial and the risk and uncertainty surrounding the plants operational viability it would not be possible to meet the heat and power objectives without further investment (35). The company decided to decommission the plant. Other plants are listed on the ITI Energy website as at the planning stage:

- Teesside
- Nottingham
- North Derbyshire
- South West

2.11 Novera

Novera Energy had originally announced intentions to build a 12 MWe facility at Rainham, London. This project ran into several planning and land ownership difficulties and consequently, the project has been sold to Biossence.

2.11.1 Technology

Novera had planned to use the Enerkem gasification technology for their project in central London, which was originally sited at Rainham and has now been "renamed" to be sited at Dagenham by Biossence [see Section 2.6 above].

2.12 Refgas

The company was formed in 2007 and developed the gasification technology with support from the Welsh Assembly's SMARTCymru scheme (36). The systems are sold as separate modules.

2.12.1 Technology

The technology is a downdraft gasification process and units are sold in modules. These are available as a 1MW unit (see Figure 4) or a 4MW unit (see Figure 5). It is claimed that the gasifiers can process waste as well as biomass feedstocks (37).

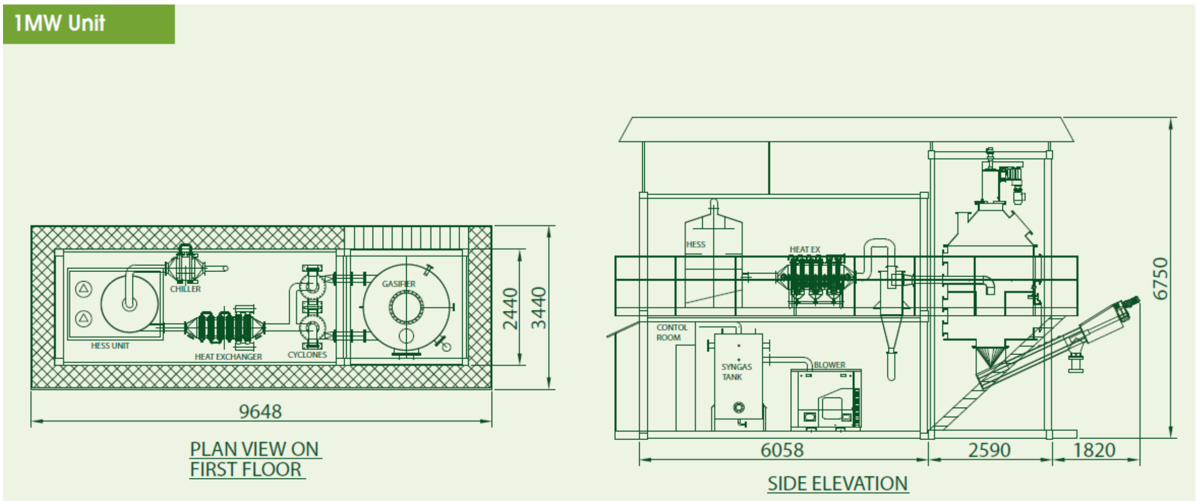

Figure 4. Refgas 1MW unit (37)

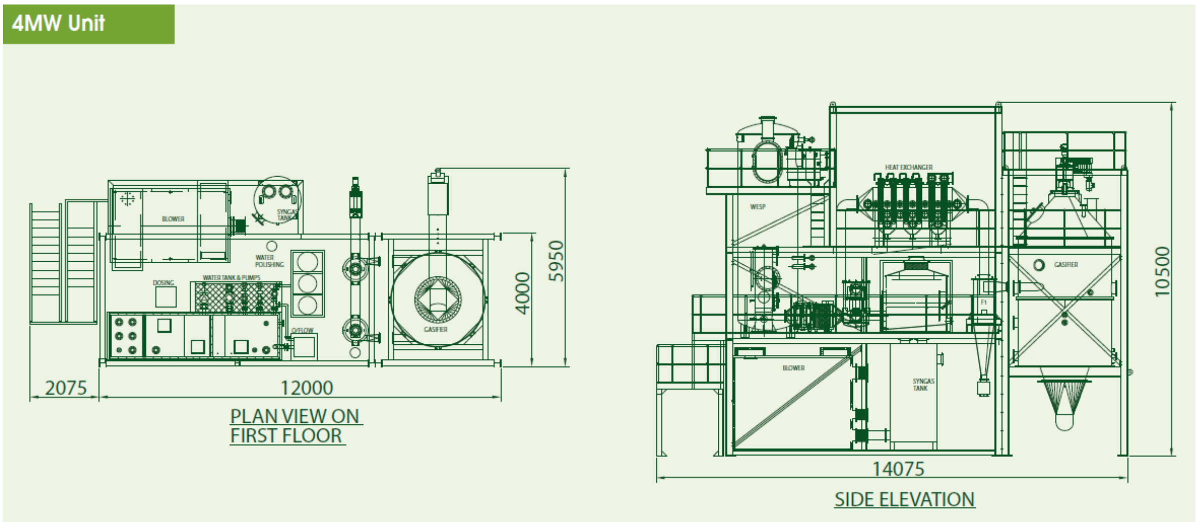

Figure 5. Refgas 4MW unit (37)

2.12.2 University of East Anglia

The plant consists of a 4MW CHP plant to provide heat and power to the Norwich campus. The UEA already had a gas fired CHP and looked to a biomass fired system to meet the increasing heat and power demand, whilst improving CO_2 emissions (38). It was stated that a biomass fuelled CHP would lead to a 24.5% reduction CO_2 compared to 1990 (38).

It would appear that the plant is not operating at full capacity and that there are a range of commissioning issues which are currently being redressed.

2.13 Rural Generation Ltd.

2.13.1 Technology

The present system is a downdraft gasification process supplied by Fluidyne, New Zealand through their agent ITI (Ireland) Ltd. The prior unit was from Belgium and did not perform to expectations, necessitating 2 hours maintenance on a daily basis to remove tars from the system. This was replaced by a Fluidyne gasifier in 2005. The present system has 3 cyclones in series, followed by a water scrubber, as shown in Figure 7. The unit is now dormant.

2.13.2 Brook Hall Estate

The target fuel for this plant was short rotation coppice willow and the target output was 100kW$_e$ and approximately 150kW$_{th}$ using a dual fuel diesel engine (39). The original plant was upgraded between 1997 and 2002 in order to improve the performance and reliability of the system. There was further development from February 2002 onwards in preparation for the arrival of a Bowman Power Systems (BPS) CHP gas turbine unit (39).

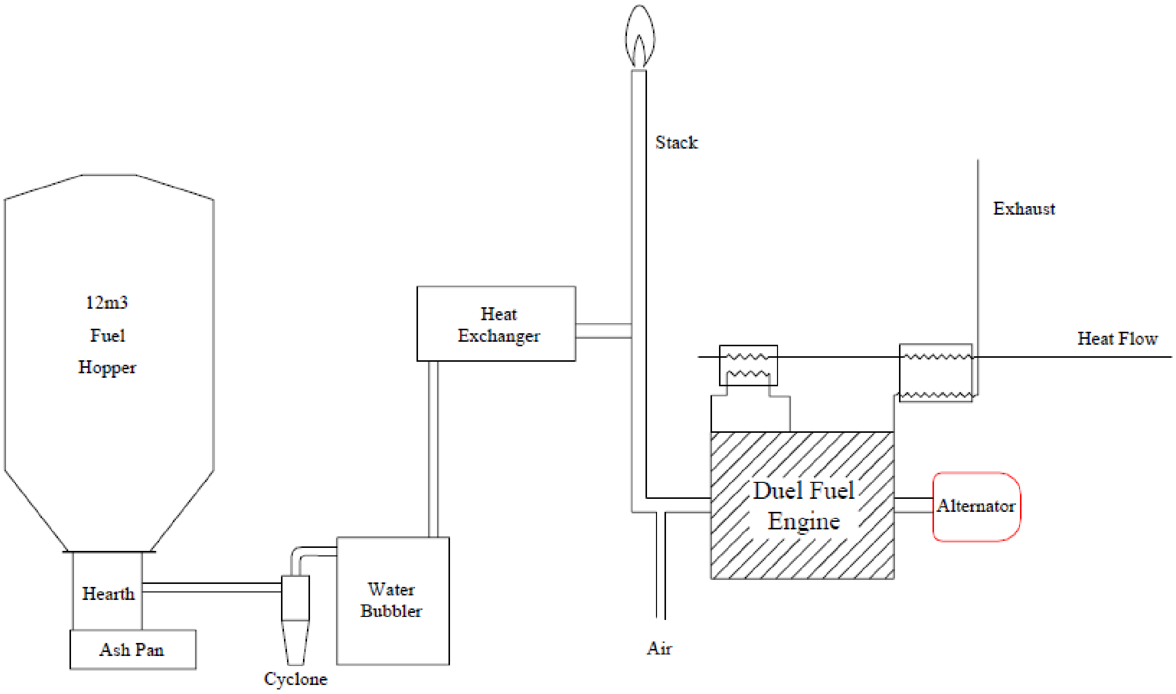

Figure 6. Brook Hall Estate original system (39)

There were a number of problems with the original system including the level of tar in the gas and fuel feed from the storage hopper. Engine control, grate blockages and inadequate pressure release in the hopper also caused problems. A number of improvements were made to the system to overcome these problems (see Figure 7).

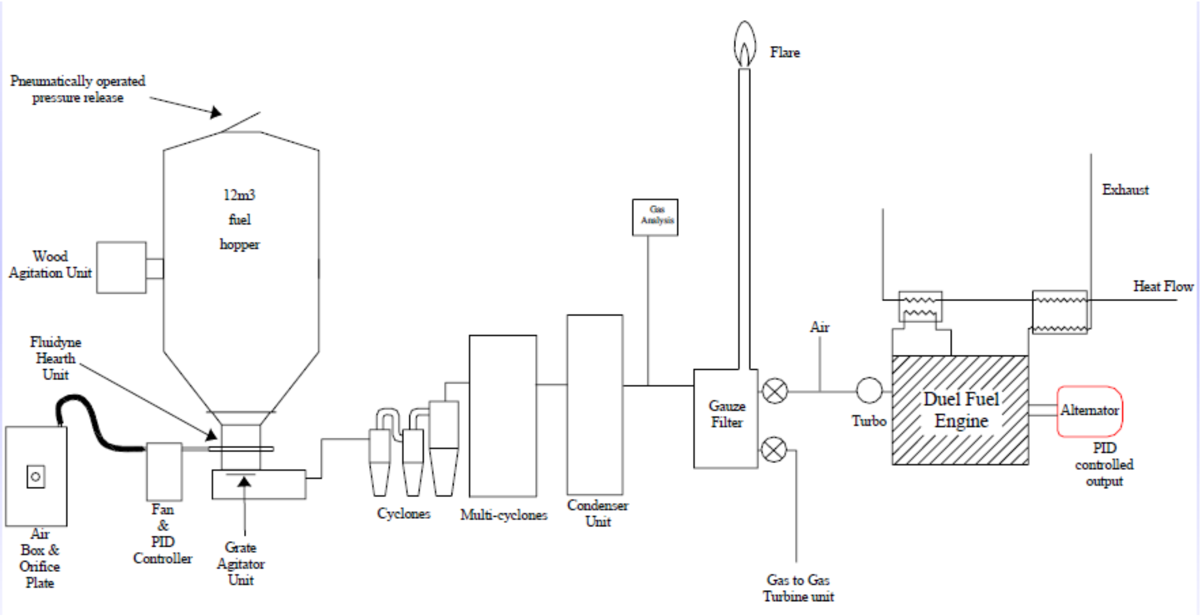

Figure 7. Spring 2003 improved Brook Hall System (39)

The gas composition is shown in Figure 8. After 2003 there were still ongoing issues with (39):

- Fuel specification and fuel flow
- Gas continuity
- Continuous feed and ash removal
- Ease of maintenance and access
- Gas cleanliness for gas turbine systems

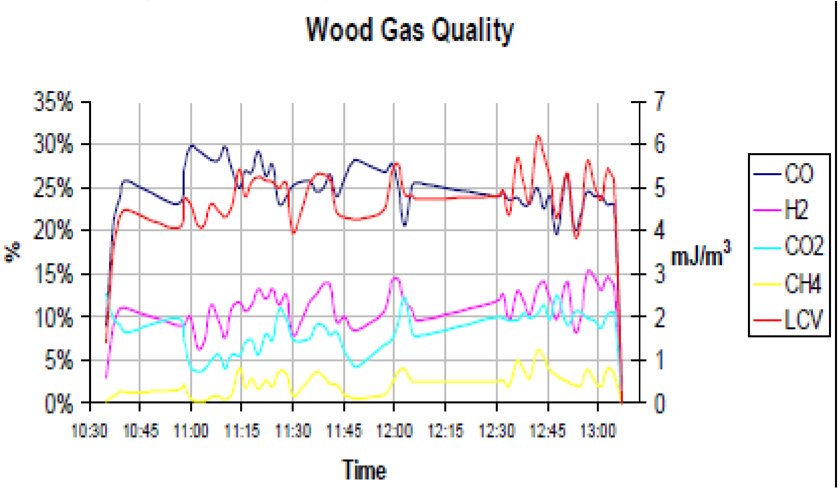

Figure 8. Brook Hall gas composition (39)

This is one of the more successful downdraft gasification projects in the UK with over 18,000 hours operational experience on locally grown SRC willow. RGI has closed the plant not for technical reason, but purely on the basis of diversification of activities into bioremediation and other related work.

2.14 Sustainable Energy Ltd., Wales

2.14.1 Technology

Sustainable Energy Limited, based in Wales, has developed an entrained flow gasifier for biomass. The claimed benefit of entrained flow gasification technology is that char and ash are recirculated to the gasification process, leading to a greater syngas yield.

2.14.2 Merthyr Tydfil Demonstrator

Sustainable Energy Ltd. state that the use of such a system will lead to an increase in gasification efficiency of 2-3% (40). Working with Cogenco as part of a Carbon Trust project to design, test and optimise a recirculation system on a prototype 50kW$_e$ biomass CHP plant (40). From the experience of this plant an optimised full-scale system was to be designed constructed, tested and coupled to a 250kW$_e$ CHP plant. The project was due for completion in October 2009.

No further details on the status of this system are available.

2.15 Thompson Spaven

The company has existed since 1936 and have been involved in mechanical, electrical and chemical engineering projects. In recent years Thompson Spaven design and build gasification systems for small decentralised biomass energy projects (41). They offer modular technologies for electricity and heat generation.

2.15.1 Technology

The gasifiers utilised in the modular units are co-current (see Figure 9). Their standard modules are 50kW$_e$ and 100kW$_e$, but they state that they are capable of producing gasifiers from 50kW$_e$ up to 500kW$_{e.}$ They also supply modules for gas cleaning using ceramic filters followed by sealed tank water scrubbing (41). Furthermore they supply modular spark ignition gensets for generating heat and power (41). The modules were designed in partnership with Intervate Limited.

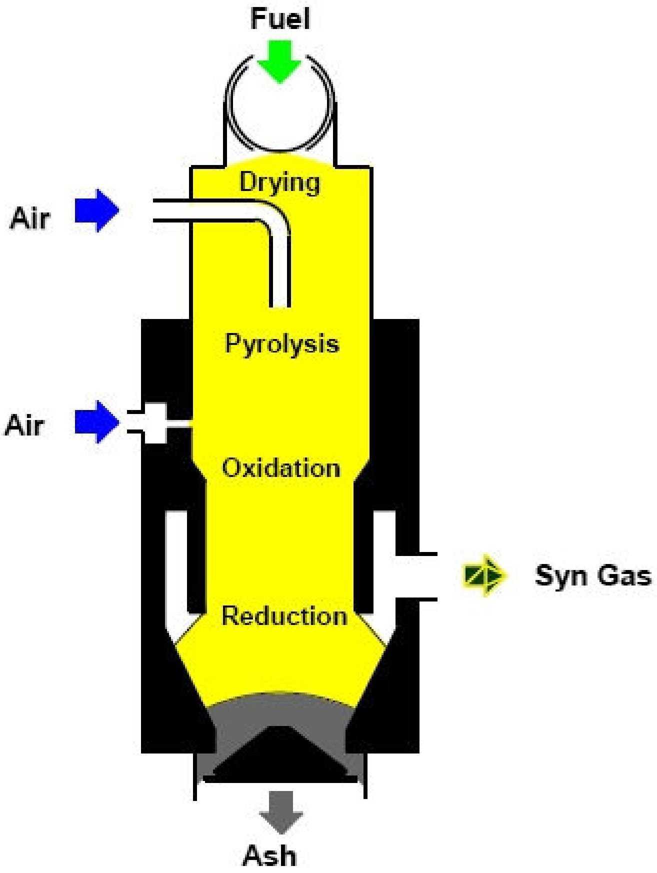

Figure 9. Thompson Spaven gasifier diagram (41)

There are no active projects in the UK and no further details are available.

2.16 Waste to Energy Ltd., UK [formerly Ventec]

Waste-to-Energy Ltd. has been in existence, formerly as Ventec, for over 17 years and has 2 notable projects, one for Anglian Water and one for BLC.

2.16.1 Technology

The Waste-to-Energy technology is a downdraft process. The gases are cleaned by wet scrubbing in a 1 or 2 stage system. Gas used to drive gas or modified diesel engine. Wide range of fuels briquetted before use for consistency. 15-20% MC fuel required, but system can incorporate drier. Regard wood waste as an easy fuel. They have “2 or 3” small scale systems (50kWe) in operation as well as larger systems. Roughly 1:1 electrical to thermal output. 50kWe from ~100 kg/hr fuel supply. Would use modified diesel engine.

2.16.2 Anglian Water

The Anglian water project was for a 1100t/h plant to process dry and briquetted sewage sludge at Broadholme in 2000 (42). This process combines a dryer, a gasification unit, and a CHP unit to help Anglian Water process 1,200 tons per year of dry sludge while generating 0.25–0.33 MW for the facility. The plant closed down in 2003 – the exact reasons are unclear. The plant cost was very high at £1.5m.

2.16.3 British Leather Corporation

Waste to Energy was also contracted out to the British Leather Corporation (BLC) to process the waste leather into energy. The ash content from the process seems to be suitable for recycling since it has a significant amount of chrome, which is used significantly in leather manufacturing.

The project ran into difficulties in producing a clean gas from the briquetted leather dust and soon BLC terminated the project with WTE. Biomass Engineering Ltd. were then contracted to take over the project and replace the gasifier in 2003 (29).

The recent death of the managing director has made obtaining detailed information about the system difficult. The website has not been updated in more than 8 years.

2.17 Wellman Process Engineering Ltd./Wellman Group

2.17.1 Technology

Wellman has designed and supplied its updraft fixed-bed gasifiers for a variety of uses. The company has been in the gasification business for 70 years and has designed reactors for bituminous coal, lignite, and coke. The Wellman gasification technology is a modular 2.5 MWe updraft process with regenerative dolomite tar cracking to reduce tar levels and give a cleaned gas for use in engines. It is based on their coal gasification technology that was used 100 years ago to supply "town gas" in the UK.

The company has no commercial projects, though has been selected as the technology of choice in public tenders, none of these have proceeded to a formal project. The DTI commissioned a detailed study of the 2.5 MWe modular process in 2000 which is available (43). Wellman have now moved into integrated waste processing using the STAR system offering the option to convert the subsequent fuel in a gasifier (44).

2.18 Ze-gen

Ze-gen is a US based firm who plan to build their second commercial waste gasification plant in the UK (45). Ze-gen recently showcased their new gasification technology at the Energy from biomass and waste (EBW) conference in the UK (45).

2.18.1 Technology

The technology called liquid metal gasification can produce tar free syn gas from waste materials including construction and demolition (C&D) and wood waste.

There do not appear to be any plants in operation in the UK.

2.19 Zeropoint/Kedco

Zeropoint was formed in 2006 and has established four international joint ventures in the UK, India, Europe and Malaysia. Kedco have partnered with Zeropoint to provide combined heat and power solutions in Europe. In March 2007 Zeropoint's first commercial scale biomass gasification system was commissioned successfully (46). The system was commissioned using hardwood pellets manufactured for home heating systems.

2.19.1 Technology

The CPC licensed technology via Zeropoint is a staged gasification process, with multiple air inlets in a downdraft design. The systems are standardised, modular and skid mounted. In 2009 Zeropoint patented a method for controlling the gas composition produced during gasification by introducing steam and oxygen through a number of injection rings (47). Conversion efficiencies of greater than 85% are claimed (48). Each system will convert ~10,000 dry tons per year of biomass into syngas, equivalent to 2MW$_e$..

2.19.2 London

In September 2010 Kedco announced that it had planning permission to build a gasification plant in Enfield, North London (49). Kedco has already signed a 10 year feedstock supply deal with a local waste supplier. The plant is expected to cost £45M and will convert ~ 60,000tonnes of waste wood.

2.19.3 Newry, Northern Ireland

Construction of this plant was almost complete in November 2010 (49) at a capital cost of £15M. The plant is to generate 4MW of electricity and the first 2 MWe are expected to start operation in April 2011.

2.20 Conclusions

The vast majority of the recent and ongoing operational plants in the UK are operating on biomass and clean wood waste, with very limited activity on wastes and no ongoing plants running on MSW or related wastes, mainly due to technical incompatibility.

Several technologies have been imported to the UK from Sweden, Canada, India, France, USA and these have met with mixed success.

3. UK AND IRELAND PYROLYSIS

3.1 Introduction

The development of waste pyrolysis in the UK has been mixed, due to the low cost of landfill and the high cost of the technology and in some cases environmental compliance. There are more indigenous pyrolysis technologies than gasification technologies, though the path of technical development has been modest.

Companies have been identified as operating in pyrolysis in the UK, as indicated in Table 6 overleaf. 17 companies are identified and reviewed. There has been more activity in the UK on waste pyrolysis than waste gasification; the principal reasons are:

- The pyrolysis process can be more controllable as all the heat is supplied externally and therefore the temperature of decomposition of the waste material can be better controlled to reduce emissions of metals.
- Less preparation of the feed material is needed
- Can handle high ash materials with low melting points (reducing atmospheres)
- Can be used to optimise yield of solid char, liquid or syngas.
- Metals and other contaminants can be concentrated in the solid residue
- Gas heating value is much higher than an air blown gasification process and therefore there is a lower duration on the prime mover.

Other considerations are:

- Feedstock must be relatively well dried – less than 10wt% moisture
- Use of waste containing plastics or other hydrocarbons can lead to excessive levels of H_2 in the gas which can be detrimental to engine performance.

Table 6. UK Waste Pyrolysis Processes for Heat, Power and Products

Company	Feedstock	Technology, Size and locations	Status	Comments
Bedminster International	Waste	Lostock Works, Northwich, Cheshire 180,000 t/y MBT-pyrolysis integrated facility	Planning permission granted in 2008 Construction began on the MBT facility in 2009	
Biomass Engineering Ltd.	Softwood	Fluid bed, 250 kg/h Newton-le-Willows	Construction	Project on hold due to a lack of funds
Brightstar Environmental SWERF	MSW	Wollongong, Australia 25,000 t/y Gas engine	Operational 2001-2004 Closed down since March 2004	No funding from Energy Developments Limited
	MSW	Canterbury, Kent 165,000 t/y	Not known	
	MSW	Sinfin Lane, Derby 220,000 t/y	Planning permission granted On hold	No funding
Charlton Energy Ltd.	Wood	0.5 t/h rotary kiln 7 t/h scale up planned Frome	0.5 t/h plant built	Project stopped. Ecotran Ltd was the technology provider and has closed down. No part of First London Power
Cynar Plc	Waste plastics	County Laois near Portlaoise 10 t/d of waste farming plastics into 7,500 litres of synthetic diesel fuel	Operational	The company is trying to commercialise the technology
	Waste plastics	SITA London 6,000 t/y	Expected to be commissioned by the end of 2011	SITA is planning to build 9 more plants at a rate of 2-3 per year

Company	Feedstock	Technology, Size and locations	Status	Comments
Energy Flow Ireland Ltd. (Ireland)	Poultry Litter Tyres	Mobile fluid bed pyrolysis 1-50 t/d No known	No plants in operation	Licensee of the ABRI, Canada pyrolysis technology and E-Sun Science tyres pyrolysis process
EPI Ltd.	Wastes including C&I waste, industrial wastes, cardboard, MBM, clinical wastes	Fixed bed high temperature pyrolysis 0.5 t/h demonstrator Westbury	Dormant	Test unit only
	C&I wastes, RDF	1 t/h Mitcham	Commercial demonstrator	Power generation capability being installed
	C&I wastes	5 t/h plant	Commissioning	
FLI Environmental (3NRG)	Wastes	Bridgend, Wales 100,000 t/y Autoclaves-pyrolysis 5 MW steam turbine	Planning permission granted	PTE has been selected to construct the plant
First London Power	MSW, industrial wastes, tyres, biomass	East London 0.5 t/h	Pilot plant, operational	Modules of 0.5 and 3 t/h dry feedstock
GEM Ltd	MSW & other wastes	0.5 t/h, Port Talbot, South Wales	Operational since 1997	Prototype unit for testing
	MSW & other wastes	1.5 t/h, Bridgend, South Wales	Operational in 2001-2003 Back to service in 2007?	150 kW Reciprocating gas engine for testing
	Poultry waste	3 x 1.5 t/h Banham Power, Attleborough, Norfolk	Granted planning permission in 2005, successful IPPC application in 2004	Banham Power chose GEM as the technology provider. No current information on the project.

Company	Feedstock	Technology, Size and locations	Status	Comments
	Tyres derived fuel	3 x 1.5 t/h Intrinergy, Coshocton, Ohio, USA (GEM America)	One unit operational since 2009. The status of the other two is not known.	Four 1 MW GE-Jenbacher reciprocating engines and one boiler planned for energy production
	MSW	1.5 t/h (12,000 t/y) Scarborough Power Ltd (SPL), Seamer Carr, N. Yorkshire 1.8 MWe	Commissioned in 2010. Not in full continuous operation.	One of Defra's NTDP 886 total operating hours 584 tonnes of MSW processed In April 2009 SPL entered into a Creditors' Voluntary Arrangement
	MSW	4.5 t/h Spain	Not known	
	MSW	WP2, Haybridge, Somerset 6 MWe	Operating permit granted in 2009 Construction expected to be completed in 2012	WP2 has chosen GEM as the technology provider
Global Advanced Recycling Technology Company Ltd.	Waste	500-1500 kg/h Pyrolysis unit for waste reduction	The company went in liquidation in 2009	Supplier – now offering only a prepared feedstock
Hudol Ltd	Wastes	High temperature pyrolysis process Rhymney pilot plant	Operational	Small capacity
	Wastes	Tythegston (Bridgend) test plant	Problems with emissions	A 3NRG plant has been granted permission at the same location

Company	Feedstock	Technology, Size and locations	Status	Comments
	Wood waste	Barry Docks South Glamorgan 75,000 t/y 9 MW Sunrise Renewables	Planning permission granted in July 2010	Prestige Thermal Equipment (PTE) (licensed Hudol technology) will construct the plant
Inetec/EnCycle	Food waste and non-recyclable packages	Immingham, NE Lincolnshire 180,000 t/y (500 t/d) 24 MWe GEM technology	Planning permission granted in 2007	Most likely abandoned EnCycle web-site is not loading
New Earth Energy	Waste derived biomass rich fuel	Canforth MBT plant in Dorset 5MWe	Commissioning	UK technology provider
	MBT residue	Dorset Green Technology Park, Winfrith 10MWe pyrolysis	Planning application approved	
	Biomass rich fuel	Blaise Farm in-vessel composting facility, Kent 3 MW pyrolysis plant	Planning application submitted	
PurePower Ltd	Mixed waste wood	Huntingdon, Cambridgeshire 49,000 t/y/ 4MWe Jenbacher 620 engines	Commissioning/operation	PTE has constructed the plant
WasteGen	See non – UK plants			
Wellman Process Engineering Ltd.	Wood sawdust	Fluid bed with heat recovery and re-use of byproducts 250 kg/h	Closed down 2002	Excessive permitting costs under IPPC meant the company did not pursue R&D work on the plant

3.2 Bedminster International

Bedminster International is headquartered in Dublin with offices in Boston and London and controls the world rights to the Bedminster BioEnergy Technology, including all intellectual property, patents and trademarks. Bedminster Bio-Conversion (1970 to 1999) and Bedminster AB (1999 to 2003) developed the Bedminster Technology as a waste to compost solution for municipalities in the USA, Australia and Japan. In June 2003, Bedminster International Limited acquired the world rights to the Bedminster Technology including the patents and trademarks. Since 2003 Bedminster International has developed the Bedminster BioEnergy Solution.

3.2.1 Process

The Bedminster Technology is a rotary kiln based pyrolysis process and can be configured to produce either a biofuel or compost material. In each case the initial part of the process uses the patented Bedminster Digester to efficiently separate the waste into biodegradable and non-biodegradable fractions. The biofuel is loaded into the pyrolyser and is indirectly heated in an oxygen depleted atmosphere to be converted into an energy-rich syngas. This prevents the formation of unwanted harmful compounds such as dioxins and furans associated with conventional combustion. The syngas is passed through a gas cleaning stage prior to being stored in gas storage tanks.

The syngas is fed to gas turbines or gas engines that power the electrical generators to produce renewable electrical energy. The syngas is subjected to such high temperatures within the turbines/engines that any traces of dioxins and furans are completely destroyed. Exhaust heat produced by the turbines/ engines is reused in a heat recovery steam turbine to increase the overall electrical conversion efficiency. This results in an available net electrical output power of approximately 1.0MW to 2.0MW per 40,000tpa of MSW input (dependent on waste input) (50).

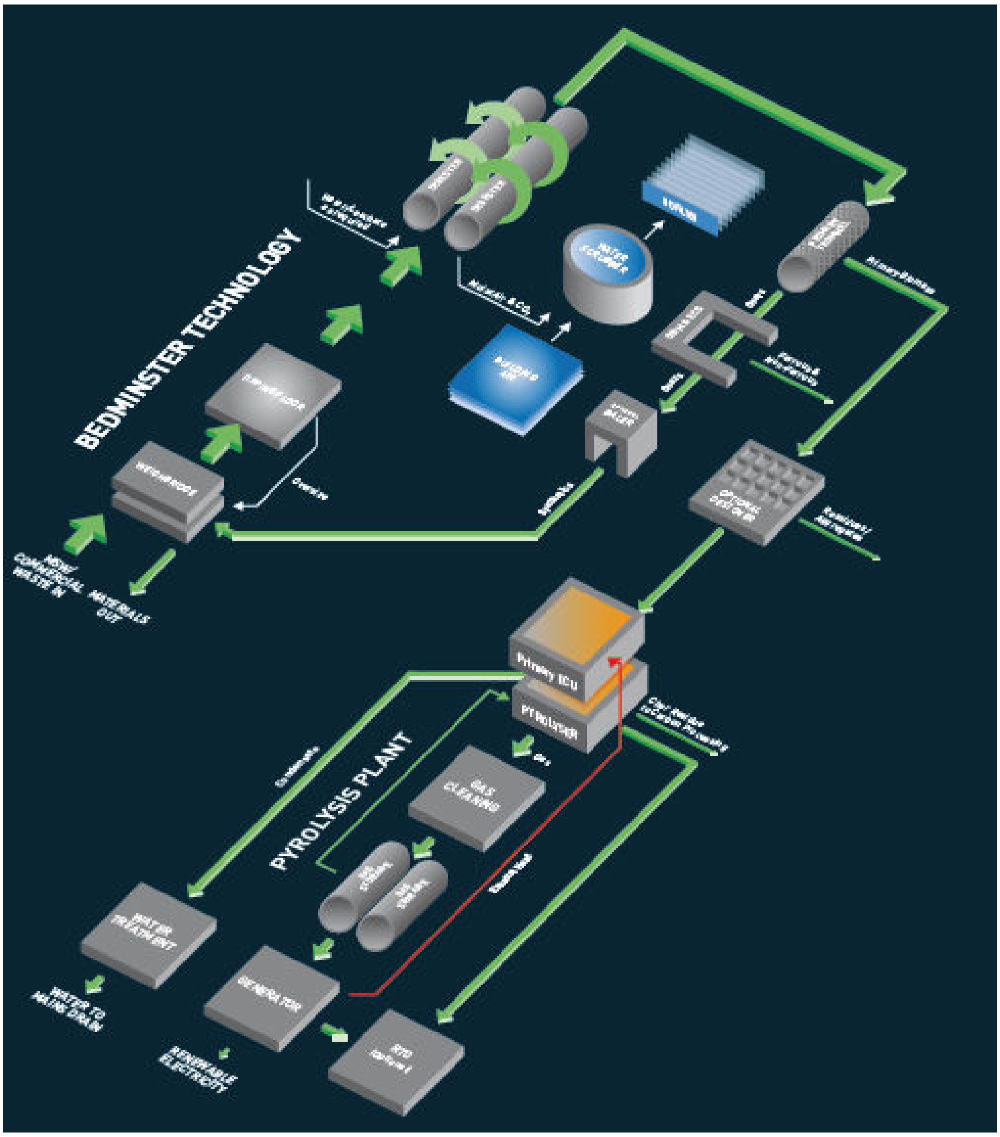

Figure 10. Bedminster Bioenergy Solution process diagram (50)

3.2.2 Lostock Works, Northwich, Cheshire

A joint venture between Bedminster International and Organic Waste Management has secured planning permission from Cheshire County Council to establish a £35 million Bedminster BioEnergy facility at Lostock Works, in Northwich (51). Construction work begun in August 2009 on the £15 million waste treatment facility which aims to use mechanical biological treatment (MBT) technology to process up to 180,000 tonnes-a-year of both commercial and local authority waste (52). The pyrolysis plant has not been progressed yet.

3.3 Biomass Engineering Ltd.

Biomass Engineering Ltd. are in the process of building a 250 kg/h fluid bed pyrolysis process. Due to a lack of funds and a focus on their gasification systems, work has halted. It is hoped to restart in late 2011/early 2012.

3.4 Brightstar Environmental - SWERF

Brightstar Environmental is a subsidiary of Energy Developments Limited (EDL) one of the world's leading renewable power producers with projects in Australia, North America, Europe and Asia. Through its relationship with Energy Developments, Brightstar Environmental has access to a substantial project development, finance, technical, manufacturing and operations capacity. Brightstar Environmental has offices in Australia, the United Kingdom and the United States of America. Brightstar Environmental is developing projects around the world. Their core business is the development, ownership and operation of SWERF®.

Brightstar Environmental revealed that Energy Developments Limited has decided to stop any further funding for Swerf schemes (53). Marketing of the technology in the UK is still continuing (179).

3.4.1 Technology

The Brightstar pyrolysis technology is an externally heated pipe coil, similar to other more conventional rotary kiln process. The overall process description is:

- Waste sterilisation in rotating steam autoclave at temperatures between 130ºC to 150ºC;
- Recovery of recyclables from cooked waste in materials separation plant;
- Drying of residual waste using steam;
- Fuel storage;
- Pyrolysis in series of externally heated pipe coils to produce syngas and liquid fuel;
- Syngas cooling and cleaning;
- Power generation using gas engines;
- Char (containing 35% to 40% carbon) is intended to be landfilled;
- Liquid fuel used for steam production and heating of pyrolyser.

3.4.2 Wollongong, Australia

A demonstration plant was commissioned in 2001 in Australia but operated intermittently and at an output of 25,000 t/y compared to the design capacity of 100,000 t/y. Gas engines were employed for power generation, but the exhaust gases did not meet WID limits. WID does not apply in Australia. For the UK market, Brightstar Environmental intends to treat the engine exhaust gases to meet WID limits but this treatment has yet to be demonstrated by the company (179). The Wollongong plant has been shut down and Brightstar's general manager, Peter Cumberlidge, confirmed that the company, and the Swerf technology, was no longer "active" (54).

3.4.3 UK plants, Kent and Derby

In the UK, Brightstar has contracts to build SWERF plants in Kent and Derby. Brightstar has worked with Brett Waste Management, who has a contract with Kent county council to build a 165,000 t/y capacity SWERF in Canterbury. The company has also obtained planning permission for a plant sited in Derby for up to 220,000 tonnes of municipal waste per year (55).

Brightstar UK, in Sinfin Lane revealed that its search for funding had been fruitless. The company, which is developing the Swerf technology, said that it was "considering its options" but admitted that it would not be able to build the plant in Derby without new cash (53). The Swerf recycling plant scheme has been shelved with the Sinfin Lane site remaining untouched, and in four years Brightstar has not handled a single tonne of waste from Derby (54).

3.5 Charlton Energy Ltd.

Charlton Energy Ltd in Frome, Somerset -received £2m from the Bio-Energy Capital Grants Scheme in 2003 to build a 7MWe and 7MWth CHP plant fuelled by forestry wood fuel and energy crops from local farmers and foresters (56, 57, 58).

3.5.1 Technology

The pyrolysis technology was designed by Ecotran Ltd., which was a rotary kiln based technology.

Attempts have been made at various times to discuss this project with Charlton Energy, but calls have never been returned. It is understood that a 0.5 t/h demonstrator was built and operated, but then closed down. No further information is available. It would appear that the technology used for Charlton Energy is now the same technology used for First London Power and most likely is the same 0.5 t/h demonstrator unit.

3.6 Cynar Plc

Cynar offers a sustainable waste solution, diverting plastic waste from landfill, utilising the embodied energy content of plastics and producing a highly usable commodity. The Cynar technology converts a variety of waste plastics into low sulphur hydrocarbon fuels incorporating liquefaction, pyrolysis and distillation. The process can handle most waste plastic types that are currently sent to landfill or incinerated (59).

Cynar is seeking to commercialise this technology in the UK and Ireland, including manufacturing, sub-licensing and operation.

3.6.1 Technology

The ThermoFuel technology is a system that converts a variety of waste plastics into high quality, low sulphur diesel that complies with EN590. The technology incorporates Liquefaction, Gasification, Pyrolysis, Catalytic Breakdown and Distillation to produce a high energy diesel fuel suitable for common road use, in all engines with no modifications required. The plant can handle most waste plastics which are currently being sent to landfill or incinerated. Contaminated plastics such as films, sheets and Municipal Solid Waste (MSW) recaptured plastics with a wide variety of residues can be treated. Each plant can process up to 20 tonnes of waste plastics per day, producing up to 19,000 litres of fuel products at a conversion rate of 95%. Each plant will divert 6,000 tonnes of plastics per year away from landfill (60).

3.6.2 Portlaoise, Ireland

This demonstration plant, which is currently converting 10 tonnes of waste farming plastics per day into 7,500 litres of compliant synthetic diesel fuel, is located in County Laois near Portlaoise. The diesel fuel can be used in existing vehicles without the need for modification (60).

3.6.3 London, UK

Waste management and recycling company Sita has teamed up with Cynar to convert plastic waste such as carrier bags and yoghurt pots into vehicle-grade diesel fuel. The companies agreed to build ten plants in the UK to convert 60,000 t/y or 4% of the UK's non-recyclable mixed plastic waste into fuel. The first 6000 t/y plant – the first of its kind in the UK - will be based in London and is due to be commissioned by the end of 2011. After that, Sita plans to build the remaining plants at a rate of 2-3 per year. The companies will use Cynar's pyrolysis process to vaporise the plastic and separate it from non-plastic materials, before separating it into its various fractions in a distillation column. The hydrocarbons are then cleaved to produce a diesel fuel with the correct average carbon chain length, and water and other contaminants are removed in a centrifuge (61).

3.7 EPI Ltd. Environmental Power International (EPi Ltd.)

EPi is a UK based pyrolysis company focused on 1 MWe modular systems to convert a broad range of wastes. EPI has experience in processing MSW, C&I, woodchip, mixed plastics, meat & bonemeal, pelletised sewage sludge and clinical wastes. The flexibility of the technology allows a braod spectrum of materials to be processed and allows the use of additives and wide process control of the pyrolysis process.

3.7.1 Technology

EPI has its own patented fixed bed pyrolysis process, operating at temperatures over 800-1000° to produce a syngas for power generation (62). Material is drawn over a fixed heated surface until pyrolysis is complete and then dropped off the heated surface. The resultant char is removed and cooled. Gases are dedusted and then cooled and quenched to give a clean syngas for power generation. The overall process description is:

- Prepared feedstock from MSW received to feed storage bin [Integral drying if required using process waste heat].
- MSW feedstock conveyed to lock hopper system and sealed.
- Feedstock fed into pyrolyser operating at >850℃
- Material converted to syngas and char.
- Char product recovered from end of pyrolyser, cooled and stored. Used as soil conditioner, alternative fuels and/or fertiliser.

- Syngas cooled and conditioned in 4 stage scrubbing system [1st stage cyclone; 2nd stage oil scrubber, 3rd stage water quench, 4th stage turbo scrubber]. 97-99% removal efficiency
- Cooled syngas fed to gas engine(s) and/or flared and/or burned for heat.

3.7.2 Energy Balance

An energy balance for the EPI process is given in Figure 11.

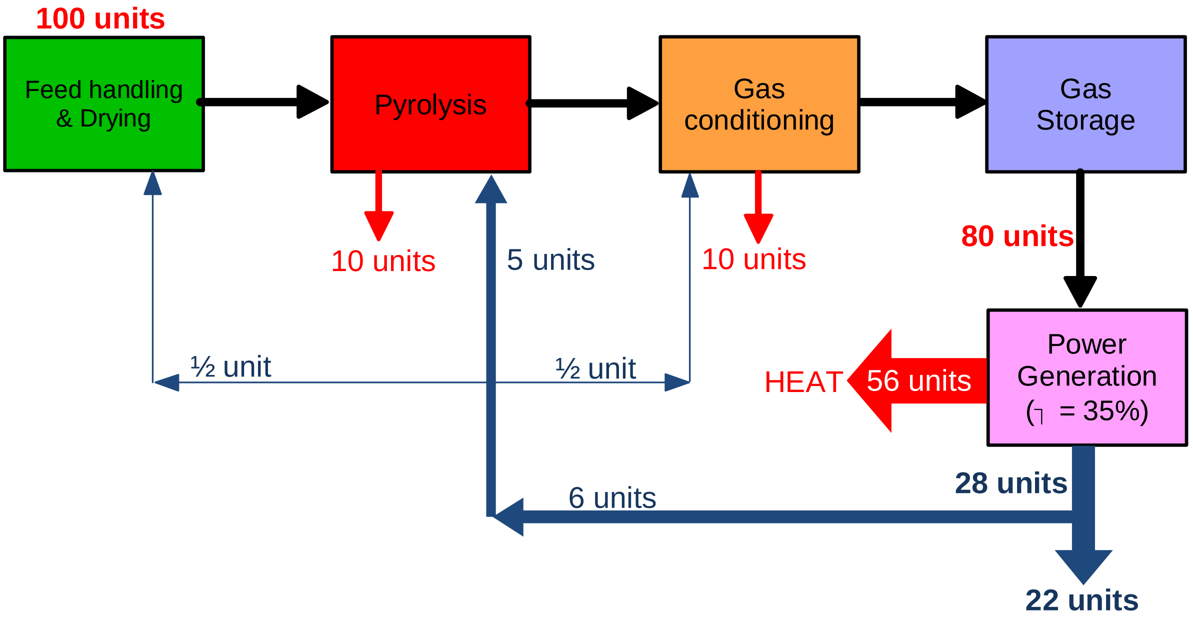

Figure 11. EPI Energy Flows

Typical gas compositions are given in Table 7 (63). As can be seen th gas LHV for C&D wastes is very high.

Table 7. EPI Gas compositions

Feedstock	wood	C&D waste
CO	41	28.3
CO_2	12.9	13.5
H_2	20.4	10.8
CH_4	16.7	23.3
C_2H_4		10.9
C_2H_6	0.24	3.6
C_3H_6		3.7
C_3H_8	0.01	0.34
C_4+C_5		0.1
N_2	2	1.7
LHV [MJ/Nm^3]	14.9	23.1

3.7.3 Emissions Compliance

Data for final plant emissions are given in Table 39.

3.7.4 Mitcham

EPi has a 12 t/h demonstrator operating in Mitcham, SW London. This plant has been in operation since 2009 and has accumulated over 5000 hours of operation on a wdie range of materials, namely C&I, C&D wastes, waste cardboard, MBM and other wastes. An engine for power generation and export will be installed on site in the next month. A picture of the plant is shown in

Figure 12. EPI plant, Mitcham

3.7.5 Costs

The costs for a 5 MWe plant are estimated to be approximately £7.5M, depending on the exact scope of supply with operational costs of £0.8M/y. The estimated disposal cost for MSW derived material is ~£55/t.

A number of plants are currently in manufacture for clients both in the UK and overseas.

3.8 FLI Environmental (3NRG), Ireland

F.L.I. Environmental is part of the F.L.I. Group of companies operating internationally in the sustainable energy and environmental sectors. Business areas include environmental containments for the mining industry, landfill construction services, anaerobic digestion, wastewater treatment and contaminated land remediation. Office locations include the UK, France and Ireland where the F.L.I. Group head office is based.

3.8.1 Technology

A twin autoclave system will operate at a temperature of 160ºC, at 5.2 bar pressure and will effectively cook and prepare the waste material for ease of downstream separation where the equipment is presented with sterile clean recyclables. Well tried and tested robust separation equipment, similar to that employed in the metals recycling industry will be used.

A combination Dryer – Pyrolyser - Oxidation unit provides energy to fire a twin boiler system, each boiler being capable of producing 12.5 tonnes of steam at the required temperature and pressure. These boilers provide steam to drive the turbine, nominally rated at 5MW. The steam required for the autoclave process is delivered by the hot gas boiler, thus eliminating the need for an alternative fuel source once the plant is operating at steady state conditions. 4MW of the 5MW power produced by the plant will be available for export to the National Grid (64).

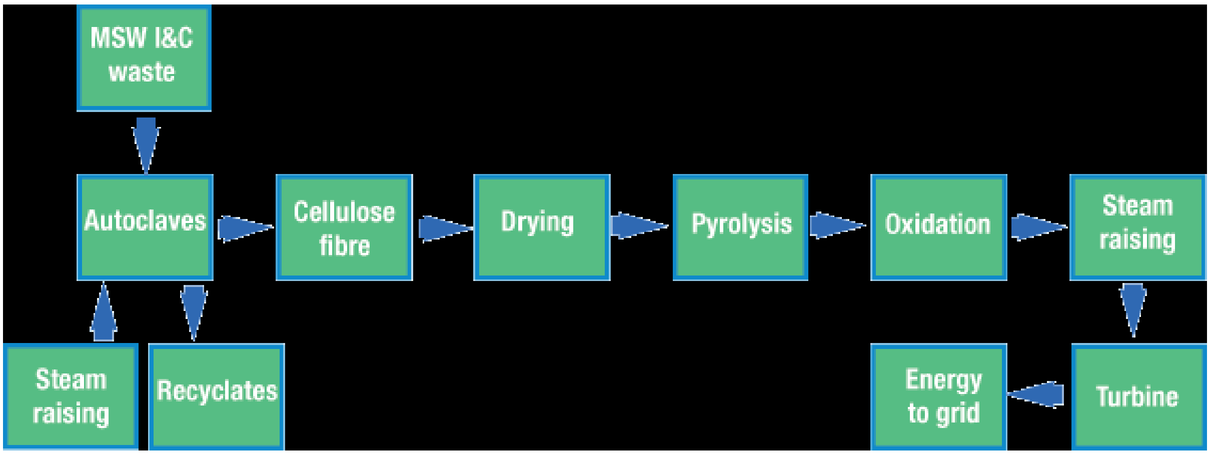

Figure 13. 3NRG process flow diagram (65)

3.8.2 Bridgend

The company 3NRG Waste Management (subsidiary of FLI Environmental) expected to have its first commercial autoclave MSW treatment facility, together with an integral power generation plant, up and running in Bridgend, Wales in 2010. The site is an existing closed landfill and holds a license to accept 100,000 tonnes per year of municipal and commercial waste.

Prestige Thermal Equipment, PTE, based in South Africa, has been appointed by 3NRG to build the Bridgend plant . The equipment for Bridgend has been designed to be accommodated within existing buildings at the site (64).

The facility will generate enough electricity to supply its own needs and an additional 4,000 homes. A pilot project has been running for some time at the 3.5 acre former landfill site at Tythegston. The site was licensed for waste processing but has now been given the green light for the construction of a £25M integrated waste processing/electricity generating plant due for completion by 2010 (66).

PTE recently withdrew from the UK market, as results at PurePower were not in compliance with their expected operational regime. The status of the Bridgend project is therefore unknown at this time.

3.9 First London Power

First London Power are focusing their initial work in London and they own the intellectual property rights to utilise the Stein Gasifier (pyrolysis) process world-wide for the production of renewable energy and the reduction of landfill and incineration. The Stein Gasifier has been developed as an efficient system to convert biomass and waste into a clean gas for use in CHP (combined heat and power) and electricity production without creating the typical dioxins produced by other technologies. Standard modules of 0.5 t/h and 3.0 t/h of dried fuel are available. A 6 t/h model is currently in the design stage (67). This process appears to be the same one used for Charlton Energy under the auspices of Ecotran Ltd., given the inventors of the Ecotran patent and their involvement in FLP (68). The patent says its gasification when it clearly is pyrolysis to give a syngas.

3.9.1 Technology

A variety of waste products can be used as fuel in the Stein Gasifier Process including crops, tyres, wood-chips, sewage sludge, bio-fuels, industrial waste and municipal solid waste (MSW). The feedstock is shredded to a size of about 15mm so that rapid heating of the fuel core can be achieved. Air and oxygen are removed prior to the material being fed at a constant rate into the gasifier retort where the conversion process takes place.

The thermal treatment of the feedstock takes place in three distinct stages (67):

- Stage 1: the incoming fuel is pyrolysed at high temperature in the almost total absence of oxygen. This separates the gas and oils in the fuel from the solids, and leaves a carbonaceous char. The gas produced is scrubbed of particulate matter, acid gases and any condensable organic compounds by a combination of cyclone separation followed by a venturi quench scrubbing stage, which is a packed bed scrubbing stage.
- Stage 2: the carbonaceous char produced by the pyrolysis stage is combusted at high temperature to generate hot flue gases that are used to heat the outside of the pyrolysis retort and drive the reactions taking place within it (as described in Stage 1). This combustion stage is fully compliant with the waste incineration directive WID and includes 2 seconds gas residence time at over 850℃, with HEPA ceramic filtration for fine dust particulates. Any resulting ash is melted

within the combustion chamber and is extracted to form a vitrified slag that can be used as a construction material.
- Stage 3: the cleaned syngas is combusted in a reciprocating engine, gas turbine or boiler to produce heat and power. The heat produced in the process can be used to provide heating and hot water to surrounding properties and/or it may be used in the fuel drying process.

Plants

A 0.5 t/h pilot plant is in operation at their East London factory. Emissions data is given in Table 8, which show environmental compliance.

Table 8. Typical emission figures using wood waste prior to any emission abatement equipment being installed (Combustion efficiency 99.9%, Temperature 1200ºC) (67)

	Stein gasifier	**WID limit**
CO	80 mg/Nm^3	100 mg/Nm^3
Hydrocarbons	10 mg/Nm^3	20 mg/Nm^3
Particulates	10 mg/Nm^3	30 mg/Nm^3
SO_2	0 mg/Nm^3	300 mg/Nm^3
HCl	3 mg/Nm^3	30 mg/Nm^3
NOx	200 mg/Nm^3	350 mg/Nm^3
Dioxins	0.000 nm/Nm^3	1.0 nm/Nm^3

3.10 GEM Ltd -GEM (Graveson Energy Management)

Graveson Energy Management (GEM) Ltd is a technology development company that since 1997 has been researching and developing a patented flash pyrolysis system that recovers energy from a wide selection of waste materials. The GEM Converter module has been designed to convert 1.5 t/h of suitable feed material into gas on a continuous basis. The process can accept a wide range of feedstock materials such as: domestic (MSW), trade/commercial, industrial, agricultural and horticultural, sewage sludge, rubber crumb, waste oils, other liquid waste, foodstuffs, rendered animal by products, crops, treated and clean wood. The fuel specification is simply a small particle size (<2mm in one plane), with a moisture content range of 5%-8% (69).

3.10.1 Process

The GEM pyrolysis technology is a vertically aligned pyrolsyer which sweeps the material over a heated surface. The reactor is shown in Figure 14. Prepared fuel is continuously fed in an externally heated stirred reactor via an auger mechanism where heat instantly penetrates the particles, efficiently cracking them into a synthetic gas. The gas is retained within the converter for up to 50 seconds to maintain the heat transfer and maximise efficiency. The hot gas then passes through insulated piping into a gas cooler; here circulating coolant, which is a mineral oil blend, rapidly cools it in order to minimise the formation of dioxins and furans. This cooler also acts as a first stage scrubber and is able to reduce any chlorine in the gas stream. Cooled gas then passes through separator pots where any condensed vapour droplets are separated from the gas and are returned to the gas cooler reservoirs. Sub cooling of the gas can now be employed if required/necessary, to reduce the benzene volume in the gas, prior to it being compressed and recirculated or stored in a gas buffer tank. Following compression, again when required, the gas can be cleaned of other contaminants such as sulphur-based compounds to allow clean non-corrosive generator usage (69). Flack emissions data is presented in Table 9. Other plant emissions are given in Table 11.

Table 9. Flare stack emissions [mg/Nm^3, 11vol% O_2 basis] (70)

	GEM, UK	EU WID
SO_2	79	50
NOx	262	400 [< 6t/h] 200 [> 6 t/h]
Particulate	3	10
CO	8	50
TOC	6 *	10
HCl	4	10
HF	ND	1
\zHg	ND	0.05
Cd + Ti	ND	0.05
As + Pb + Cr + Cu + Mn +Cu + Co + V + Sb + Ni		0.5
PCDD/F, 1-TEQ	0.02	0.1 ng/Nm^3
Total metals		500 µg/Nm^3

Notes: * reported as VOCs

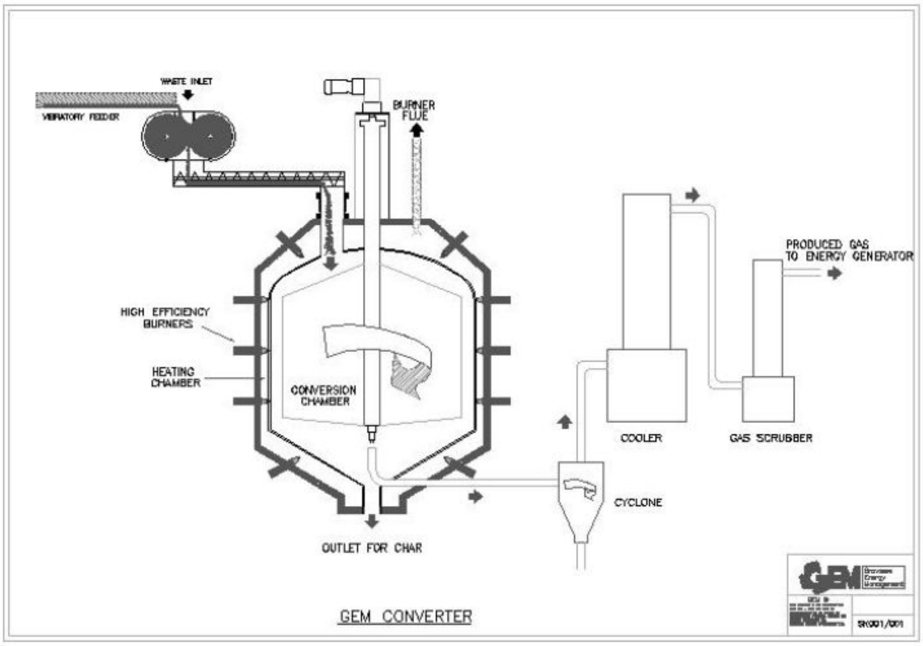

Figure 14. GEM converter (179)

Data has been published on the costs of the GEM process given in Table 10. This is also compared with other technology providers in Table 48. The net disposal cost is much higher than conventional landfill in the UK.

Table 10. Cost of technology, 2005 basis, US$ (71)

	GEM America, USA
Technology	Pyrolysis
Capacity [t/y]	30,000
Capital Cost	13,215,317
Annual O & M	2,071,450
Annual Capital Recovery	2,316,680
Annual Revenue Generated	1,244,340
Net annual cost: [(O&M + Capital Recovery) - Revenues]	3,143,790
Net cost $/ton MSW delivered	105

3.10.2 Bridgend, Wales

GEM operated a commercial size 36 tpd (1.5 t/h) unit in Bridgend, South Wales from 2000 to 2002 for the processing of MSW. The unit in South Wales was planned for expansion from 1.5 t/h to 6 t/h, but financial issues for the operator have put this project in limbo (72). The gas from the test plant was normally flared. A gas engine was on site for about 4 weeks for trials but it is not clear how many operating hours were actually clocked up by the gas engine during this period. The gas engine exhaust from the tests showed high levels of CO and NOx and special dispensation was given by the EA for these trials. The plant came back into service in 2007. A 150 kWe reciprocating engine has been used for testing (73).

Table 11. Bridgend plant's emissions in 2003 (74)

Plant	**Bridgend**
Power generation	Gas engine
SO_2 (mg/Nm^3)	55
NO_x (mg/Nm^3)	250
CO (mg/Nm^3)	1000

Based on data provided by GEM, the derived net power generation efficiency of the Bridgend plant was published in study commissioned by ESTET in 2004 (179).

Table 12. Overall net power generation efficiency, GEM Bridgend (179)

Thermal input (MWth)	27.2
Syngas energy (MWth)	20.2
Power generated (MWe)	6.9
Power used on site (MWe)	0.5
Power exported (MWe)	6.5
Conversion efficiency	74%

Generation efficiency	34%
Overall gross efficiency	25%
Site power use	7%
Overall net efficiency	24%
Include power consumed in pretreatment?	Yes
Include chemical energy loss in pretreatment?	No

3.10.3 Banham Power, Attleborough, Norfolk

Planning permission was granted in November 2005 to Banham Power for the establishment of an energy from waste plant in Attleborough. This approval followed a successful IPPC application in 2004. The proposed project would convert certain poultry waste products into energy, utilising GEM Technology. GEM would supply modules capable of generating 5.5 MWe (75). No information on current status of the project could be found. The website has not been updated since 2005.

Table 13. Banham power (GEM) Syngas analysis (76) - estimated

Feedstock	**Chicken litter**
Feedstock H_2O [wt%, dry basis]	< 0.1
CO	14.58
CO_2	10.80
H_2	24.23
CH_4	34.44
C_2H_4	8.42
C_2H_6	0.70
C_3H_6	
C_3H_8	0.65
n-C_4H_{10}	0.36
C_5+	1.63
Organics	
N_2	3.70
O_2	0.49
LHV [MJ/Nm^3]	26.57

3.10.4 Intrinergy, Coshocton, Ohio, USA

In April 2006 Intrinergy placed an order for one converter on GEM for a project based in Ohio, USA. The objective of the project is to convert a tyre derived fuel into synthetic gas for direct use in an industrial application replacing natural gas. The US Environment Protection Agency (EPA) permit system allows -build at risk- and then conducts an assessment over a short period of operation to grant a permit based on total plant emissions. Therefore Intrinergy has ordered 1 GEM converter for full scale testing (phase 1) and Phase 2 will include another 2 GEM converters and the construction of the gas pipeline to enable sale of gas to the local industrial user (75). The plant was due to come into service in mid-May 2009. The syngas is utilised in four 1 MW GE-Jenbacher reciprocating engines and one boiler (73).

3.10.5 Scarborough Power, Seamer Carr, North Yorkshire

The Scarborough Power Ltd., GEM Flash Pyrolysis Thermal Process is located at Seamer Carr on the southern edge of Scarborough town and is designed to convert a municipal solid waste derived solid recovered fuel (SRF) into a synthetic fuel gas for combustion in a gas engine to generate electricity with the potential for further recovery of heat for offices / process use. It was one of the Defra supported New Technologies Demonstrator plants. The Seamer Carr site is owned and operated by Yorwaste and includes a non-hazardous landfill, a Materials Recycling Facility (MRF) and a green waste windrow composting system. The flowsheet is shown in Figure **15** and Figure 16.

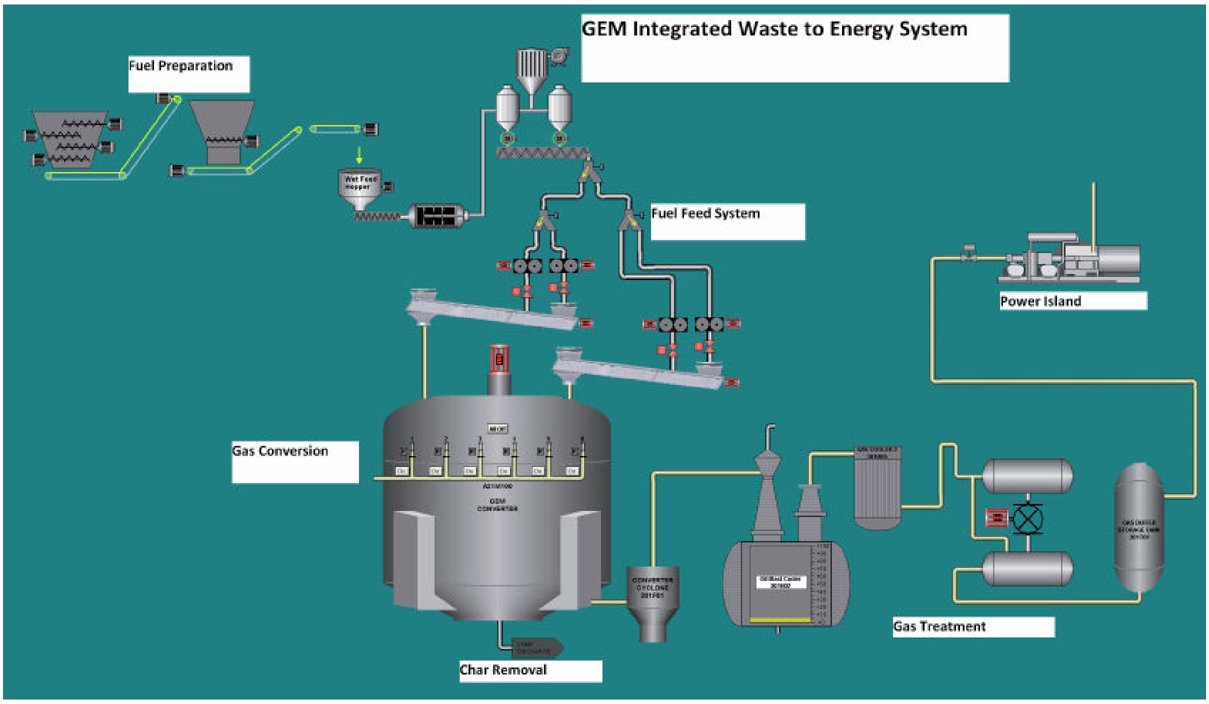

Figure 15. Yorwaste flowsheet

The main fuel feedstock is prepared on site by Wastec Ltd. from residual domestic waste (mostly in green wheeled bins) delivered by Scarborough Borough Council / Yorwaste. The designed 18,000 tonnes (undried) per year input from the Wastec Ltd. plant is converted to 12,000 tonnes per year throughput of dried SRF which equates to a maximum throughput of 1.5 tonnes/hour of SRF into the GEM pyrolysis converter. The downstream equipment is sized for the GEM pyrolysis converter to operate on a continuous basis, i.e. to operate 168 hrs per week (i.e. 24 hours/day, 7 days/week). The electricity generator (Deutz, reciprocating engine) is designed to produce 1.8MW of electricity from the syngas produced by the GEM pyrolysis converter. The complete process flow sheet is shown in Figure 16. Detailed descriptions of the process can be found in the Scarborough Power DEFRA reports

(77, 78). It would appear from recent reports that the plant is not meeting its design criteria,

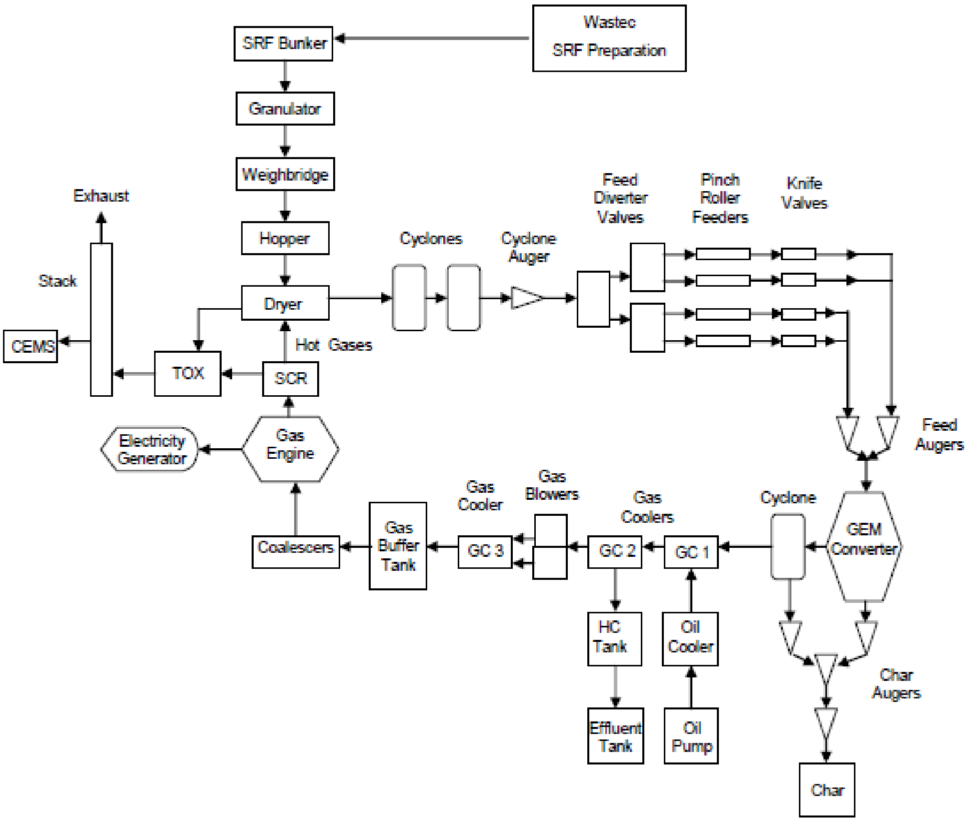

Figure 16. Schematic diagram of the Scarborough Power Ltd. Plant

Since summer 2008 through to the end of the extended Defra contract deadline of December 31st 2009, the Scarborough Power Ltd plant has suffered continual commissioning problems and did not produce a continuous and extended fully operational period to design specification. The plant is a genuinely new process in terms of the throughput and commercialising of the concepts developed and trialled at pilot scale by the technology supplier, GEM Ltd. It is unfortunate that continuous operation of the Scarborough Power Ltd., plant could not be completed during the Defra New Technologies Demonstrator Programme time frame. However, it is understood that Scarborough Power Ltd., remain committed to completing the modifications needed to permit the plant to be fully commissioned (79).

Given the limited period that the plant was operational, only 60% of the intended operational target was achieved. A total of 242 MW of electricity was produced during the operational phase; this was exported to the grid. The system had a parasitic demand of 0.4MW.

The total operating hours achieved by the integrated system was 886 hours and treated 584 tonnes of MSW, meaning the same 584 tonnes of MSW was diverted from landfill. Unplanned downtime cannot be determined as the plant was never in continuous operation. It is estimated that approximately 70 tonnes of char was produced. The exact quantity cannot be given as there were no accurate measurements taken due to a lack of instrumentation (79).

Figure 17. Scarborough Power Ltd. Plant

In April 2009 Scarborough Power Ltd entered into a Creditors' Voluntary Arrangement (CVA). This solution met with the approval of the shareholders and creditors who would continue to stand by the project for a period of at least two years during which time the process would be fully operational and commercially viable. The success of the project will open up more conventional routes for funding. It is anticipated that having completely funded the build and operation of the SPL project from established private and public funds, reaching financial close for the next phase of projects with clients will be far less complicated with lenders being slightly less risk averse (78).

In January 2010 Scarborough Power ltd announced it has partnered with a large power company that will enable the continued development and potential expansion of the SPL site. In November 2010 GEM announced that it has worked closely with its delivery partners Imtech Process and Otto Simon to produce a Technical Development Strategy that sets out what is required to commercialise the SPL plant and deliver the GEM technology to market.

3.10.6 Haybridge

Energy from waste company WP2 was granted with an operating permit (IPPC) in March 2009 by the Environment Agency to use a flash pyrolysis process provided by GEM to operate the energy from waste plant to be built at Haybridge, near Wells, Somerset. Planning permission was given by Somerset County Council in April 2007 and the granting of this permit paves the way for WP2 to progress its plans to develop the brownfield site at Haybridge to provide up to 6MW of electricity when the plant becomes fully operational in 2012 (75, 80).

3.11 Hudol Ltd

The Hudol technology has been pioneered by the Hendre Holdings Group (HHG), which is based in Carmarthen [81]. The Hudol Treatment unit is robust and able to treat a wide variety of materials, including oily sludge, contaminated soils, biomass, refuse derived fuels and plastics. The unit complies with the requirements of the WID. Currently work is continuing to evaluate suitability of other materials (82).

3.11.1 Technology

The Hudol pyrolysis technology consists of a vertical pyrolysis shaft that is externally heated. A wide variety of materials ranging from contaminated soils to oily sludge or biomass can be treated at a rate of 4 t/h. After passing through an air lock, the temperature of the material is raised from ambient to 500ºC. Travel time through the zone is variable depending upon material type. Two independently controlled heating zones allow very accurate temperature profiles to be created. The material passes automatically from the pre-pyrolyser to the gasification tower. Within the tower the temperature is raised to 900ºC.

Six independently controlled heating zones allow precise temperature profiles to be created. The retention time can be automatically adjusted depending upon material type. The shape of the inside of the gasification reaction vessel and path length can be varied remotely. Superheated steam injection allows conversion of small amounts of residual carbon into gas of high calorific value. The gas is directed via a reticulation system into a gas engine that allows electricity to be generated. After parasitic loads approximately 10 MW to 20 MW of syngas is produced depending upon the material input (82).

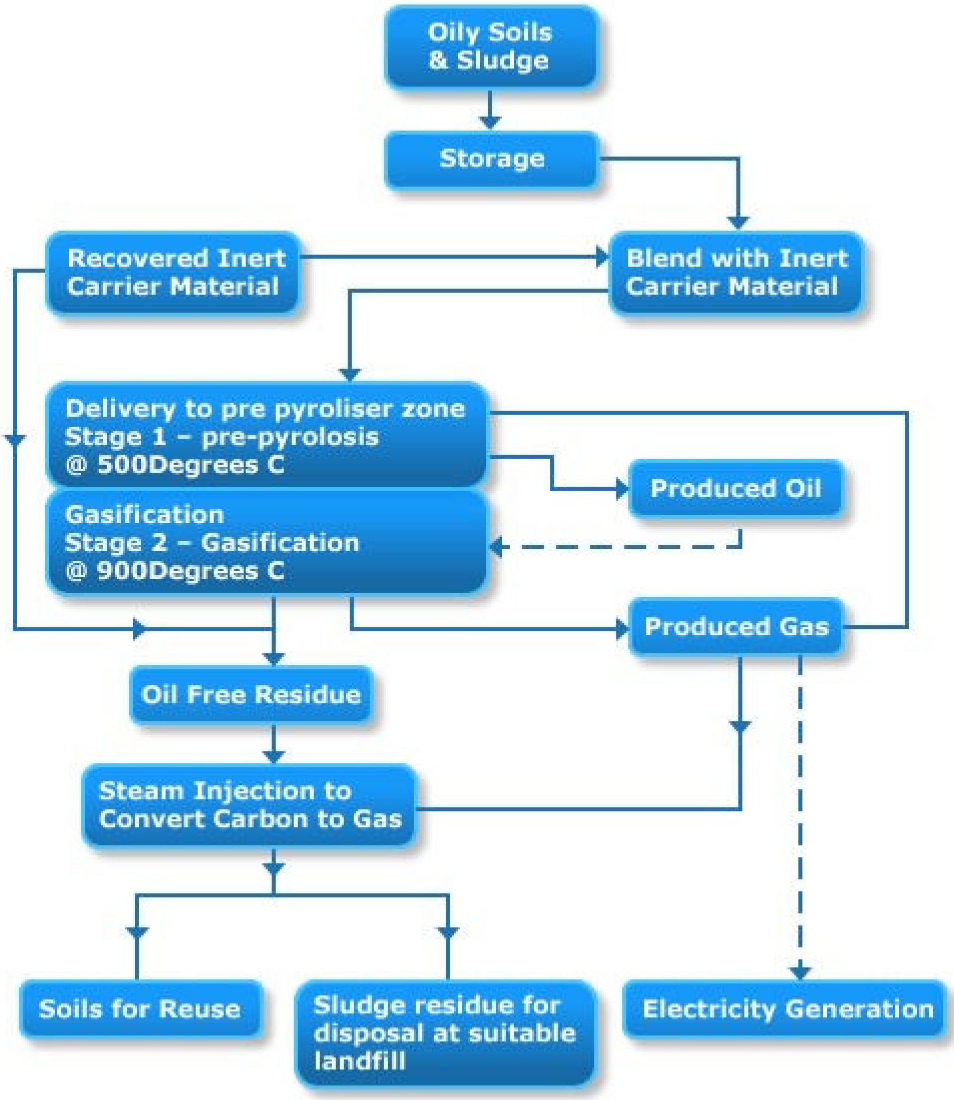

Figure 18. Hudol process flow diagram (83)

3.11.2 Rhymney

The Hudol technology has been designed to decontaminate oily sludge and tarry wastes by converting them to syngas. A demonstration site has been established in Rhymney; at present the demonstration site has a very limited capacity. The site holds an A1 Permit and is regulated by the EAW in Cardiff. The plant also complies with WID. HHG believe that the system will soon become BAT for the thermal treatment of organic materials.

The syngas produced by the system is similar in composition to natural gas and is cleaned before being directed to engines to produce electricity. It is estimated that each HUDOL unit is capable of producing around 10 to 30 MW of gas when running on oily waste: If directed to engines this can produce around 2 to 9 MW of electricity (81).

3.11.3 Tythegston (Bridgend)

A test plant has been operated at Tythegston (Bridgend). Over ten years the plant never worked well with domestic wastes, transgressing NOx and CO limits on several occasions. “Technical problems have prevented the plant from operating to its full potential” HUDOL say, and Bridgend Council granted permission last year for autoclaves to be substituted, working on steam from combustion of the output fibre (83).

3.11.4 Barry Docks, South Glamorgan

A Welsh Assembly Government (WAG) planning inspector overturned in July 2010 the Vale of Glamorgan council's decision to refuse planning permission for a pyrolysis plant at Barry Dock, which is set to process 72,000 tonnes of waste wood per year (84).

The technology is supplied by Carmarthenshire-based firm Hudol (85). Hudol’s technology has been taken on by a small consultancy called Sedgwick Associates under “Sunrise Renewables”(83). Sunrise Renewables Limited propose to operate a 9MW biomass pyrolysis plant to generate renewable energy on land at Ramsden Dock on Barrow Island. The proposed plant will be manufactured by Prestige Thermal Equipment (PTE) Limited who are based in Wadeville, South Africa and will provide on-line remote monitoring and diagnostics for the plant (86). PTE also have a 100-MW facility for India in the pipeline (87).

Given that PTE have withdrawn from the UK market and the lack of positive newsflow from PurePower [see Section 3.14], it is difficult to see how these projects will be delivered.

3.12 Inetec/EnCycle

Inetec was formed in 1997. It designs, builds, owns and operates waste to energy plants. Inetec’s technology converts food and non-recyclable packaging waste into electrical energy by anaerobic digestion and/or biomass fuel without the need for significant segregation. The biomass fuel can be burned on or off site to generate electricity. Any WID compliant system may be used to burn the fuel (88).

3.12.1 Technology

Inetec does not provide a waste pyrolysis process. It selects the appropriate technological solution for the material.

3.12.2 Immingham, NE Lincolnshire

EnCycle, Inetec’s wholly owned subsidiary, has been granted planning permission for the UK’s first food waste to renewable electricity power station. The plant is to be located near Immingham Docks in NE Lincolnshire and was due to begin operations early in quarter two of 2008. The facility will process up to 500 tonnes a day of food and non-recyclable packaging waste. It will divert around 180,000 tonnes of waste away from landfill per year and will generate 24MW of renewable energy; enough to power 37,000 average UK households. With contracts already secured with Northern Foods, Greencore and Greggs food producers in the UK the plant is already at capacity. The cost of the development is estimated to £80 million [89]. GEM is the gas conversion technology provider (75).

There is no current information on the status of this project. The EnCycle website is not loading and there is no reference to the Immingham project in the Inetec website.

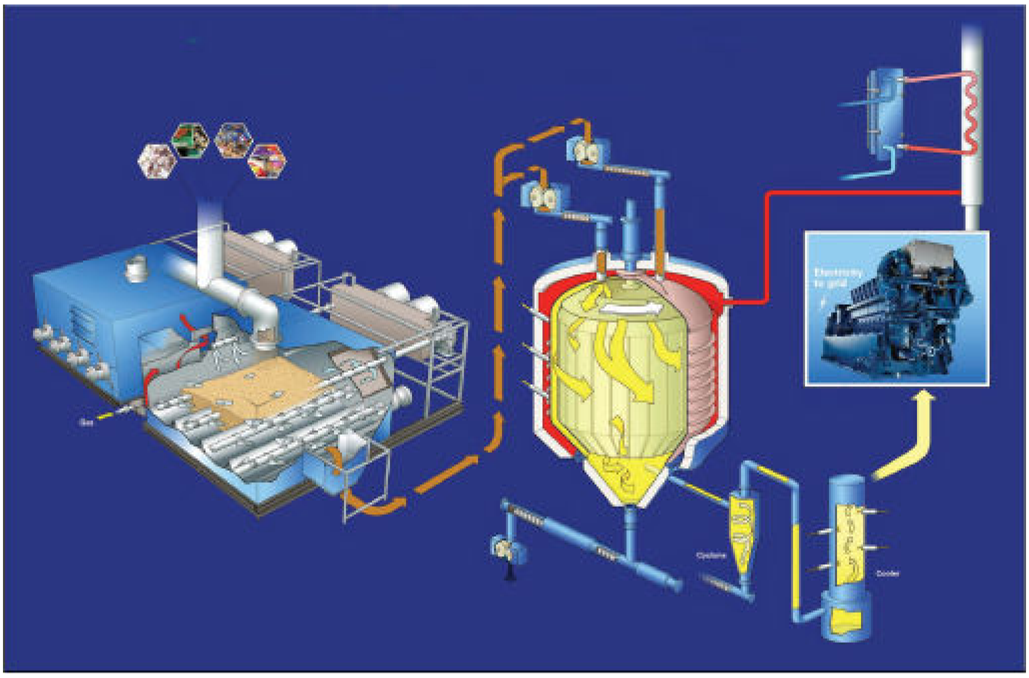

Figure 19. Process diagram of the proposed EnCycle plant in Immingham (90)

3.13 New Earth Energy

New Earth Energy was created in Autumn 2008 to close the loop between waste treatment and energy recovery and achieve a first to market position in the successful commercial application of advanced thermal energy recovery technologies, namely gasification and pyrolysis.

3.13.1 Technology

NewEarth does not provide a waste pyrolysis process. It selects the appropriate technological solution for the material.

3.13.2 Canford

NewEarth is presently commissioning a 1 MWe plant at Canford. There are plans to extend this to 5 MWe. No further details are available at this time.

3.13.3 Further developments

The 7.5 MW gasification and pyrolysis plant at Avonmouth will be the second energy recovery facility to be developed by New Earth. New Earth Energy is also planning to build a 10MW, stand-alone pyrolysis facility at the Dorset Green Technology Park in Winfrith, to take residue from the Canford MBT and act as a merchant facility. The planning application for the facility has been approved without objection (91). Plans are also in the pipeline for a 3 MW pyrolysis plant to be developed at New Earth's Blaise Farm in-vessel composting facility in Kent, to help power the site. A planning application has been submitted (92).

3.14 PurePower Ltd [PTE Technology, South Africa]

PurePower Holdings Ltd (PPL) develops small renewable energy projects (circa 3MWe) utilising Advanced Conversion Technology (ACT) and wood fuels. PPL has offices in Cirencester and Stokesley with ongoing project development through the UK.

3.14.1 Technology

The technology is that of Hudol, licensed to PTE, South Africa. The syngas generated in the pyrolyser is routed through a direct contact water scrubber, prior to the syngas being used within a spark ignition gas engine (GE Jenbacher 620). The emissions from the pyrolyser and gas engines are routed through a thermal oxidiser. The thermal oxidizer is designed and operated in such a way that the gas resulting from the process is raised to a temperature of 850ºC for at least 2 seconds (93).

3.14.2 Huntingdon

PurePower operates a new facility at the site of the existing Huntingdon Recycling Ltd composting site near Huntingdon, Cambridgeshire. The plant has been built by Prestige Thermal Equipment (South Africa) and is WID compliant. Production capacity is approximately 49,000 tonnes per year. The waste management licence for the neighbouring Huntingdon Recycling Ltd facility currently allows a maximum of 24,000 tonnes of waste wood to be held on site at any one time (93).

The energy efficiency of the key components of the Huntingdon plant is as follows:
Pyrolysis plant: Approximately 83% efficient (key losses being casing losses (1.278 GJ), cooling losses (0.7GJ), heat losses (to oxidiser 2.371GJ). The generator sets are stated as being 39% efficient.

The parasitic load of the entire plant accounts for approximately 19% (840KW) of the total energy generation of the plant, with a further 10% (460KW) being used to power the fuel pelleting line associated with the installation (93). There is very limited information in the public domain as to the operational status of the plant and all requests to see the plant or provide further information are declined by PurePower.

3.15 Wellman Process Engineering Ltd.

Wellman Process Engineering Ltd designed, constructed, commissioned and operated an integrated fluidised bed fast pyrolysis reactor system for the optimal production of liquids. The development of a reliable fast pyrolysis system, capable of continuous operation is essential for subsequent commercialisation. The plant was finished in 2001 and ended operation early in 2002.

Figure 20. 250 kg/h fast pyrolysis plant, Oldbury

3.15.1 Technology

The process is a fluid bed pyrolyser with char recovery from the hot product gases prior to being quenched with recirculated cooled liquids and aerosols removal in 2 electrostatic precipitators in series. Non-condensable gases are recirculated for heat and fluidisation to the pyrolysis reactor. Char is burnt for heat in an annular char combustor.

The design biomass feed rate was 250 kg/hr softwood [dry basis] with anticipated pyrolysis liquids of 75% at a pyrolysis temperature of ~500°C. The pyrolysis char and gas yields are expected to be ~12-14 wt% each. The energy provided by the by-products is more than sufficient to provide the heat required for the pyrolysis process, based on detailed mass and energy balances over the system.

Although the plant was built and hot commissioning started and authorisation granted under IPC, with the changeover to IPPC, R&D plants were forced to comply to the same standards as commercial plants. To ensure that dust emissions from the char combustor met a IPPC limit of 20 mg/nm^3, the Environment Agency insisted that a particulate scrubber had to be fitted to the combustor exhaust to ensure compliance. The additional cost of the scrubber [~£100,000] and the increased cost of IPPC compliance forced the project to be terminated in 2002.

3.16 Wastegen Ltd.

The WasteGen UK Materials and Energy Recovery Plants or MERPS, combine pyrolysis with recycling and composting in an integrated design. Broadly, it comprises of a Materials Recycling Facility (MRF), a pyrolysis plant and a power generation plant. The core of the design is the pyrolysis kiln, which typically would have a throughput capacity of 50,000 tonnes per annum (TPA). The modular design allows plants of various sizes to be configured, based on site space limitations and specific Local Authority needs. TechTrade GmbH will be subcontracted to design, supply and install the pyrolysis unit (94).

3.16.1 Technology

The pyrolysis process consists of the following steps (179):

- Pyrolysis in rotary kiln with lime addition;
- Syngas combustion;
- Generation of electricity via steam cycle;
- Selective non catalytic reduction (SNCR) for NOx control;
- Flue gas cleaning by fabric filter with sodium bicarbonate and activated carbon injection.

Wastegen has 2 key reference plants in operation, in fact 2of the longest in Europe.

3.16.2 Burgau, Germany

The pyrolysis plant at Burgau was engineered in the 1970’s and was commissioned in 1984. It has been operated continuously since then with an annual input of 34,000 tonnes of municipal waste. Different types of waste, such as residual domestic waste, commercial waste, bulky waste and sewage sludge, have been processed successfully [94].

The two-unit plant consists of:

- Refuse treatment (2 refuse shredders: 30 t/h)
- Two rotary kilns (3 t/h each)
- Dust separation
- Combustion chamber for pyrolysis gas incineration
- Waste heat boiler with turbine generator (max 2.2 MWe)
- Bag house filter with addition of sodium bicarbonate and activated carbon
- Draught and stack

Gas analyses are given in Table 14. Emissions are presented in Table 15 and Table 16.

Table 14. Average analysis of permanent gas (20ºC)

Syngas composition	
Hydrogen	15%
Carbon monoxide	20%
Carbon dioxide	39%
Methane	12%
Hydrocarbons	13%

Note: Under operating conditions (500ºC), the pyrolysis gas furthermore contains 40 to 60% of steam and approx. 15 % of organic condensation products (tar, oil, etc.).

Table 15. Continuously monitored emissions

Pollutant	Authorised limit (mg/Nm^3)	Annual average (mg/Nm^3)
Dust	10	1.8
HCl	10	5.5
SO_2	50	8.0

Table 16. Discontinuously monitored emissions

Pollutant	Limit (mg/Nm^3)	Measured value (mg/Nm^3)
C total	20	1.6
Cadmium/ Thallium	0.05	0.0006
Mercury	0.05	0.0013 (ng/Nm^3)
Dioxins / Furans	0.1 (ng/Nm^3)	0.0013 (ng/Nm^3)

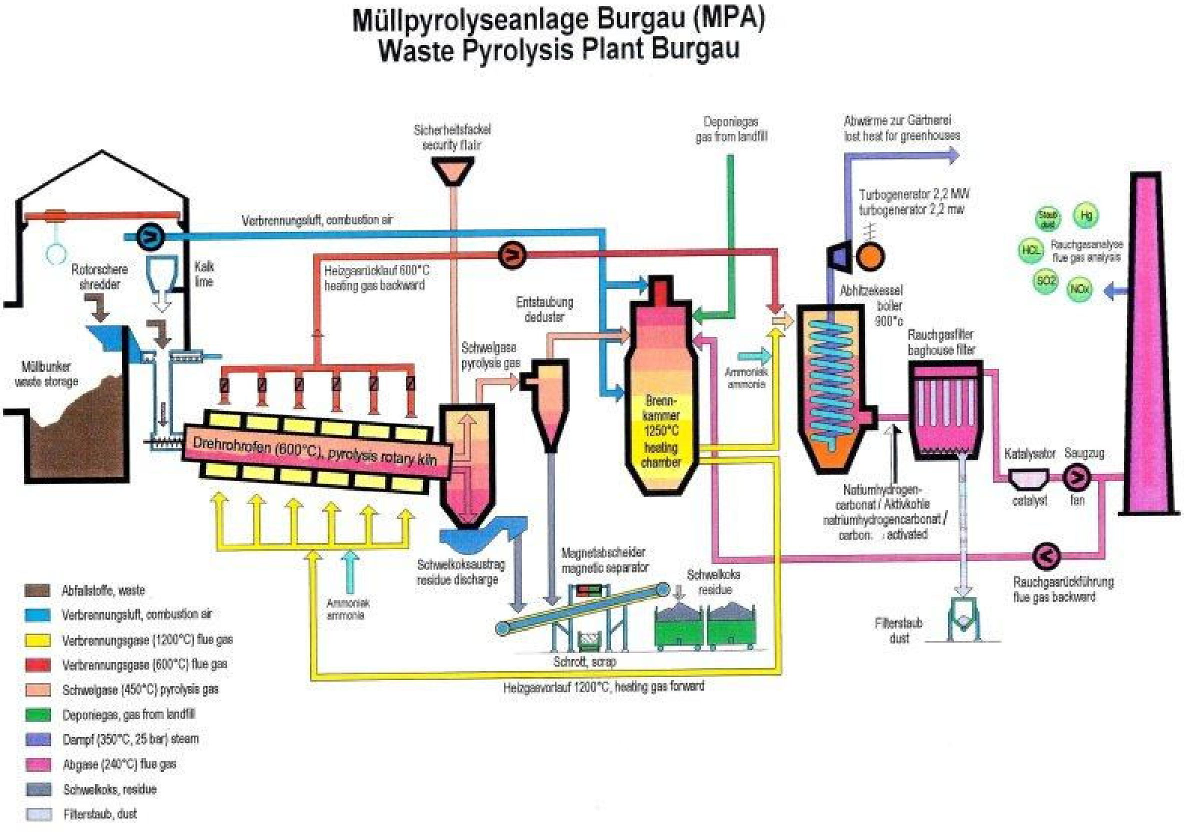

Figure 21. Process diagram of the Burgau waste pyrolysis plant (95)

3.16.3 Hamm, Germany

The power station is owned and operated by RWE Energie, the waste and power generation company that owns Thames Water and Innogy in the UK. The pyrolysis plant has a capacity of 100,000 t/y and costs £50m. It started operating in 2002 and serves as a processing unit for high calorific municipal waste and the generated fuels, pyrolysis gas (pygas) and pyrolysis char provide supplementary fuel to the coal-fired power station. These fuels replace approximately 10% of the combustion heat performance. The pyrolysis plant produces ~75 MW of gas energy, which is around 15 MWe at a normal steam turbine conversion efficiency. The plant is operating at 95% availability (96).

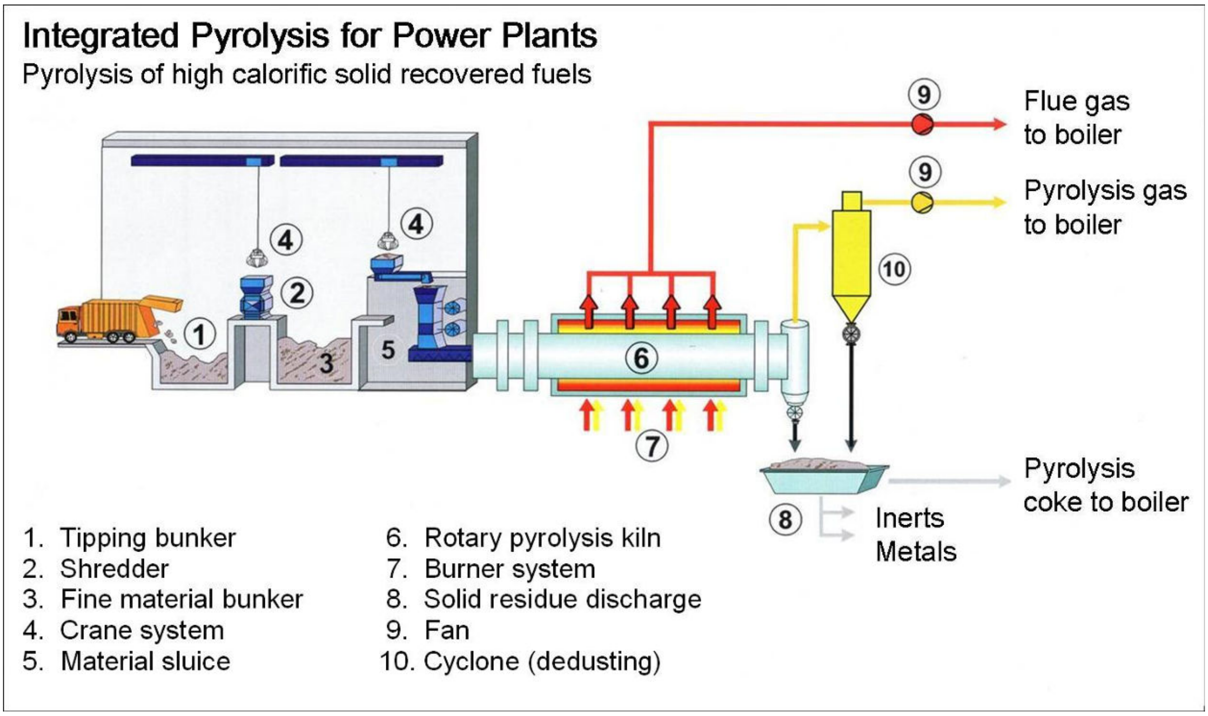

Figure 22. **Process diagram of the Hamm waste pyrolysis plant owned by RWE (95)**

Despite the success of the plants in Germany, Wastegen has not developed a similar facility to these in the UK. Attempts to contact the company have failed – emails are returned and they would appear to have stopped trading.

3.17 UK Pyrolysis

The market for waste pyrolysis is clearly increasing in the UK as landfill and transport costs rise, therefore this market sector is expected to expand significantly in coming years. There are some UK technology developers, however, these have met with limited success and there is competition from other systems.

4. Europe and/or Worldwide Waste Pyrolysis and Gasification Processes for Heat, Power and Products

In order to support the lack of active projects in the UK, a few key reference companies in Europe and Japan have been reviewed to highlight the range of commercial waste gasification and pyrolysis technologies that are available with a substantial track record, as given in Table 17 and Table 18.

These Tables show that there is an active track record of achievement in pyrolysis for waste conversion, mostly for waste minimisation and few activities in pyrolysis coupled with power generation.

Table 17. Notable Waste Gasification Companies and Projects

Company	Feed	Technology and size	Status	Comments
Austrian Energy Energietechnik GmbH (AEE)	Biomass	Zeltweg demo plant 10MW$_{th}$ gasifier	Operational	Part of BioCoComb project
Bellwether Gasification Technologies Ltd.	Unsorted MSW, industrial waste, agricultural residues, hazardous waste	Brasov, Romania 13tph MSW (LHV 11MJ/kg) Syngas 188M m^3/year (LHV 4.5MJ/m^3) 234MW$_{th}$ per year Syngas transported to local power plant	Commissioned November 2008 14month construction time	IMG process Thermal efficiency ~85% Electrical efficiency 40%
Biomass Engineering Ltd	Biomass	Three downdraft/ engine systems in Germany. Operating reliably as CHP units for district heating	Close feedstock size control, ceramic filter	
Carbona	Biomass	Skive Fjernvarme, Denmark 5.5MW$_e$ 11MW$_{th}$	Operational	
DB/ Austrian Energy/ Repotec	Wood chips	Gussing Indirect gasifier operating for over 20,000 hours. Fuels 2.5MW$_e$ reciprocating engine TIC€10M	Start up 2001	Ceramic filter with liquid scrubber containing bio-diesel
EnviroArc (PyroArc process)	Tannery waste and other wastes	Plasma torch gasification Pilot plant 15,000tpa IC engine for electricity generation		

Company	Feed	Technology and size	Status	Comments
Envirotherm	Wood waste	Rudersdorf, Germany 100MW_{th} Syngas into cement kiln Fluidised bed	Commercial	Offers Lurgi technologies taken over in asset deal
		Amer-9, Essent 83MW_{th} Demolition wood	2001 start up Number of problems limited operation Taken over by Essent	
Ferco/Silvagas Corporation/ Rentech	Wood	CFB gasification Demo plant, Vermont Battelle (USA)	>22,000hrs operational testing	
		McNeil Generation Station, Burlington, Vermont 300tonnes per day	Operational since 1999 Number of problems	
Foster Wheeler	Waste & RDF	Lahti, Finland 45MW_{th} Syngas in power station	Commercial	
		Electrabel Ruien Wood chips 45-70MW_{th} Connected to power plant	Commercial since 2003	
		Karhula pilot plant CFB gasifier		
Hitachi Metals	MSW	Utashinai, Japan 200-280 tonnes per day 1.5MW_e	Operational 2003	
Novera/Enerkem	MSW	Fluid bed technology Pilot scale plant Sherbrooke, Quebec 2.5 tonnes per day	Since 2001 >4000hrs since 2003	

Company	Feed	Technology and size	Status	Comments
		Alberta MSW to biofuels facility 100,000ton per year	Construction began summer 2010	
		Mississippi MSW to biofuels facility 36M litres per year ethanol $140M	Funding awarded 2009 Expected operational 2012	Signed MOU with Three Rivers Solid Waste Management for the supply of unsorted MSW
		Westbury waste to fuels, Canada 5M litres per year ethanol Treated wood feed	Construction began 2007 Alcohol production began 2010	
Rheinbraun AG	Biomass	Hurth-Berrenrath, Germany HTW pilot gasifier		Technology used by Thyssen Krupp
Techtrade – see Waste gen	Waste	Hamm, Germany Syngas in power station		
Thermoselect	MSW, C&I	Karlsruhe, Germany 225,000tpa (3MW$_e$)	Started 1998 Commercial operation 2002 - 2004	Swiss company with licences in Japan & Germany Fixed bed oxygen blown gasification process
		Chiba, Japan 100,000tpa	Start up 1999	
		Mutsu, Japan 50,000tpa (2.4MW$_e$)	Start up 2003	
		Kurashiki, Japan 3 x 185 tonnes per day	Start up 2005	
		Isahaya 3 x 100 tonnes per day 8MW$_e$	Start up 2005	
		Yokushima 2 x 60 tonnes per day 1.8MW$_e$	Start up 2005	

Company	Feed	Technology and size	Status	Comments
		Izumi 2 x 60 tonnes per day 1.7MW$_e$	Start up 2005	
		Yorii 3 x 150 tonnes per day 10.5MW$_e$	Start up 2006	
		Fondotoce, Italy Original pilot plant, 1.1MW$_e$ 30,000tpa		
TPS Termiska	RDF	Pilot plant 2MW Gasification atmospheric CFB bed	Commercial Early 1990's plant constructed Plant shut down 2000??	
		Reference plant Greve in Chianti, Italy Two 15MW$_{th}$ gasifiers (40,000tpa each) produce gas for boiler, coupled to steam turbine and cement furnace	Operational since 1992	
		Värnamo, Sweden 18MW$_{th}$ 4tonne/hour 8,500 operating hours	Constructed early 90s Plant mothballed 2000 Recommissioned for hydrogen rich syngas production	

Company	**Feed**	**Technology and size**	**Status**	**Comments**
Thyssen Krupp/Uhde	MSW	Sunitomo Heavy Industry, Sikuku, Japan Pilot plant 20tpd	Commissioned 1999 Japanese SHI working on further commercialisation in Japan (97)	Gasification High temperature Winkler (HTW) fluidised bed gasifiers
Zeropoint Clean Tech Inc	Biomass	Potsdam, NY Pilot plant Syngas and electricity production Modular systems Downdraft gasifier Each system $2MW_e$	Commissioned March 2007	4 International joint ventures (UK, India, Europe, Malaysia)
		Tonawanda, NY Commercial system		

Table 18. Notable Waste Pyrolysis Companies and Projects

Company	Feedstock	Size and locations	Status	Comments
WasteGen UK Ltd.	MSW and other wastes	Burgau, Germany 35,000 t/y 2.2 MW steam turbine	Operational since 1984	
	MSW	Hamm, Germany 100,000 t/y	Operational since 2002	Owned by RWE Syngas and char are combusted in the coal fired power station

4.1 Non-UK Waste Gasification Companies

Some key examples are given below. This is not a comprehensive review of all technologies.

4.2 Bellwether Gasification Technology Ltd.

Bellwether Gasification Technologies was created in 2006 and specialises in gasification technologies. The company developed and patented the IMG process.

4.2.1 Technology

The patented Integrated Multifuel Gasification I(MG) technology is gasification process followed by plasma gas cleaning. The steps involved in the gasifier are input/feeding, drying, gasification and slag vitrification (Figure 26).The resulting heat is re-used within the process to pre-heat gasification streams. The resulting low calorific value syngas can be utilized directly in gas engines. In addition the process generates and inert slag.

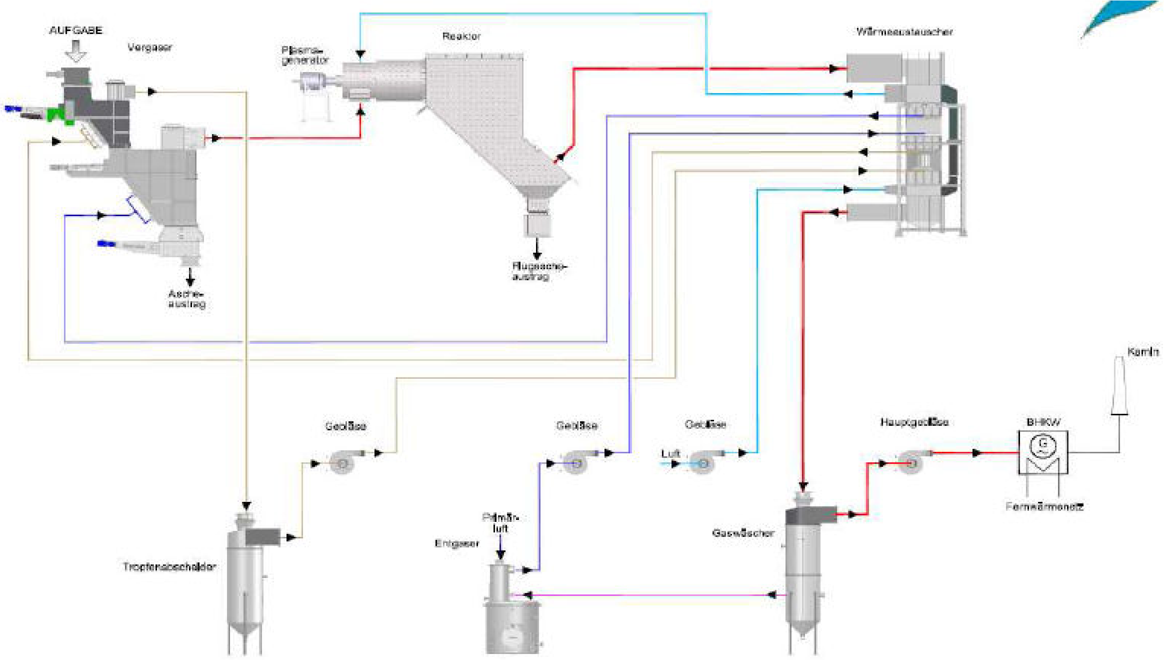

Figure 23. Bellwether IMG process scheme (98)

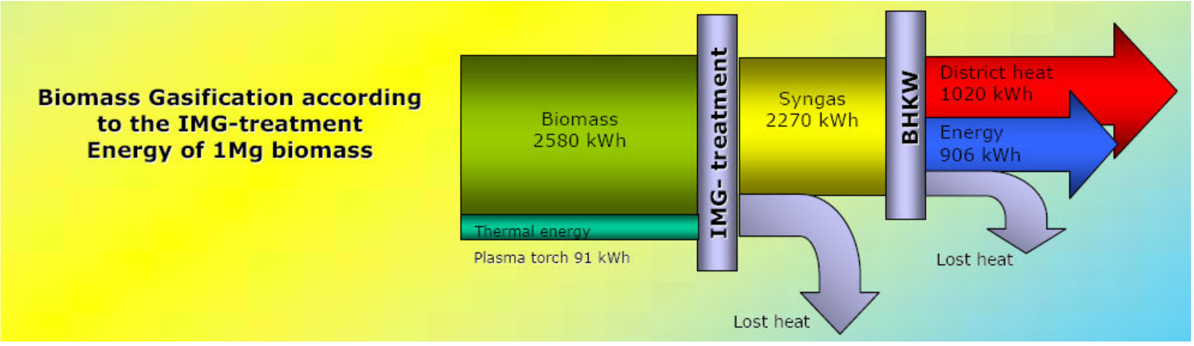

Figure 24. Bellwether IMG process (98)

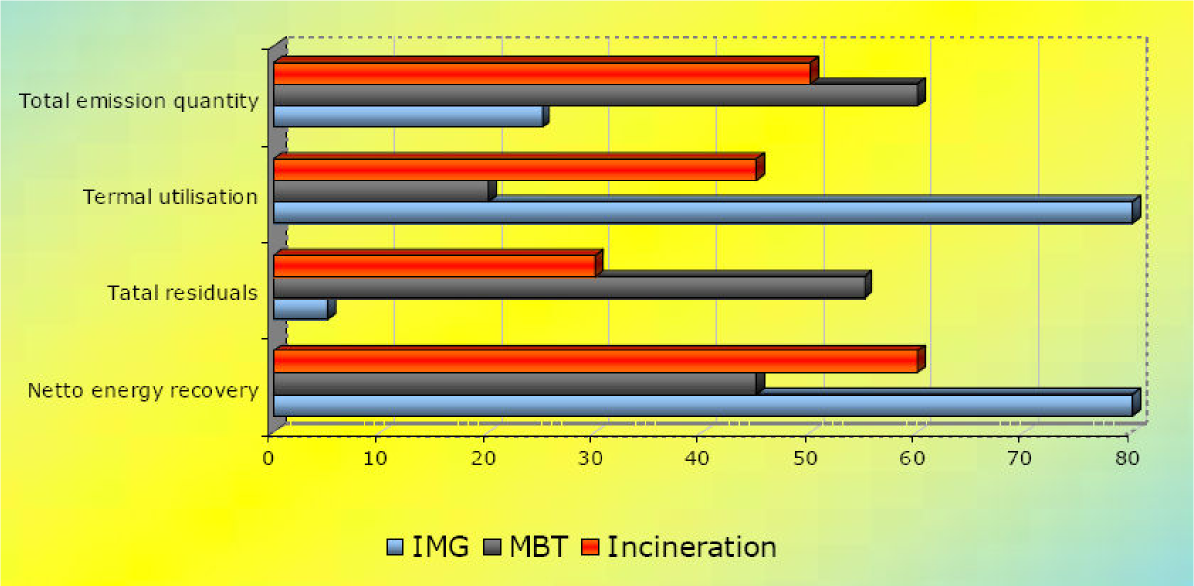

Figure 25. Bellwether waste treatment comparison (98)

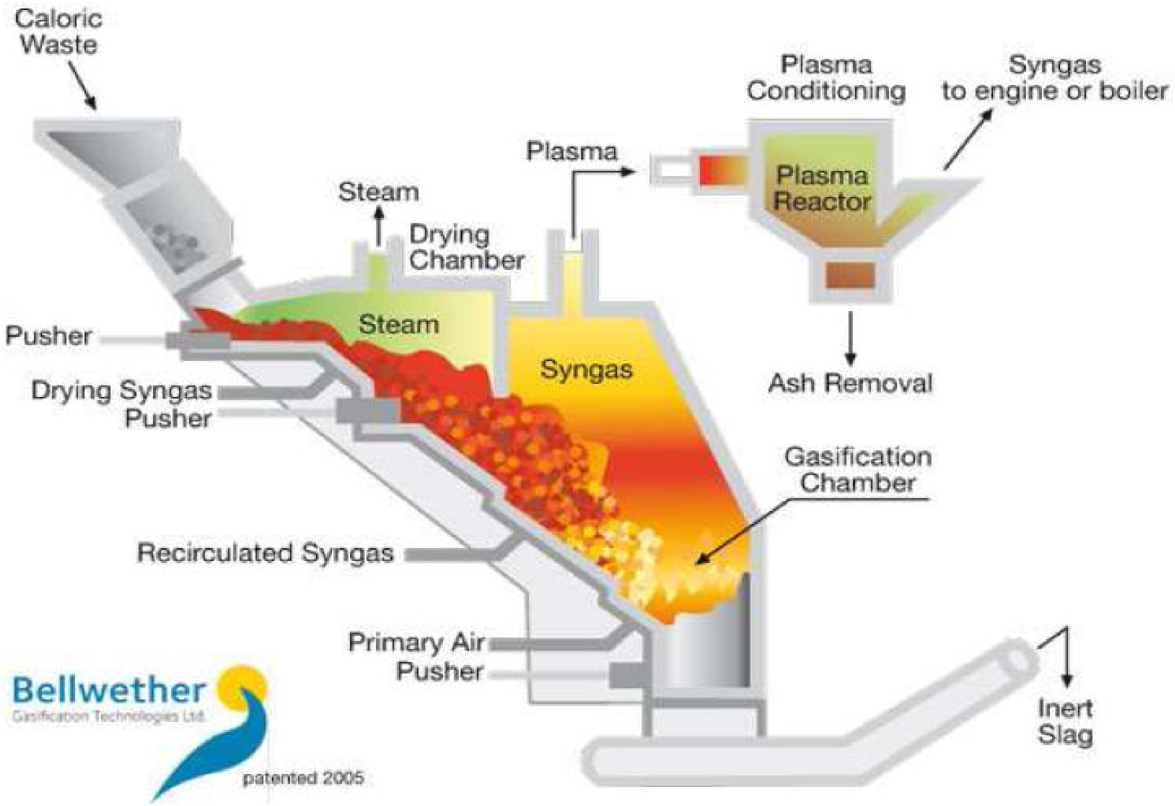

Figure 26. Bellwether IMG diagram (98)

The syngas is cleaned by means of plasma conditioning. All tars within the gas are decomposed and toxic radicals are destroyed. This occurs in the absence of oxygen so no NO_x is produced. No dioxins are generated in this process.

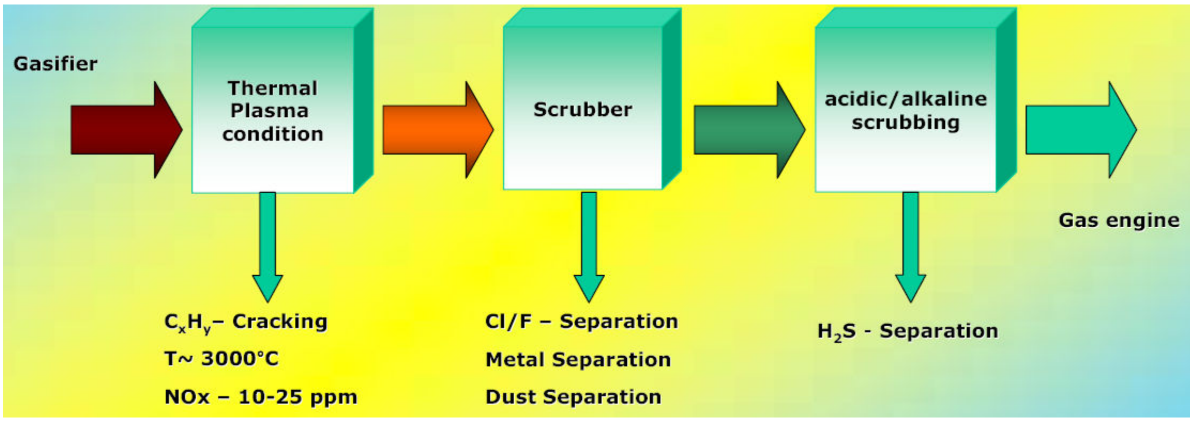

Figure 27. Bellwether gas cleaning steps (98)

4.2.2 Brasov, Romania

Commissioned in November 2008 following a 14 month construction time. The plant emissions are shown in Table 19 and the syngas composition in Table 20.

Table 19 – Bellwether Romania plant emissions (98)

Emission	Unit	Pollutant concentration, average daily value
Dust	mg/m^3	<3
HCl	mg/m^3	<2
HF	mg/m^3	<0.1
SO_x (as SO_2)	mg/m^3	<25
NO_x (as NO_2, 95% NO)	mg/m^3	<20
NH_3	mg/m^3	<0.2

Table 20 – Bellwether Romania clean syngas composition (98)

Component	%
Co	19-23.1
CO_2	7-8.7
H_2	13-17.6
H_2O	5-8.5
N_2	46-49.6
Total	100

4.3 Envirotherm / Lurgi

In spite of success in the gasification and pyrolysis and waste, Lurgi has withdrawn from the waste gasification pyrolysis market in 2003/4 (179). They stated ‘that in the short to medium term neither technology will be developed and commercially proven to the point where it can compete’ (179). Envirotherm took over the technologies previously offered by Lurgi.

4.3.1 Technology

The Envirotherm/Lurgi process includes and atmospheric air blown CFB operating at about 800°C and 140kPa (99). The gas is cooled to 600°C by preheating the gasification air. The gas is then further cooled to 240°C in a waste heat boiler for steam generation. Char and particulates are removed by a cyclone and bag filter. The gas is then washed in a wet scrubber and cooled to 45°C. The gas is compressed and then delivered to the gas turbine (99).

Table 21 - Gas composition for Lurgi CFB gasification of wood (99)

Compound	Bark (air)	Wood (air)	Wood (oxygen)
Carbon monoxide	19.6 %v	15 %v	33.5 %v
Hydrogen	20.2 %v	15 %v	33.4 %v
Methane	3.8 %v	5 %v	4.9 %v
Higher hydrocarbons	As methane	1.1 %v	1.7 %v
Carbon dioxide	13.5 %v	17 %v	26.6 %v
Nitrogen	42.9 %v	47 %v	-
Water vapour	As dry	As dry	As dry

4.3.2 Rudersorf plant

Gasification occurs in a CFB with the syngas is fired in calciner of the cement plant (99). Commercial operation of the 100MW$_{th}$gasifier began in 1996. The plant supplies up to 40% of the energy demand of the cement process (99). The ash produced is used as a raw material for the cement process. A plant diagram is shown in Figure 28 with a diagram of the gasifier shown in Figure 29.

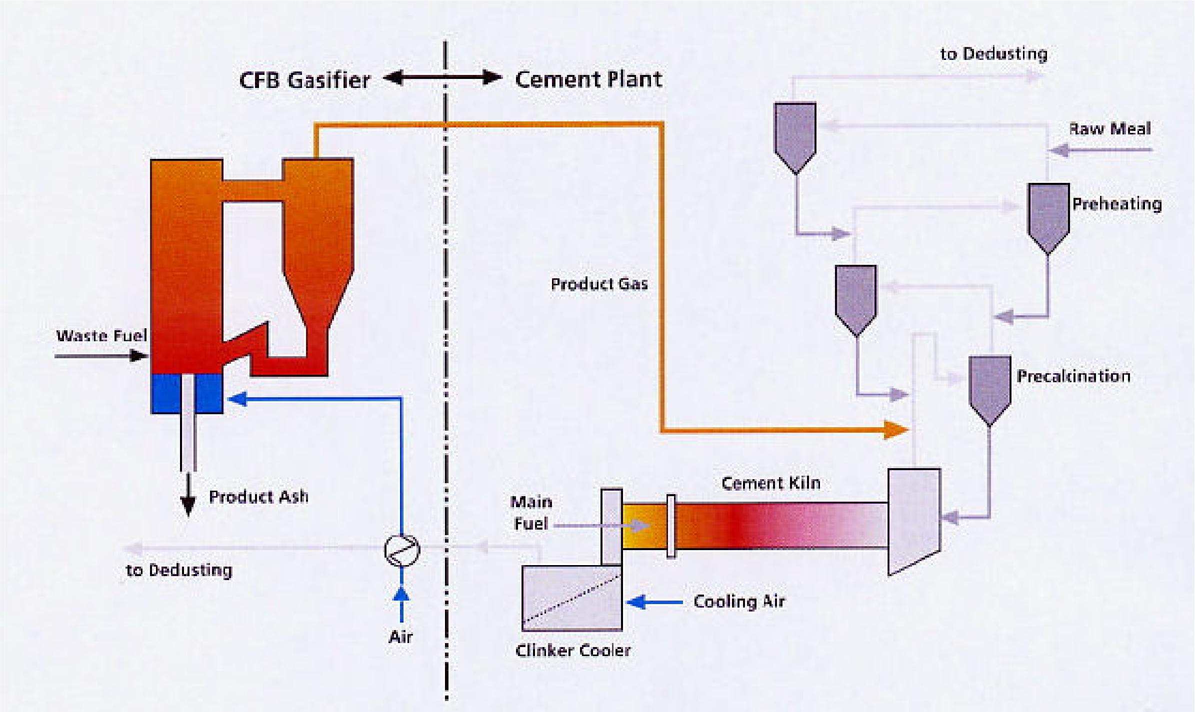

Figure 28. Lurgi Rudersdorf plant diagram (Ref Envirotherm)

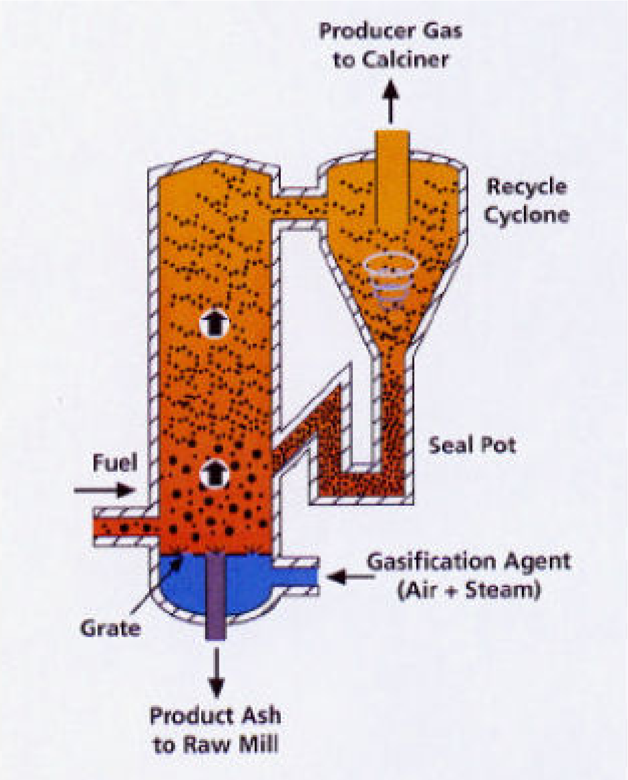

Figure 29. Lurgi fluidised bed gasifier (Ref Envirotherm)

4.4 Ferco

Ferco stands for Future Energy Resources Corporation and they developed the SilvaGas gasification technology to convert biomass into a gaseous fuel. The company is a privately held technology and project development company formed in 1992.

4.4.1 Technology

A Battelle (commercialized by FERCO) gasifier sized for 200 t d-1 wood chips was installed next to the boiler at the McNeil Generating Station in Burlington Vermont. The McNeil facility is a 50 MWe Rankine steam cycle biomass fired plant. The project consisted of scaling up the Batelle dual-fluidized bed gasifier to produce gas for co-firing in the McNeil boiler initially, followed by staged implementation of gas cleaning systems and a gas turbine to be operated on the producer gas as an IGCC. The gasifier uses steam and hot sand to gasify the biomass.

Steam supplied as the medium to remove syngas from reaction site. Char combustion tales place in a second fluidised bed to provide heat to sand carried back over to the gasifier. The syngas from the demo plant used in power station but FERCO intends to offer CCGT for power generation. Some testing of syngas in small 200kW Solar Spartan gas turbine has been undertaken at the pilot plant (179). The Ferco SilvaGas gasification process is illustrated in Figure 30. Over 22,000 hours of operation have been obtained making gas (100).

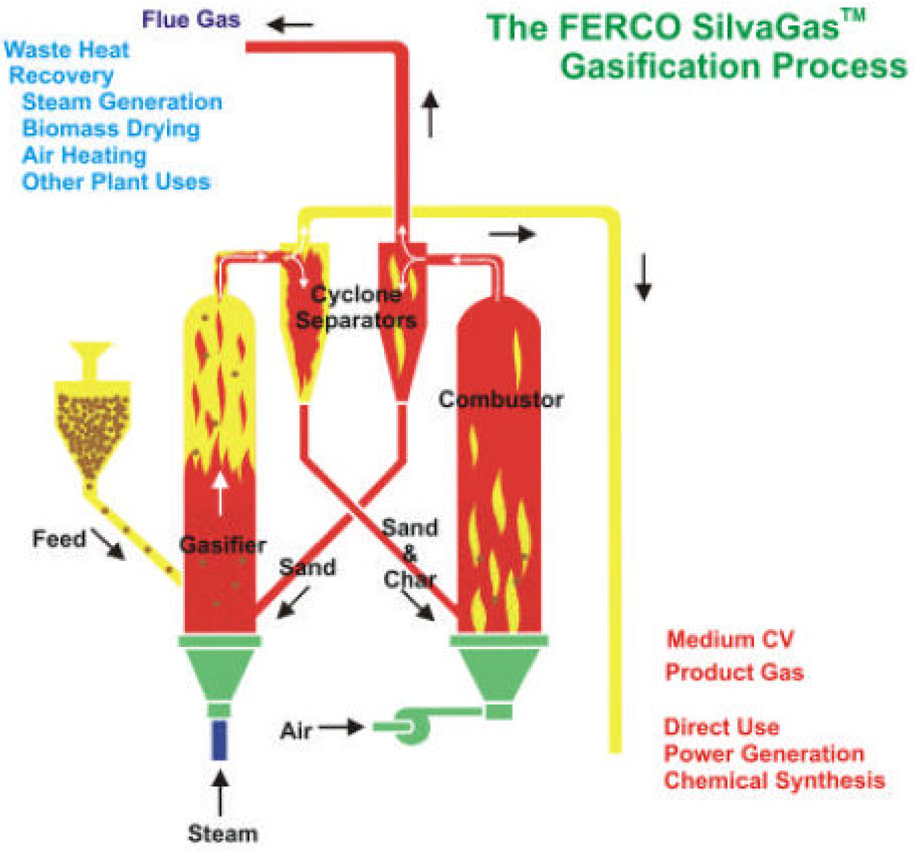

Figure 30. **Ferco process (179)**

4.4.2 Burlington plant

For more detailed information about this plant please see the paper by Paisley et al. that gives details of operational experience at the Burlington plant (101). The plant has had some operational problems, with the refractories falling off the inside of the main gasifier.

The project was successful in creating and co-firing producer gas in the McNeil boiler. A gas turbine was not installed. It is uncertain if DOE will support demonstration with the gas-turbine as the emphasis on federal renewable energy research is now focusing on transportation fuels because of energy security issues. FERCO is not able to finance the demonstration with a gas turbine by itself.

4.5 Foster Wheeler

Foster Wheeler Power Group Europe has headquarters in Helsinki, Finland (99). Foster Wheeler is recognized as a leader in engineering design and supply of fluidized bed boilers, supercritical and sub-critical coal units, heat recovery steam generators, industrial steam generators, package boilers, selective catalytic reducers and general boiler services (99). Foster Wheeler owns several gasification technologies.

4.5.1 Technology

Foster Wheeler offer a number of different gasification technologies. These are the atmospheric updraft gasifiers (Bioneer), atmospheric circulating fluidised bed gasifiers (Pyroflow) and a pressurised circulating fluidised bed gasifier (Bioflow). The Bioflow scheme is shown in Figure 31.

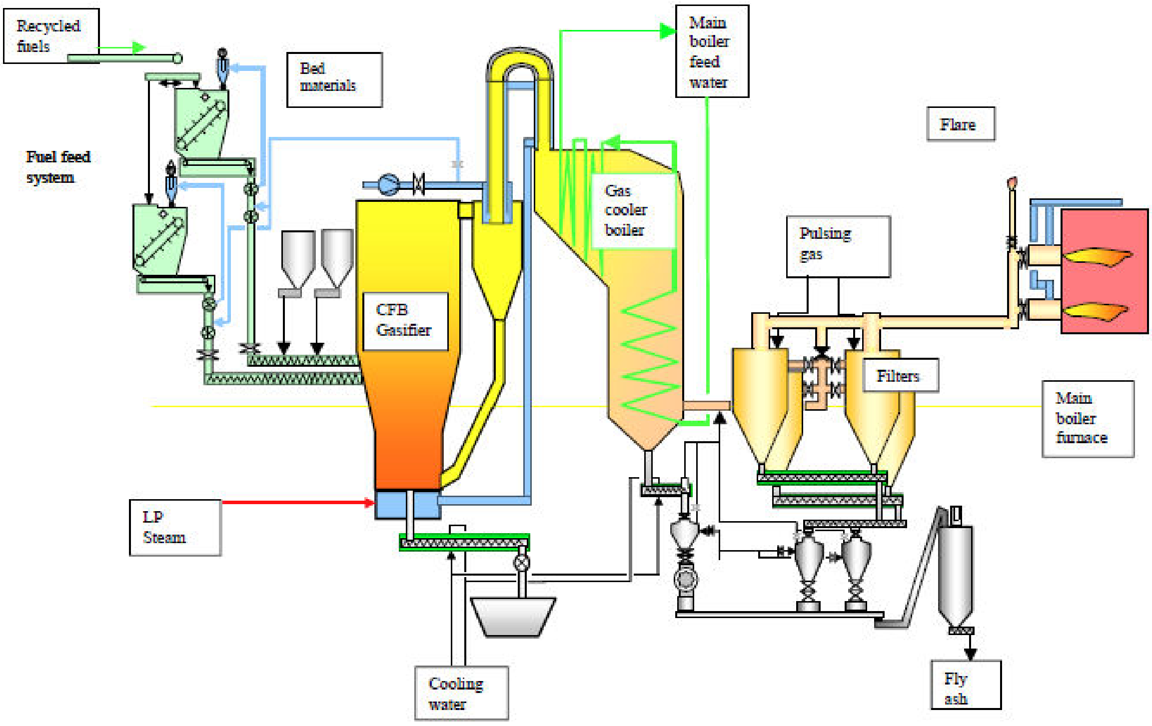

Figure 31. The Foster Wheeler concept for recycled fuels (Ref. Foster Wheeler).

4.5.2 Lahti, Finland

They have a plant at Lahti, Finland that processes a RDF containing plastics, paper, cardboard and wood. The gasifier started commercial operation in 1998 and initially used clean biomass feedstocks (99). A diagram of the CFB gasifier is shown in Figure 32. In subsequent years the share of waste based fuels has increased with the gasifier operating well with the varying fuel mixes (99). The syngas is co-fired in a conventional power station which produces 167MW$_e$ and 240MW$_e$ of district heat for the city of Lahti. The gasifier delivers 50MW$_{th}$ and has a reported availability of 97.5% (99). Figure 32 illustrates how the gasifier is linked to the power plant. In 2004 they had processed a total of 400,000tonnes of biomass fuel and had been operating for 27,000hours (99). The gas composition is given in Table 27.

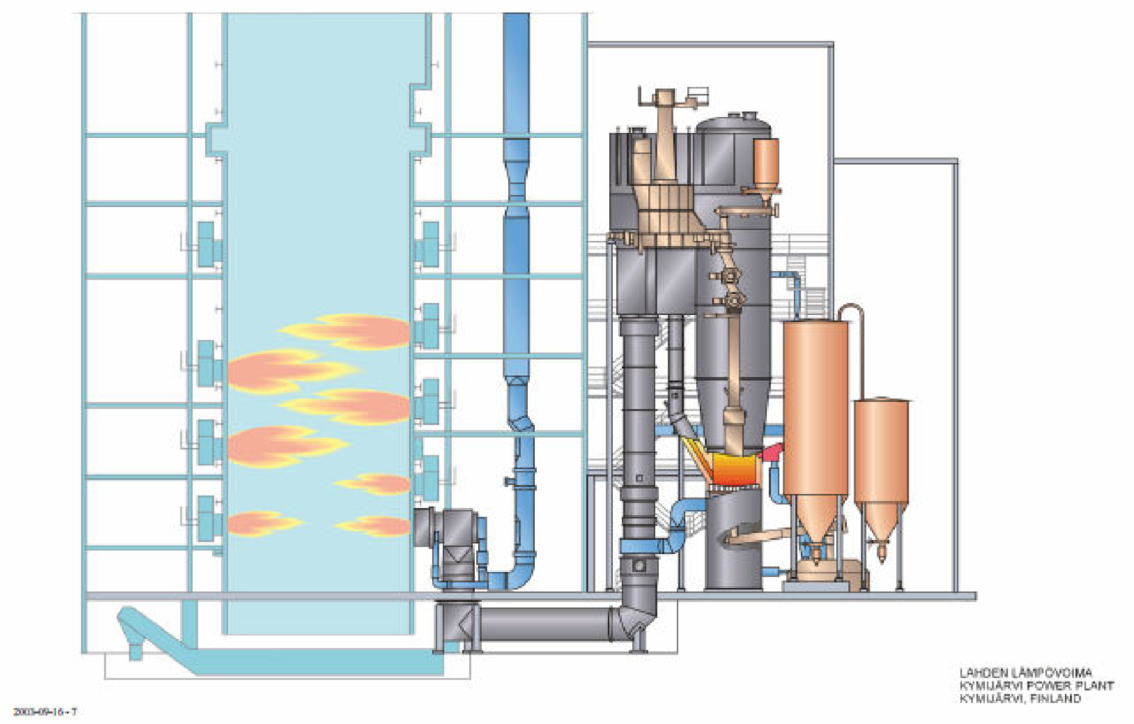

Figure 32. The Foster Wheeler Lahti CFB gasifier (Ref. Foster Wheeler).

The company has thus been very active in commercialising biomass gasification (also with gas engines), however no current BIGCC projects are known.

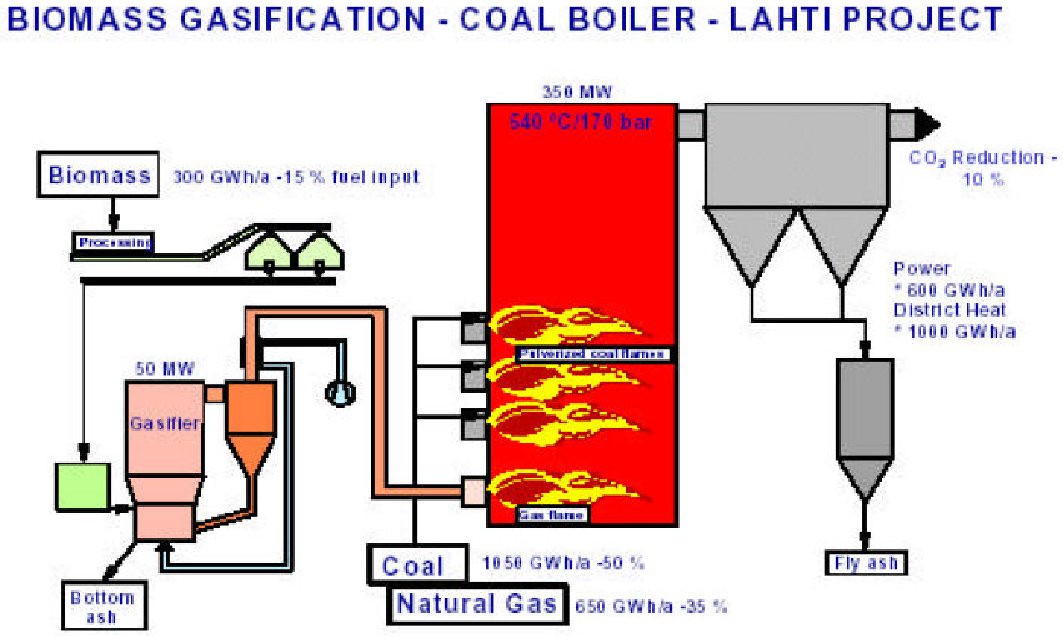

Figure 33. Foster Wheeler Lahti flow diagram (179)

4.6 Novera/Enerkem

Enerkem is focussed on waste to biofuels and chemicals and was founded in 2000 (102). Enerkem's headquarters are in Montreal, Canada and they employ over 80 people (102). Enekrem is a private company majority owned by institutional, clean technology and industrial investors (102). The plants are based on a standardised packaged system.

The technology developed by Enerkem is marketed in Europe by Novera (179). The technology is aimed at processing of plastics or RDF. Novera are offering the gasification and power systems on a build, own and operate basis tied to gate fee, rather than as a contractor installing the plant for others. Novera was established in 1998 and in November 2009 were acquired by Infinis Energy Limited. Novera are involved in a number of renewable energy technologies including landfill gas, onshore wind and hydro plants.

4.6.1 Technology

The processis a fluid bed gasifier. It includes feedstock reception, pelletisation and storage. A simplified flow diagram is shown in Figure 34. A lock hopper system is used to feed into the gasifier. The process accepts particle sizes up to 5cm with a moisture content of up to 20% (103). The waste is gasified in a BFB with silica alumina as the fluidising medium. The amount of air, or oxygen, fed into the bed is about 30% of the stoichiometric amount required for complete combustion (179). Typical operating conditions in the gasifier are 2-6atm and 800-1000^{o}C. Coarse char particles are removed from the hot syngas by cyclones Gas cleaning and cooling takes place in a gas quench tower, venture scrubber, demister, electrostatic precipitator and dehumidification to produce clean syngas suitable for gas engines. Power generation takes place using gas engines or a steam boiler and turbine. Alternatively, the cleaned syngas can undergo catalytic conversion into high value biofuels.

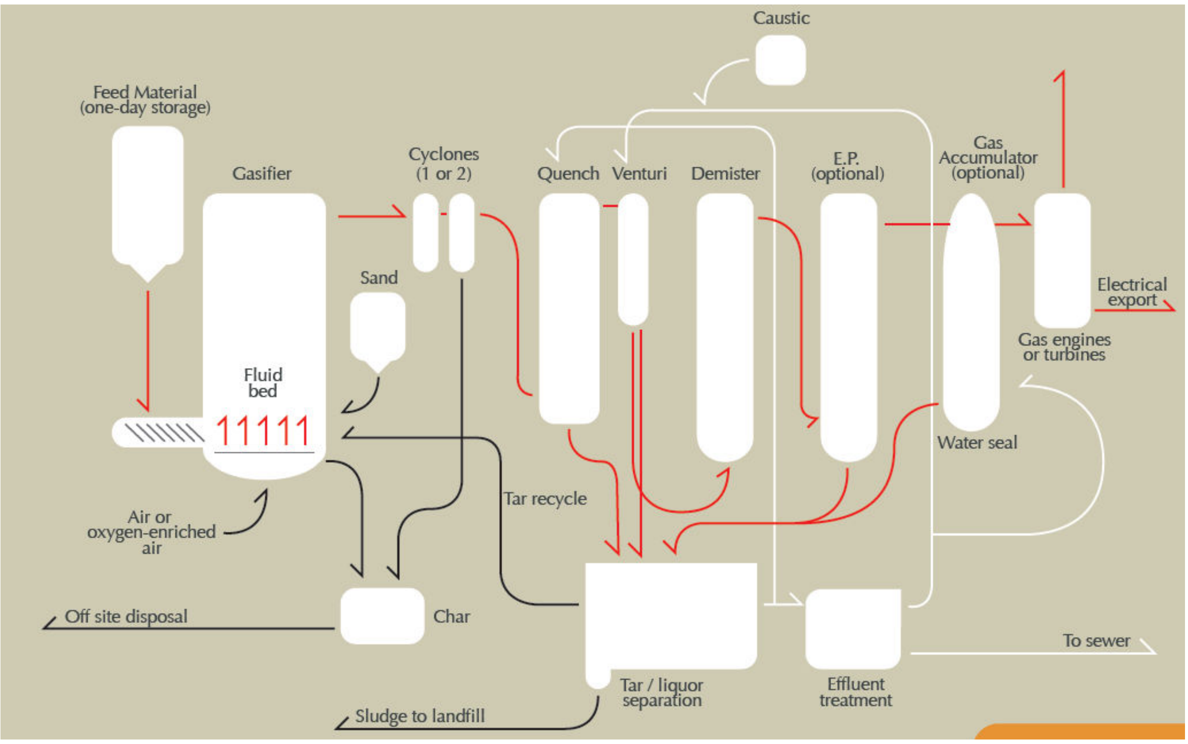

Figure 34. Enerkem simplified flow diagram (104)

4.6.2 Sherbrooke

Enerkem's pilot plant at Sherbrooke has run for more than 4000 hours since 2003 and has successfully produced syngas, team, power, methanol, ethanol and acetates (105). It has a capacity of 475,000litres alcohol per year. The plant has tested over twenty different feedstocks.

4.6.3 Westbury, Quebec

This commercial scale plant has been in operation since 2009 producing ethanol. The feedstock is used electricity poles and the main products are syngas, methanol, acetates and ethanol. The plant is located near a sawmill that recycles used electricity poles. It has a capacity of 5 million litres of alcohol per year. This plant was Enerkem's first commercial scale bio-fuel facility (106).

4.6.4 Edmonton, Alberta

Enerkem, under Enerkem Alberta Biofuels (EAB) will build own and operate the ethanol plant fed by MSW (107). The capacity of the plant is 36 million litres per year ethanol. Enerkem has a 25 year agreement with the City of Edmonton to supply 100,000tons per year of sorted MSW. Construction of the plant began in summer 2010 with operation expected to commence towards the end of 2011. The cost of construction is $80M.

4.6.5 Pontotoc, Mississippi

This project has been awarded funding of US$50M from the US Department of Energy (DOE). It will convert 100,000tons of MSW and biomass feed into 36million litres of ethanol per year. Construction is due to start in 2011 with completion towards the end of 2012. The SilvaGas technology is now offered by Rentech.

4.7 Thermoselect

The Thermoselecct process was developed by Thermoselect in Switzerland with the construction of a demo plant in Italy in 1992. There are a large number of Thermoselect units in operation in Japan. The availability of the plants is about 80%.

The Thermoselect process is a pyrolysis/gasification and melting technology which uses a gas reforming process to recover purified synthesis gas from municipal waste and industrial waste by gasifying the waste and reforming the gas obtained. While minimizing environmental impacts, the process also realizes chemical recycling (108).

4.7.1 Technology

The raw MSW is fed into a high pressure hydraulic press and the solid plug is fed through a pyrolysis barrel. The barrel is indirectly heated using a thermal fluid. The temperature is increased until about 800^{o}C (109). The pyrolysis gases and solid residue are carried forward into an oxygen blown gasification reactor. The exit temperature is in the region of 1200^{o}C (109) the gas syngas is cooled to around 70^{o}C by means of a water jet quench. Following the quench the cooled gas enters an acid gas scrubber to remove HCl and HF. An alkaline scrubber unit, desulphurisation stage and finally a gas drying scrubber result in a clean syngas for use in gas turbines or engines.

3,000 hours operating experience at Chiba of gas engine consuming syngas at rate of 1,700Nm^3/h. Total annual costs (operating and cost of capital) for 100,000tpa plant £114/tonne equating to £11.4M/year in 2004 (179).

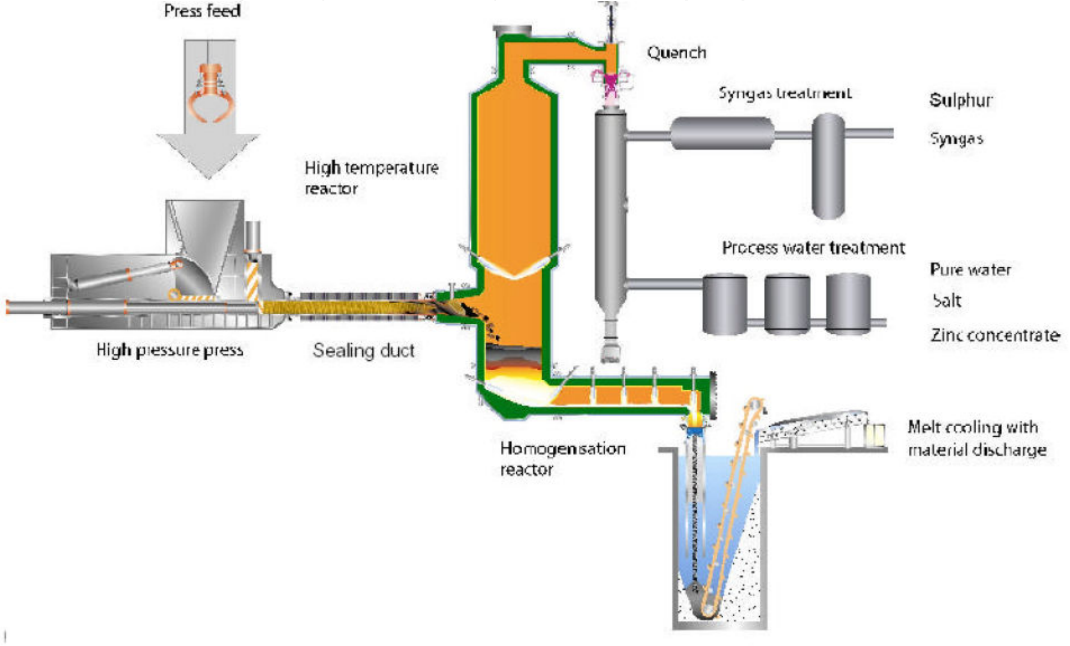

Figure 35. Thermoselect diagram

4.7.2 Karlsruhe

The plant was designed to process 225,000 tons of MSW per year but recurring operational problems meant that it never reached full operating capacity (110). During its operation the facility was only capable of processing a fraction of the contracted waste, forcing cities to find alternative disposal routes (110). By the time the plant closed in 2004 it is estimated that it had lost €400M. The plant consisted of three gasifiers, two steam boilers and one steam turbine (111). The design values are given in Table 22.

Table 22. ThermoSelect Karlsruhe design parameters (111)

Number of lines		3
Capacity per line of waste processing	tonnes per hour	10
Annual waste processing capacity	tonnes per annum (tpa)	225,000
Additives		
Oxygen	Mm^3/a	82
Natural gas	Mm^3/a	7.2
Water	tpa	135,000
Other additives	tpa	6,000
Products		
Synthesis gas production	tpa	215,000
Water (pure)	tpa	180,000
Granulate production	tpa	49,500
Metals	tpa	6,500
Sulphur	tpa	450
Salt residues	tpa	2,700
Metal precipitation products of water purification	tpa	1,700
Heat recovery		
Thermal performance	MW_{th}	100
District heating power	MW	50 maximal
Power to grid	Mw	2.7
Power production	Mw	12.7

The plant was blighted with many operational problems including releases of toxic gases in 2000, an explosion and faults in the equipment (110). In 2002 the facility used $17Mm^3$ of natural gas to process the waste and did not deliver any electricity back to the grid. A detailed case study on the Karlsruhe plant was completed by IEA Bioenergy Task 36 in 2002 (111) which contains more operating details and the problems that the plant encountered. The owners of this facility, ENBW Energie Baden-Württemberg AG, closed the facility at the end of 2004 (112).

Costs

Total annual cost (operating cost and cost of capital) for a 100,000 t/y plant is estimated at £114/tonne equating to £11.4M/year, 2004 basis. However, this is an exceptionally complex plant with sophisticated syngas cleaning equipment and pure oxygen in the gasification process. Thermoselect states that this plant is profitable in Japan (179).

Table 23. Cost of Thermoselect technology, 2005 basis, US$ (71)

Throughput (TPD)	300
Capital Cost	75,511,000
Annual Net Cost	18,615,132
Annual Revenue	4,430,873
Tipping Fee or Break Even Tipping Fee ($/Ton)	186.00

4.7.3 Chiba, Greater Tokyo, Japan

The first facility in Japan has been in operation in Chiba in Greater Tokyo since autumn 1999. It is a 2-line facility with a capacity of 100,000 tonnes per annum. The facility is used for waste disposal of domestic, commercial and industrial waste. Approx. 80% of the synthesis gas (see Table 24 for composition) is passed on to a neighbouring steelworks in Chiba. A 1.5 MW gas engine module is used to generate electricity in the plant itself. The gas engine emissions are shown in Table 25. Working in collaboration with Toshiba, a 200 kW fuel cell is currently undergoing trials for synthesis gas utilisation in order to achieve the highest possible efficiencies for the conversion into electric energy in future (112).

Table 24. Syngas composition (Error! Bookmark not defined.**)**

Feedstock	**MSW**	**Industrial waste**
Syngas composition		
H_2 (%)	30.7	32.4
CO (%)	32.5	43.1
CO_2 (%)	33.8	18.8
N_2 (%)	2.3	-
Dioxins (ng-TEQ/m^3)	0.00039	NK
Dioxins (O_2:12% conversion value) (ng-TEQ/m^3)	0.00009	NK

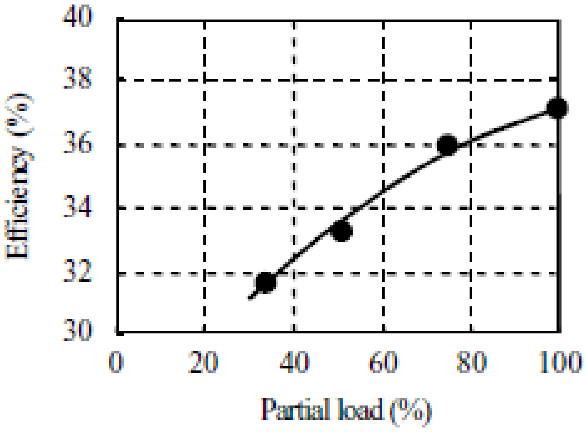

Figure 36. Gas engine electrical efficiency in partial load at Chiba (Error! Bookmark not defined.**)**

Table 25. Emissions of gas engine at Chiba (Error! Bookmark not defined.**)**

Dioxins (ng-TEQ/Nm^3)	0.0000072
Dust (mg/Nm^3)	0.2
NOx (ppm)	14
HCl (mg/Nm^3)	<5

4.7.4 Mutsu, Japan

Since April 2003 a Thermoselect plant is in commercial operation in Mutsu in the north of Japan. The plant is equipped with two thermal treatment lines and has a capacity of 140 tons per day. The plant operates on municipal solid waste (MSW). A gas engine power production facility is integrated into the plant, transforming the syngas efficiently into electrical power with two 1.2 MW engines.

Five more Thermoselect facilities are operating in Japan processing MSW and industrial wastes (112).

4.8 TPS

TPS is a privately owned Swedish research and development company that began work on gasification in the early 1980s (113). TPS has subsequently been purcahsed

4.8.1 Technology

Gasification takes place in a CFB reactor with gas cleaning by means of a catalytic tar cracker and cold gas cleaning in a filter. The tar cracker operates at atmospheric pressure and approximately 900°C (113).The raw gas contacts the dolomite within the tar cracker and is broken down into lighter components. As the gas from the tar cracker is cooled, HCl is absorbed by the dolomite to form $CaCl_2$ which is removed in a downstream filter (113). Depending on subsequent gas usage a wet scrubber may or may not be added as a final gas cleaning step. A schematic of the TPS gasification process is shown in Figure 37.

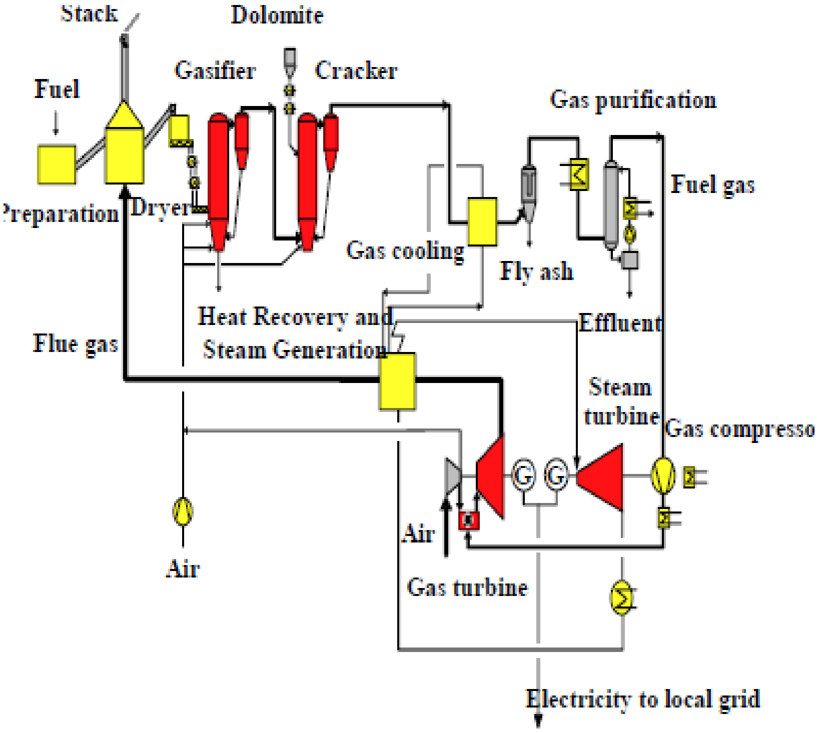

Figure 37. Schematic of TPS gasification process (99, TPS)

4.8.2 Greve-in Chianti, Italy

This plant consists of two gasifiers and has been in commercial operation processing RDF since 1992. The gasifiers operate under atmospheric pressure at approximately 850°C (113). The raw gas is not cleaned (apart from solids removal) before being sent to the adjacent cement plant furnaces or to a boiler. The gas produced has a LCV of about 8MJ/Nm^3 with a composition shown in Table 26. Steam produced in the boiler drives a 6.7MW$_e$ steam condensing turbine. The plant has been operated intermittently due to difficulties in supply of RDF pellets of required quality (99).

Table 26 – TPS Italy, gas composition (113)

Component	vol%
H_2O	9.5
CO	8.8
H2	8.6
CO_2	15.65
N_2	45.8
CH_4	6.5
C_xH_y	4.9
H_2S	48.6 ppm

4.8.3 Värnamo, Sweden

This co-generation plant was constructed in the 1990s and uses the Bioflow technology (now owned by Foster Wheeler). This plant was a biomass fuelled integrated gasification combined cycle (BIGCC). The plant was commissioned in 1993 and completed in 1996. The plant was mothballed in 2000 but has been reconstructed for syn gas production (99, 114). The biomass fuel consisted mostly of bark and wood chips, but other fuels including RDF were trialled successfully.

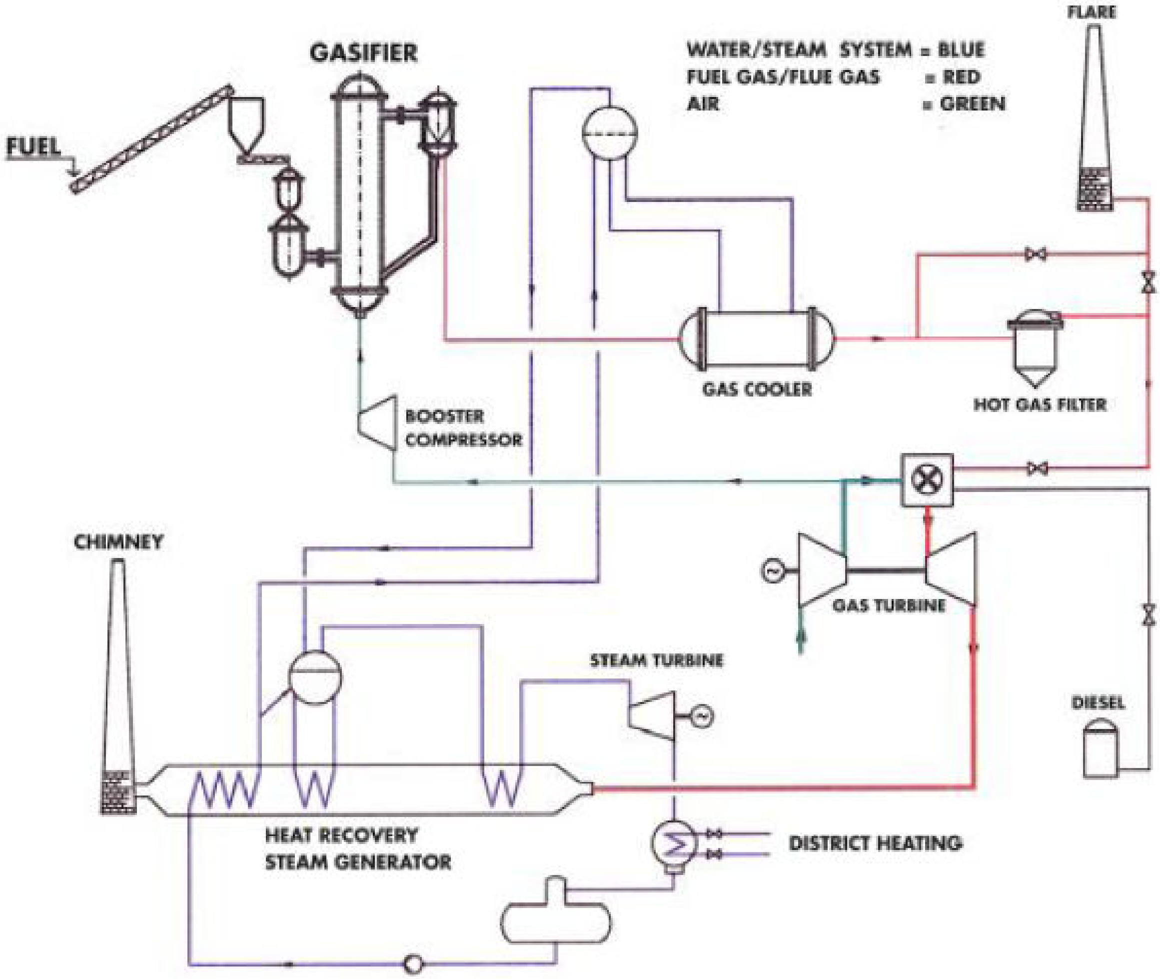

Figure 38. Varnamo plant diagram (114)

The plant consists of an air blown pressurised CFB gasifier followed by a Typhoon gas turbine. The plant diagram is shown in Figure 38. The plant generated 18MW_{th} with a 4tonne per hour feed. Over 8500 hour of operation were achieved with 3600 hours including the gas turbine. Ammonia was not removed from the fuel gas and the emissions of oxides of nitrogen were typically 50-100ppmv in the gas turbine exhaust. This is two to four time higher than from a natural gas turbine (99). The gas composition reported for Värnamo compared to the Lahti CFB gasifier is shown in Table 27.

Table 27 – Gas composition, Värnamo compared to Lahti (wood fuelled) (99)

Compound	**Värnamo Wood (typical)**	**Biomass (Lahti)**
Carbon monoxide	15.5-17.5 %v	4.6 %v
Hydrogen	10-12 %v	5.9 %v
Methane	5-7 %v	As higher HC
Higher hydrocarbons		3.4 %v
Carbon dioxide	14-17 %v	12.9 %v
Nitrogen	45-50 %v	40.2 %v
Water vapour	As dry	33.0 %v
Ammonia	0.13-0.17 % vol	0.1-0.13 %v
Hydrogen sulphide		50-80 ppmv

4.9 Non UK Pyrolysis Companies

Companies who operate a pyrolysis process for waste minimisation typically burn the gases for heat and then possibly steam generation, such as the Mitusi R21 process and the Ebara TwinRec process. As these do not fit within the definition of a pyrolysis process where the gas iscleaned up for power generation in a prime mover, these have not been extensivelt reviewed.

A complete worldwide review of waste pyrolysis and gasification technologies is out of the scope of this work. For further information the authors suggest the following reports:

- Final Report, Waste-to-Energy Review of Alternatives, Prepared for Regional District of North Okanagan, May 2009, CH2M HILL Canada Ltd.
- Robert B. Williams, Technology assessment for biomass power generation UC Davis, Draft Final Report, SMUD ReGEN Program, October 2004.
- Solid Waste Conversion: A review and database of current and emerging technologies, Final Report, University of California Davis, December 2003.
- Thomas Malkow, Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal, Waste Management 24 (2004) 53–79.
- “Conversion Technology Evaluation Report'' Prepared by URS for the County of Los Angeles Dept of Public Works and the Los Angeles County SWM Committee/IWM Task Force’s ATA Sub-committee, August 2005.
- Fichtner Consulting Engineers Ltd, The Viability of Advanced Thermal Treatment of MSW in the UK, ESTET, March 2004. http://www.esauk.org/publications/reports/thermal%20treatment%20report.pdf

There are a number of companies with carbonisation technologies that could be used for waste disposal, with the appropriate gas cleaning technology. The number of manufacturers of slow pyrolysis plants world-wide is limited and some are listed in Table 28 with details as known.

Further details on potential companies and how they clean their gases in some case are given in Table 31. It should be noted that a reasonable number of these could clean the syngas up for power generation instead of combusting the gas for heat for steam raising.

Table 28 Conventional or established Charcoal production – some example companies

Company	Plant biomass throughput	Location(s) & start date	Description of gas cleaning unit operations (in order)	End gas use	Efficiency or commercial status	Refs.
Agoda, South Africa	8000 t/y	Not known	Not known	Not known	Commercial	115
Alterna Energy Inc., Canada and South Africa	Up to 50 kt/y	South Africa and Canada since 1999	Not known	Combusted for heat in steam turbine	Company claims commercial, but no track record to back that up.	116
Armco Robson	16000 t/y	South Africa	None – gas burnt for heat	Gas burnt for heat		
B. V. Carbo Engineering VMR, Netherlands	Modules of 4000 t/y	Namibia, South Africa, Estonia, Ghana, Belgium, USA, China and France	Not known		No reply to enquiries	
CML/JKCB France	12000 t/y	Valbois, France, 1993	None	Gas burnt for heat	Commercial	117
	12000 t/y	Eurotrada, Belgium, 1997	None	Gas burnt for heat	Commercial	
	30000 t/y	Dordogne, France, 1997	None	Gas burnt for heat	Commercial	
	15000 t/y	Sarthe, France, 1999	None	Gas burnt for heat	Commercial	
	15000 t/y	Lot et Garonne, France, 1999	None	Gas burnt for heat	Commercial	
	6000 t/y	Garonne, France, 2000	None	Gas burnt for heat	Commercial	
	9000 t/y	Les Landes, France, 2002	None	Gas burnt for heat	Commercial	

Company	Plant biomass throughput	Location(s) & start date	Description of gas cleaning unit operations (in order)	End gas use	Efficiency or commercial status	Refs.
Degussa (Reichert), Germany	70,000 t/y	Bodenfelde, Germany	19 stage distillation and chemicals recovery process	Gas burnt for process heat	Commercial	
International K&K Enterprise, Korea	Not known	Not known	Not known	Not known	Commercial	118
Lambiotte	7000 t/y	Belgium and France	Multi-stage condensation process on original plant in Clemency, France	Burnt for heat	Commercial - offered	
Lurgi	70,000 t/y	Bunbury, Australia, 1989	Not known	Not known	Commercial - offered	
O.E.T. Calusco	6000 t/y	Milazzo and Mortera, Italy	Not known	Not known		
Okadora, Japan	15 t/d	Not known, 1997				119

4.10 Commercial/demonstration slow pyrolysis companies

Commercial pyrolysis companies are defined as those which have sold and subsequently operated their technology for more than 10,000 hours with performance guarantees and have operated a plant for over 2 years. The summary of the available technologies over the past 10-20 years are given below in Table 31 with the details of the gas cleaning system used and other plant data. These plants have been used mainly for waste minimisation, most without power generation.

Fast pyrolysis companies were not included as their primary aim is liquids production from biomass and the pyrolysis gas is typically flared or used within the process for purging or for additional heat. Dynamotive is the only fast pyrolysis company who is at present carrying out R&D on the use of their commercially produced char as they use natural gas to heat their fast pyrolysis process, so it is not consumed within the process. See the extensive review of Bridgwater and Peacocke for a summary of fast pyrolysis activities up to year 2000 (120). A more recent, limited review is available (121).

In some cases, the technology distinctions have not been clear – some companies operate processes with separate pyrolysis, gasification and combustion sections. The focus has been on those technologies where the production of a syngas by the primary decomposition of organic matter is the primary objective in the absence of oxygen. In some cases, the pyrolysis and char gasification system have been closely coupled and there is no objective of making a syngas. Some processes also describe their technology as ultra high temperature gasification, when it is in fact pyrolysis with no O_2 present.

Steam gasification is one technology which was not included as the steam is used as a reactive medium and produces a producer gas by chemical reaction with the organic substrate and not by primary decomposition of the organic matter. The Güssing process and MTCI are examples of this.

From the extensive list of companies in Table 28 and Table 31, it was a significant conclusion that of the 120+ companies assessed, only 9 had experience of burning the syngas from the pyrolysis process in a gas engine and none had any gas turbine experience. Several companies claim that the syngas can be used for power generation, but the main use is combustion of the raw gas for process heat or raise steam for power generation using a conventional steam turbine. The companies with syngas and engine experience are noted in Table 29.

Table 29 Companies with syngas use in engines and/or gas turbines

Company	Prime Mover	Electrical Output	Ref
BEST Energies, Australia	Dual fuel diesel engine	150 kWe	122
Ebara, Japan	Not known	1.57 MWe gross 992 kWe net]	132
EPI, UK	Gas engine	300 kWe	
GEM UK	GE Jenbacher J620 Yorwaste [Banham power project]	1504 kWe each	123
Klean Industries, Canada	Gas engine	220 kWe	124
Pyromex, Switzerland	Gas engine [unspecified]	1380 kWe	130
PKA, Germany	Gas engine [unspecified]	NK	136
PTE, South Africa	GE Jenbacher J620 (?)	1.5 MWe each	
Waste Gas Technology [now part of Energos, UK and Norway]	Gas engine [unspecified]	55 kWe	136

Although many pyrolysis companies claim that their gas is suitable for use in engines or turbines, the paucity of information on such prime movers would suggest otherwise. The main reason is the gas cleaning requirements to ensure that the gas quality is suitable for an engine from a feedstock that is usually a heterogeneous waste of varying composition. Some limited work on engines using syngas has been published using gases of 5.0-8.8 MJ/m^3 LHV in a single cylinder test cell (125).

Three of these companies are reviewed above, information on Ebara and Pyromax is given below. Ebara generally combusts the gases for heat, then steam to a turbine, but they have also done work on cleaning up the gases and burning them in an engine, hence their inclusion.

4.11 Ebara Corporation Japan

4.11.1 Technology

The pyrolyser, though oftern termed a gasifier, is a proprietary internally circulating fluidised bed of compact dimensions, operated at temperatures between 500 - 600ºC. Shredder residues are fed to the pyrolyser without any additional preparation, just as delivered from the shredder plant. Together with the resulting fuel gas, fine particles are entrained into the gas flow leaving the pyrolyser. The low pyrolysis temperature in the fluidised bed leads to easily controllable process conditions.

The pyrolyser's main function is separation of the combustible portion and the dust from the inert and metallic particles of the shredder residues. Metals like aluminium, copper and iron can be recycled as valuable products from the bottom off-stream of the gasifier as they are neither oxidised nor sintered with other ash components. Together with these metals, larger inert particles are removed. Smaller inerts are returned to the pyrolyser where they serve as bed material. The fine inerts are blown out of the pyrolyser to enter the next stage.

Fuel gas and carbonaceous particles, both produced in the pyrolyser, are burnt together in the cyclonic combustion chamber at temperatures between 1350-1450°C by addition of secondary air. Here, the fine particles are collected on the walls, where they are vitrified and proceed slowly through the furnace. The molten slag is quenched in a water bath to form a granulate with excellent leaching resistance, meeting safely all common regulations for recycling in construction. The high combustion temperature ensures that the most stringent dioxin emission regulations down to 0.1 ng TE/Nm^3 are met with minimal additional measures. The energy content of the waste is converted into electricity and/or district heat with high net efficiency (126).

Table 30. Cost of TwinRec Ebara Technology, 2005 basis, US$ (71)

Technology	Ebara Corporation, Japan TwinRec
Capacity [t/y]	21,160
Capital Cost	47,490,000
Annual O & M	3,590,000
Annual Capital Recovery	2,850,000
Annual Revenue Generated	327,865
Net annual cost: [(O&M + Capital Recovery) - Revenues]	6,112,135
Net cost $/ton MSW delivered	289

Ebara Corporation has 25 Twin Rec TIFG (Twin Internally Circulating Fluidized-bed Gasification and Ash Melting) installations worldwide with 6 facilities in Japan using MSW with capacities up to 155,000 t/y. The estimated conversion to electricity via steam turbine (boiler/steam turbine generator) is approximately 360 net kWh/t (127).

4.11.2 Sakata City, Japan

The municipal waste fluidized-bed gasification-melting furnace system at Sakata City, Japan is processing 72,000 t/y. The dioxin concentration in the exhaust gas of this system meets the local standard. The produced slag meets leachability requirements and is used as pavement material (inter-locking blocks). The exhaust gas from the furnace is used in a heat recovery boiler to produce steam for a steam turbine (max. output 1990 kW). Excess electricity produced is being sold to the local electricity company (though net power to the grid is not known) (72).

4.11.3 Aamori, Japan

The Aomori plant has a thermal capacity of 2 x 40 MW corresponding to 2 x 60,000 tonnes of automotive shredder waste per year. The shredder waste is delivered from 5 shredder plants (input to shredder: cars and brown/white goods) and by 2 non-ferrous separation plants. All shredder residues are fed to the gasifier without pre-treatment. In addition to the shredder waste, the plant is treating mechanically dewatered sewage sludge, in amounts from 0 to 30% of the shredder waste. Other waste plastic materials are treated at times. A hospital waste feeding system has been installed, which is now feeding sealed boxes of hospital waste directly into the TwinRec gasifier.

The plant was commissioned in February 2000. Until January 2003, more than 170,000 t of shredder waste and 30,000 t of sewage sludge had been treated. The flexibility concerning sewage sludge co-treatment was demonstrated with various amounts of sludge, including shredder waste treatment alone. The energy content of the shredder waste is converted to electricity, i.e. 17 MWe gross electricity output (126).

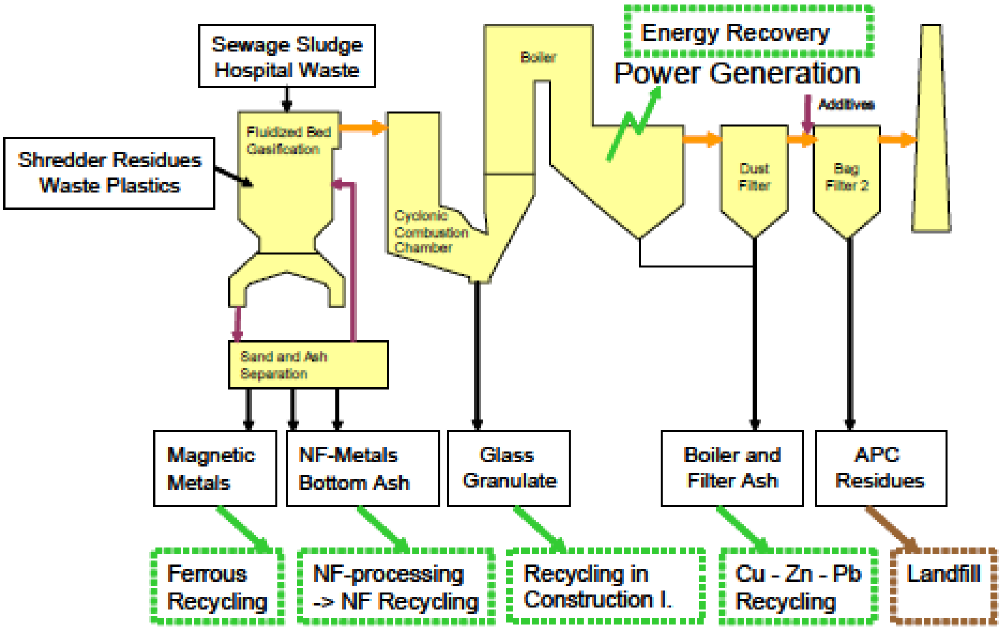

Figure 39. The Aamori plant process diagram (126)

4.11.4 Super Eco Town, Tokyo Bay

EBARA Corporation has constructed a 550 t/d TwinRec gasification plant for the Tokyo Rinkai Recycle Power Corp. The plant treats various industrial waste materials and is part of Tokyo's "Super Eco Town" project, located on an island in the Tokyo Bay. Rinkai is a joint venture company for waste management established by The Tokyo Electric Power Company, Inc. (TEPCO), Tokyo Electric Power Environmental Engineering Co., Inc., EBARA Corporation, Shimizu Corporation and ORIX Eco Services Corporation.

The plant capacity is 550 tons / day in 2 process lines, dealing with non-hazardous industrial waste; net power Generation: 23 MW. The plant started operation in August, 2006 (128, 129).

4.12. PyroMex, Switzerland

The Pyromex company started in 1993 and deleveoped their technologyin the UK in 1995 at Brentwood (130). Since then they have developed the process to a commercial product and are one of the few pyrolysis companies who are cleaning up the syngas for power generation.

At the beginning of 1999 a plant was delivered to a Public Waste Water Treatment Plant in Germany, in order to treat heavily contaminated sludge. This plant was operational until mid 2002 and allowed the company to gain enormously valuable field experience. In July 2004, a large industrial plant was commissioned. Pyromex now possesses a reference plant in Germany.

The company has also constructed a mobile demonstration trailer which is used to show the system's abilities on the spot. It permits potential clients to have tests conducted with their own material, as well as testing of waste products and residues where they occur. This mobile demonstration unit is supported by technical facilities and laboratories in England, Germany and Switzerland.

4,12.1 Technology

The pyrolysis technology is an induction heated rotary kiln, which allows precise control of the kiln temperature at over 1200℃ to give a high quality syngas with low tar content. The gases are cooled and scrubbed prior to engine use. This is one of the highest temperature indirectly heated pyrolysis processes known.

4,12.2 Mass and Energy Balance

A detailed mass balance based on sewage sludge is shown in Figure 40.

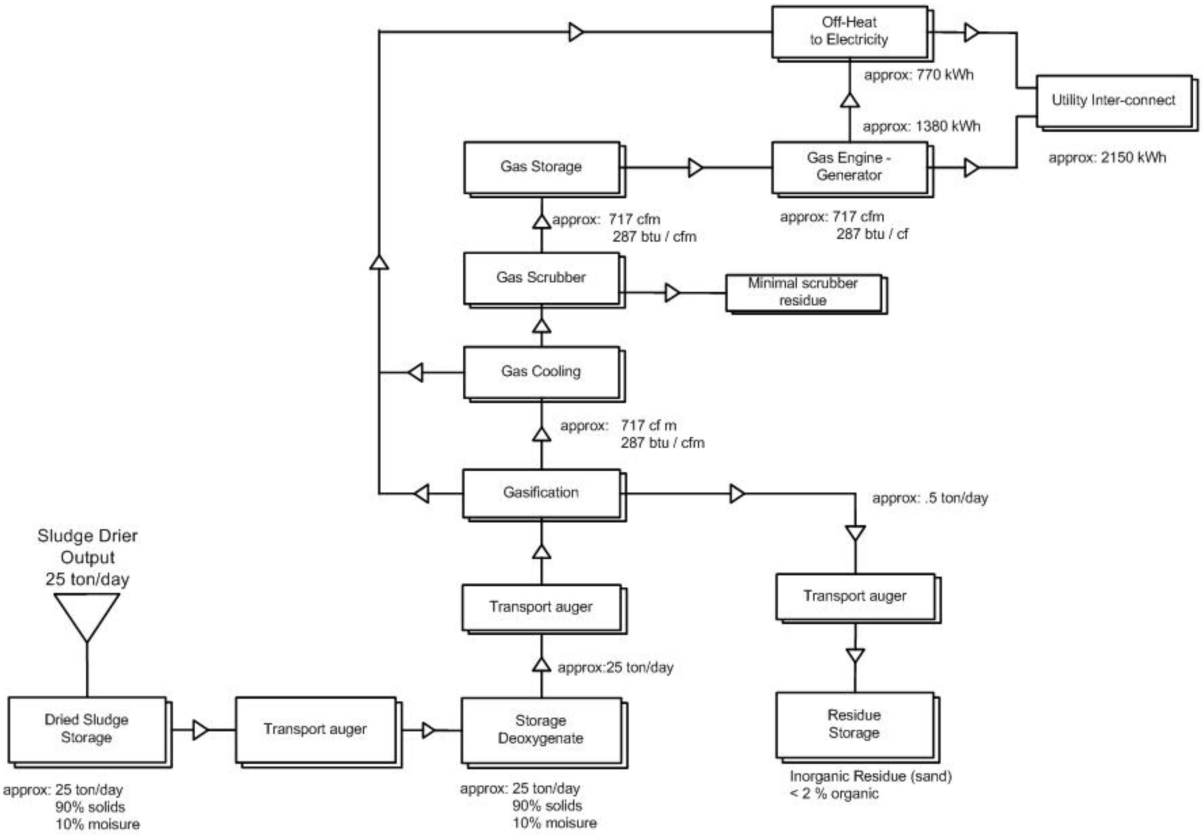

Figure 40. Pyromex Mass and Energy Balance – 25 t/d

4,12.2 Process Emissions

Details on the process emissions are given in Table 40. The emissions comply with EU WID requirements.

4.12.3 Emmerich, Germany

Pyromex's first commercial plant was operated in Emmerich in 2004 and then was moved 3 years after operation and environmental compliance to a water treatment facility in Neustadt. The plant is shown in Figure 40.

Figure 41. Pyromex 25 t/d plant, Germany

Pyromex are also active in the USA. Two large plants were announced in 2006, however neither appear to be been progressed. Data on plant performance is available (131).

Table 31 Advanced Pyrolysis technologies and syngas cleaning approach

Company	Plant throughput	Location(s) & start date	Description of gas cleaning unit operations (in order)	End gas use	Efficiency or commercial status	Refs.
ACM Polyflow	Batch 1.6 t/d	Ohio, USA	Liquids quenched out of gas	Heat for process	Pilot plant	
Adherent Technologies Inc. USA [with Titan Technologies, USA]		Pilot plant New Mexico	NK	NK	Pilot plant	132, 133
Alcyon Engineering (Ti-rec Process) Switzerland	24000 t/y (2 lines)	Kaoshiung, Taiwan 2000	Proprietary “quench” system	Power generation	Commercial Demonstrator operating	134
Babcock Krauss-Maffei Industrieanlagen GmbH (BKMI) a BBP subsidiary [see Wastegen]	2 x 3 t/h 2 x 7.3 t/h	Burgau, 1984 Hamm, 2002	Pyrolysis gas is de-dusted in an aerocyclone Modified to a fabric filter, a superposed dry sorption and an ancillary catalyst after gas cooling to 200℃ with >99wt% dust removal	Power generation in a steam turbine 2.2 MWe CHP plant	Commercial	135, 136
Balboa Pacific Corporation, USA	Up to 360 t/d Modules offered 1 t/h pilot	Projects up to 1800 t/d planned in 2000 1 project in Australia delivered, but never operated	Particulate filter on combusted gases only No gas cleaning	Syngas burnt for steam generation additional heat recovery options offered	Commercial	137
BEST Energies, Australia and USA	0.3 t/h Australia	Gosford, Australia 2005	Syngas cleaned prior to use to heat the process and for power generation	Syngas burnt in a dual fuel diesel engine	Pilot	138
CMI NESA, Belgium	4 -10t/h	15+ reference plants since 1980	None	Syngas burnt for steam generation	Commercial	139

Company	Plant throughput	Location(s) & start date	Description of gas cleaning unit operations (in order)	End gas use	Efficiency or commercial status	Refs.
Compact Power, UK	1 t/h [2 x 0.5 t/h modules] multiples	1 t/h Bristol, UK 2001 0.15 t/h unit for QinetiQ 2007	Combusted syngas is passed through a dry a scrubber with Na_2CO_3 addition SCR treatment of gases	Syngas burnt for steam generation – heat or power production	3 stage: pyrolysis, gasification and combustion Closed down 2008	140, 141
Conrad Industries, USA [see KleenAir Products Co. technology]	3.5t/d & 24 t/d (pilot plants)	Chehalis, Washington, USA	Wet scrubber to remove liquids and tars	Syngas burnt to heat the pyrolysis kiln	Commercial offered	132, 142
Cynar PLC, UK [licensee of Ozmotech Pty. Ltd., Australia]	10-20 t/d modules	9 plants in Japan [no details]	2 stage condensation Catalytic tar cracking Water removal	Syngas burnt to heat the pyrolysis kiln	Commercial Only for plastics	143
Ebara Corporation, Japan	4950 t/y	Nakasode 3-2, Sodegaura City, Japan 2004	Syngas is cleaned in a water scrubber	Syngas is combusted in a reciprocating engine for power production [1.57 MW gross/992 kWe net]	Commercial [Also operate a gasification process]	132
Entech, Australia (IET Technology Ltd in UK)	0.25-100 t/d	Extensive reference list available since 1989	None	Steam generation for power production or processes	Commercial ''Pyrolytic gasification''	144
EPI, UK	1 t/h C&I wastes 5 t/h 1 t/h	Mitcham, UK Canforth, UK Kula, Turkey	Cyclone for dust removal 2 stage quench and scrubbing system Gas filter	Power generation	Commercial demonstrator	
GEM Ltd., UK [Also GEM America and GEM Canada]	14,000 t/y 36,000 t/y 12,000 t/y	Bridgend, Wales 2000-2002 Spain, 2006 Yorwaste, 2009	Syngas cleaned using a cyclone to remove solids then quenched in ~½ second to 24℃ using a spray quench column employing recycled mineral oil. Chlorine compounds are removed. Other compounds removed in wet scrubber.	Syngas to power generation. UK experience on a GE Jenbacher engine. No details.	Commercial	145, 146

Company	Plant throughput	Location(s) & start date	Description of gas cleaning unit operations (in order)	End gas use	Efficiency or commercial status	Refs.
Hebco, Canda	NK	Quebec, 1995	NK	NK	Not actively promoted	132, 142
International Environmental Solutions Inc., USA	50 t/d	Romoland, Ca, USA 2004	None	Gas burned for heat	Commercial system offered	132, 147
JND Thermal Processing, UK	Various up to 8 t/h	None published	Water quench Water scrubbing	Gas engine as required	Commercial Kiln only	148
Klean Industries Inc., Canada	Modules up to 20 t/d offered	2.5 t/d, Okayama, Japan 16 t/d, Odo, Japan 2000 32 t/d, Zarnovica, Western Slovakia 2007	Gas scrubbing and cooling	Syngas is used for heating the process, steam generation or co-fired with producer gas in an engine	Commercial	149
Kubota, Japan and Ishikawajima-Harima Heavy Industries (IHI), Japan	NK	NK	Syngas burnt to heat kiln	Process heat	Assumed available	150
LIG (Weidleplan technology), Germany	NK	NK	NK	NK	Status unclear	132
Mechanical Waste Conversion Corp., USA	1 t/d	Saginaw, Michigan, USA 1998	Condensation of liquids	Combusted for heat	Demonstration	
Metso Minerals, USA	0.1 t/h	USA 2000	2 stage packed tower	NK	Pilot	151, 152
Mitsubishi Heavy Industries, Ltd. (MHI), Japan	3 t/h x 2	Yokohama Dockyard and Machinery works, 1984	NH_3 injection $Ca(OH)_2$ addition Bag filtration Dioxin in flue gas: 0.0013 ng/nm^3	Combusted for steam generation Steam at turbine inlet: 2.6MPa 300ºC Generator output: 2200kWe		153

Company	Plant throughput	Location(s) & start date	Description of gas cleaning unit operations (in order)	End gas use	Efficiency or commercial status	Refs.
Mitsui Recycling R21 (Siemens licencee)	16 t/h MSW	1 t/h demonstrator, Yokohama (moved to Chiba 1999) 2 x 5 t/h Yame Seibu, Japan, 2000 2 x 9.2 t/h Toyohashi City, Japan 2002 2 x 3.2 t/h Ebetsu City, Japan 2003 2 x 4.8 t/h Nishi Iburi, Japan 2003 2 x 3.7 t/h Kyouhoku, Japan 2003 2 x 6 t/h Koga Seibu, Japan 2003	Agent to remove HCl [not specified] CO < 10 ppm Dioxins < 0.1 ng-TEQ/nm^3	Syngas burnt for heat for steam generation for power	Commercial Technology licence from Siemens who withdrew from market after fatality at 8 t/h plant in Furth, Germany, 1992	154, 155
Noell KRC Energie – und Umwelttechnik, Germany	5 t/h 0.7 t/h	Salzgitter 1996-1999 test unit Freiburg 1984	2 stage quench alkaline scrubbing Flue gases after combustion are dry scrubbed using lime and activated carbon and SNCR for deNOx	Gas can be used to heat process, or burnt in an engine or turbine	Discontinued Technology bought by Future Energy GmbH bought out by Siemens Power Generation in 2006	136
North American Power, USA	11 or 50 t/d	Las Vegas, USA 2003	none	Syngas burnt for heat Option of wet or dry scrubber on burner exhaust to meet emission limits		132, 156, 156

Company	Plant throughput	Location(s) & start date	Description of gas cleaning unit operations (in order)	End gas use	Efficiency or commercial status	Refs.
Pan American Resources, USA	100 t/d	None in operation	Particulate removal Gas scrubbed to remove Hg and acid gases	Steam generation for steam turbine	Commercial but none in operation	165
PKA, Germany	0.13 t/h 1 t/h 1.5 t/h	Aalen-Goldshöfen [1994-2002] Bopfingen, Germany 1993 Freiberg, Germany 2000	Partial high temperature oxidation [1000℃] Gas cooling Initial quench and scrub NaOH scrub H_2S filter Activated carbon filter	Syngas burnt in gas engine [Aalen-Goldshöfen]	Status unclear (possibly closed down)	136
Pyromelt, [ML Entsorgungs und Energieanlagen GmbH, Germany]	NK	NK	Syngas scrubbed with liqht and medium fractions of pyrolysis liquids Syngas burnt to heat kiln	Syngas burnt for heat for kiln	Commercial Not being marketed	136
Pyromex, AG Switzerland Pyromex , USA	25 t/d 400 t/d 150 t/d	Emmerich, Germany 2000-2002 Anaheim, USA 2005 Palm Springs USA 2005	Cyclone Gas scrubbing with additives	Gas engine [1380 kWe]	Commercial Status unclear Status unclear	130
PYROPLEQ process by Mannesmann Demag Energie- und umwelttechnik GmbH (MDEU) [see Technip]	see Technip	see Technip	None	see Technip	see Technip	
Seiler, Austria	7-84 t/d	NK	None	Syngas burnt for heat	Commercial Pyrolytic combustion	157
Serpac Pyroflam, France	1 t/h 2 t/h	Budapest 1996-2003 Keflavic, Iceland 2005	none	Syngas burnt for heat for steam and power generation	Commercial	136, 158

Company	Plant throughput	Location(s) & start date	Description of gas cleaning unit operations (in order)	End gas use	Efficiency or commercial status	Refs.
Siemens KWU, Germany – see Mitsui R21 and Takuma	2 x 5 t/h,	2 x 5 t/h, Furth, Germany 1997	none	Steam generation for heat or for power production	Commercial Licensed to Mistui R21 and Takuma, Japan	132
Takuma, Japan [Siemens licence]	2.5-3.5 t/h MSW	Kanemura Co. Ltd., 3.5 t/h, 1998 [2 MWe] Kokubu, 2003, 1.6 MWe Oshima 2.5 t/h x 2 Kakegawa 2.7 t/h x 2	Gas quenching (cooling) Activated carbon injection De-dusting Lime addition Further dust removal Activated carbon reduce dioxins from 0.026 to 0.002 026 ng-TEQ/nm^3	Flared or burnt in combustion chamber to melt ash and raise temperature. 2 MWe through steam turbine on hot combusted gases	Commercial	132, 136, 145, 159, 165
Terra Humana, Hungary	0.1 t/h biomass	0.25 t/h, Hungary, 2005	Gas burnt for process heat	Heat the kiln and/or drying	Claimed commercial. Licensed to VERTUS Ltd. (a subsidiary to Nviro Clean Tech Ltd.)	160
Thide [EDDITh Process], France	0.5 t/h 1.25 t/h 2.5 t/h 3 t/h 8 t/h	Vernouillet, France 1998 Nakaminato, Japan 2000 Itoigawa, Japan 2002 Arras, France 2003 Izumo, Japan 2003	None – gas burnt directly after reactor for process heat	Syngas burnt for heat for the kiln and to raise steam for power generation in a steam turbine	Commercial	136, 161, 165
Titan Technologies, USA [see Adherent]	150 t/d	2 in S. Korea 1 in Taiwan			Commercial	
Traidec DTV, France	0.6 t/h	France 1993	None	Steam generation	No commercial units	165
VTA, Germany	60 t/d	USA	Not specified	Not stated	Commercial	162

Company	Plant throughput	Location(s) & start date	Description of gas cleaning unit operations (in order)	End gas use	Efficiency or commercial status	Refs.
Waste Gas Technology – [now owned by Energos, Norway]	0.5 t/h	0.05 t/h Eastleigh 1992 0.5 t/h Nash, Wales 2000	Hot cyclone to remove solids Waster quench and scrubbing Tars removed in a wet electrostatic precipitator	Power generation Heat the pyrolysis reactor	Commercial No units in operation	165
WasteGen [licensee of Techtrade], UK and Germany Bought Technip technology	40,000 t/y 110,000 t/y.	Burgau, Germany 1984 Hamm, Germany 2002	Syngas passed through primary cyclone followed by ceramic filter Syngas burnt for heat Flue gases treated with activated carbon for heavy metals, Na_2CO_3 and $Ca(OH)_2$ injection	Steam generation for heat or for power production [2 MWe] Steam generation for heat or for power production [12 MWe]	Commercial (MERP) Company no longer active in UK	136, 163, 165

Note: NK Not known

5. PROCESS DATA

Most of the companies listed in Table 31 do not burn the pyrolysis gases for power generation, but they do burn them for heat for steam generation. Data on final emissions are summarised in Table 38 to soil and Table 39 and Table 40 to air. There was a lack of information on scrubbing water or other liquid discharges from any of the processes listed in Table 31. Most of the systems detailed in Table 31 employ flue gas cleaning prior to discharge, depending on the material which is being converted and the end use of the gas.

There is also a general lack of mass balance data for processes, although summaries are given for a range of technologies in (132). This lack of data does make assessment of the overall performance of systems difficult.

Fichtner Consulting Engineers Ltd wrote a detailed report on gasification technologies (179). As part of this work they generated data using different technology suppliers for a theoretical plant processing 100,000tpa of feedstock. Theoretical mass balances are shown in Table 32 for Foster Wheeler and Thermo Select technologies. The data for power generation using a steam cycle is shown in Gas compositions from a range of commercial processes are given in Table 35 and plant mass balance data in Table 36 and Table 37.

Table 33. Upgrading to gas engines or CCGT gives the values shown in Table 34.

Table 32- Theoretical mass balance, 100,000t/y (179)

	Foster Wheeler	Thermo-select
Process	Gasification	Pyrolysis-gasification
Power generation	Syngas only	Syngas only
Input		
Waste	100,000	240,000
Bed material	7,027	
Air	186,216	
Oxygen		127,808
Water		17,528
Gas cleaning consumables		13,032
Total input	293,243	405,226
Output		
Ash/char/slag	30,351	56,136
Gas cleaning residues		8,600
Water		139,136
Total output	291,541	405,224

Gas compositions from a range of commercial processes are given in Table 35 and plant mass balance data in Table 36 and Table 37.

Table 33. Power generation efficiencies based on 100,000tpa theoretical plant (179)

		Novera/Enerkem	IET/Entech	Energos
		BFB gasification	Grate gasification	Grate gasification
		Steam cycle	Steam cycle	Steam cycle
Thermal input	MWth	35.4	34.4	32.1
Syngas energy	MWth	19.4	No data	26.8
Power generated	MWe	6.0	7.3	6.0
Site power use	Mwe	0.7	0.4	1.5
Export power	Mwe	5.3	6.8	4.5
Conversion efficiency	%	55%	No data	84%
Generation efficiency	%	31%	No data	22%
Overall gross efficiency	%	17%	21%	19%
Site power use	%	11%	6%	25%
Overall net efficiency	%	15%	20%	14%
Include power consumed in pretreatment	Yes/No	No	No	Yes
Include chemical energy loss in pretreatment	Yes/No	No	No	No

Table 34. Overall new power generation efficiencies based on theoretical 100,000ktpa plant (179)

		Novera/Enerkem	FERCO	Theoretical
		BFB gasification	CFB gasification	Gasification
		Gas engine	CCGT	CCGT
Thermal input	MWth	35.4	66.0	~
Syngas energy	MWth	25.8	49.5	~
Power generated	Mwe	8.8	26.6	~
Site power use	Mwe	1.0	4.0	~
Export power	Mwe	7.8	22.6	~
Conversion efficiency	%	73%	75%	75%
Generation efficiency	%	34%	54%	41%
Overall gross efficiency	%	25%	40%	31%
Site power use	%	11%	15%	15%
Overall net efficiency	%	22%	34%	26%
Include power consumed in pretreatment	Yes/No	No	No	No
Include chemical energy loss in pretreatment	Yes/No	No	No	No

Table 35 Syngas analyses for various pyrolysis processes and one comparative gasification system [vol%, dry gas]

	GEM, UK (123)	JND, UK [vol%] (164)	PKA, Germany	Pyromex, AG (130)	Thide EDDITh, France (161, 165)	Waste Gas Technology, UK	Biomass Eng. Ltd.	EPI, UK
Process	Pyrolysis kiln	Pyrolysis kiln	Pyrolysis kiln		Thermolysis [1]	Pyrolysis kiln	gasification	Pyrolysis
Feedstock	Chicken litter		MSW		MSW	Sewage sludge	Mixed conifer	C&D waste
Feedstock H_2O [wt%, dry basis]	< 0.1				10 wt%		24.5 wt%	NK
CO	14.58	30.5	14	36	19.1	20	21.24	28.3
CO_2	10.80	15.0	7	18	28.8	14	11.82	13.5
H_2	24.23	24.6	15	33	12.7	23	15.38	10.8
CH_4	34.44	21.8	1	11	16	17	2.05	23.3
C_2H_4	8.42	5.6		2	5.5	8	0.48	10.9
C_2H_6	0.70	0.7			4.9	4	0.03	3.6
C_3H_6					13 [2]	4	0.01	3.7
C_3H_8	0.65	0.4					0.00	0.34
n-C_4H_{10}	0.36 [3]					2	0.00	0.1
C_5+	1.63					3		
Organics							0.07	
N_2	3.70	0.9	62		0		48.97	1.7
O_2	0.49	0.5	0.9		0			
Particulate [mg/Nm^3]			1					
H_2S [mg/Nm^3]			500			10		
HCl [mg/Nm^3]			200			10-15		
NH_3						5-10		
HF [mg/Nm^3]			10					
HHV [MJ/Nm^3]					27.0	26.8	5.39	
LHV [MJ/Nm^3]	26.57	17.5	4		25.1	24.8	5.03	23.1

Notes: 1 high temperature cracked gas 2 C_3+'s 3 1,2-butadiene

Table 36 Plant Mass Balance Data I

Company	CompactPower, UK (165)			Conrad Process, USA (132)	Hebco, Canada	JND, UK (165)	Metso Minerals, USA	Nexus Softer (136)	Noell KRC, Germany
Feedstock	MSW	Hospital waste	Tyres	Tyres	Haz wastes	MSW	Tyres	Tyres	MSW
Additives/supplementary fuels/purge gas [wt%, of feedstock]	1.3	6.2	4.4	1.9					
Process Primary Outputs									
Char [and/or ash, wt%,]				33 [2]	44.0	36 [1]	36.0	32	
Syngas [wt%, feed basis]				19.1	21.0	64	10.0	33	
Liquids [tars or oils, wt%, feed basis]				35.5	13.0 [4]		40.0	25	
Secondary outputs [wt%, feedstock]									
Char (and/or ash)	26.0	19.0	5.0				11 [3]	12 [5]	5.8
Gas cleaning residues	1.4	0.7	5.0		0.7		3		
Stack gases	73.7	79.3	94.0						
Liquids [tars, oils, wastewater]					12.0				

Notes: 1 includes minerals and metals [14.5%] 2 carbon black, includes steel [2 wt%]
3 steel 4 25% used in process 5 includes metals

Table 37 Plant Mass Balance Data II

Company	PKA, Germany (165)	Pyromex Switzerland (130)	Serpac Pyroflam, France (165)	Siemens KWU, Germany	Thide EDDITh France		Waste Gas Technology UK (165)
Feedstock		Sewage sludge		MSW	MSW (165)	MSW (136)	MSW
Additives/supplementary fuels/purge gas [wt%, of feedstock]	11.6 [1]		1	0.75-1.2			1.5
Process Primary Outputs [wt%, feed]							
Char [and/or ash]					32	24	30
Syngas		80			22	40	62 [7]
Liquids [tars or oils]					33 [6]		8
Secondary outputs [wt%, feed]							
Solids	16.0	20	15-25	26.3 [3]	13	12	
Gas cleaning residues			1-1.5			2	
Stack gases							
Liquids [tars, oils, wastewater]	1.8 [2]			2-2.3 [4]			

Notes:		
	1	O_2 [10wt%], $Ca(OH)_2$ [0.4 wt%]
	2	heavy metal sludge
	3	metals [9.5wt%], slag [16.8wt%], gypsum [0.7-1 wt%]
	4	HCl
	5	recovered steel
	6	steam [26wt%], tars [7wt%], 37wt% burnt for heat

There generally is a paucity of published information on most processes as companies are generally no utilising the gas outside of their process. Most of the commercial pyrolysis processes combust the gases for heat and only a few, less than 10, clean the syngas up and use it in gas engines in pyrolysis.

Data on leachate from the solids is given in Table 38. Further data on flare stack emissions are given in Table 39 and Table 40 for selected processes. Detailed information on present projects requires an involvement with the technology provider if data on particular wastes is needed.

Table 38 Solids leachate data [mg/kg] from various processes

Parameter	**Nexus Softer process (165)**	**PKA Process [mg/l] (165)**	**Waste Gas Technology, UK (165)**	**Balboa Pacific, USA (166) [mg/l]**	**Compact Power, UK (140)**	**GEM, UK (132) [ppm]**
Parameters determined on the waste						
% residue relevant to input		**15-25**	**30**			**10**
TOC (w/w %)		2.7				
Limit values (mg kg^{-1}) for compliance leaching test using BS EN 12457- 3 at L/S 10 l kg^{-}						
As (arsenic)	< 1	0.002		0.05		< 100
Ba (barium)				0.37		
Cd (cadmium)	< 0.05	< 0.001	< 0.001	0.1	4	< 100
Cr (chromium (total))	< 0.05	< 0.01		0.01		1330
Cu (copper		0.072	< 0.001			406
Hg (mercury)	< 0.5	< 0.002	< 0.001		0.1	< 100
Mo (molybdenum)						
Ni (nickel)		0.014				
Pb (lead)	< 1	0.002	< 0.004	0.58		< 100
Sb (antimony)						
Se (selenium)						
Zn (zinc)		0.014	< 0.004			
Cl (chloride)						
F (fluoride)						
SO_4 (sulphate)						
All metals					289	
Phenol index		< 0.1				

Table 39 **Flare stack emissions or emissions to atmosphere analysis I [mg/Nm^3, 11vol% O_2 basis]**

	BalPac Pyroconverter, USA (166)	Compact Power, UK (140)	GEM, UK (165, 167)	Mitsui R21 [Siemens] (168)	Noell/Technip /TechTrade (165, 168)	Biomass Engineering Ltd.[1]	EPI, UK	EU WID
SO_2	13	< 25	79	< 0.7	< 5	1413	72.3	50
NO_x	100	< 37	262	< 70 [2]	< 10	532	53.1	400 [< 6t/h] 200 [> 6 t/h]
Particulate		0.2	3	< 0.05	< 1	80-95	0.033	10
CO	36	trace	8	<2.3	< 5	1195	23.7	50
TOC		trace	6 [5]	<1	1	444 5	0.03	10
HCl	6	2	4	< 0.5	< 0.5	13		10
HF		< 0.1	ND	< 0.05	< 0.1	0.15		1
Hg		0.006	ND	0.006	< 0.006	< 0.0237		0.05
Cd + Ti		0.006	ND	< 0.002	<0.0035		0.0028	0.05
As + Pb + Cr + Cu + Mn +Cu + Co + V + Sb + Ni	0.5 [3]	0.006		< 0.05	< 0.04	Cr (VI) < 0.01 µg/Nm^3 Cr (III) < 0.229 mg/Nm^3	0.077	0.5
PCDD/F, 1-TEQ		< 0.003	0.02	< 0.005	< 0.01	0.000284	0.002	0.1 ng/Nm^3
O_2	15.7	< 1				15.2		
Total metals								500 µg/Nm^3
Nm^3 per tonne of waste				3470	2800			

Notes 1. Leather wastes producer gas – flare stack
2 230 excluding deNOX system
3 For elements Cu + Cr + Pb + Mn + Ni + Cd
4 at 11vol% O_2
5 reported as VOCs

Table 40 Flare stack emissions or emissions to atmosphere analysis II [11vol% O_2 basis]

	PKA, Germany (165)	Pyromex, Switzerland (130)	Serpac Pyroflam, France (165)	Technip Pyropleq, Germany (165)	Thide, France (165)	Waste Gas Technology(165)	WasteGen, UK (169)	17BImSchV limits
SO_2	7.7	20	0.6-5.2		< 200	2.4 [3]	8.0	50
NO_x	54	135 [8]	61.3-188.7		470	< 5	167	200
Particulate	2.3	1	4.2-5.2	3		< 0.01	1.4	10
CO	38		0.5-2.5		50	40	< 10	50
TOC	2.3	0.5	0.2-0.5		< 15		1.6	10
HCl	2.3	1	1.7-5	5	30	1 [4]	5.1	10
HF	0.15	0.03	< 0.1	0.2	< 1	0.9 [5]		1
Hg	0.002	0.002	0.03	0.02		< 0.01	0.011	0.05
Cd + Ti	0.002	0.002	0.0008-0.001	0.02 [1]	0.2 [2]	< 0.01 [6]	0.006	0.05
As + Pb + Cr + Cu + Mn +Cu + Co + V + Sb + Ni	0.07	0.07	0.08-0.11	0.2	< 2.1			0.5
PCDD/F, 1-TEQ [ng/Nm^3 I-TEQ]	0.02	0.0005	0.002	0.001		0.03	0.001	0.1
Total metals						< 0.01		

Notes

1	Cd only	2	Cd + Hg only	3	noted as Sulphate	4	noted as Chloride	5	noted as Fluoride
6	Cd only	7	VOCs as carbon	8	as NO_2				

6. GAS CLEANING FOR ADVANCED CONVERSION PROCESSES

6.1 Introduction

Below is a review is given of the principal approaches and where possible, data on specific technology efficiencies and overall collection elimination efficiencies are given, based on actual operating systems, predominantly from the UK and Europe.

A wide range of gas cleaning configurations can be used in waste gasification and pyrolysis systems, highly dependent on the material to be processed and the concentrations of contaminants, metals and the production levels of tars and particulates. Most companies have limited experience in the design of such systems and therefore use specialist gas cleaning companies, however, generally they do not have much experience dealing with tars and particulates from gasification and pyrolysis processes. Some companies therefore develop their own in-house expertise to deal with specific contaminants.

For IC engine applications, the particle and tar levels in the raw producer gas from a good co-current gasifier must typically be reduced to approximately 1wt% of the original values or less. This represents a significant demand on the reliability of any gas cleaning system. 10 years ago, the requirement would have been a 90-95wt% reduction in tar – now its over 99wt%. Techniques for wet and dry scrubbing systems are given below. Prior to gas cleaning, tar levels may be reduced by catalytic or thermal cracking of the tars (170). "Tar" is now officially defined as

Engines and turbines are susceptible to “tars” – organic compounds in the gas. There are a a range of definitions, but CEN TC BT/TF 143 defines “tar” as:

> "generic (unspecific) term for entity of all organic compounds present in the gasification product gas excluding gaseous hydrocarbons (C_1 through C_6)"

This definition is not generally applied to pyrolysis processes, which can cause some issues as there is no definition for the tar content of pyrolysis gases. The same requirements and "tar" definition have been assumed for pyrolysis processes, in particular in conforming with engine requirements as discussed in Section 8.

Suitable gas cleaning methods were proposed by Baker and Mudge, relating to the end use of the gas, as summarised in Table 41 (171). Their review was carried out in 1986, but gives a good indication in the range of unit operations that may be employed.

Table 41. Suitable gas cleaning methods for gasification products related to end use

	Close-coupled boiler	Diesel/SI engine	Gas Turbine	Syn gas
Final Tar loading	2-1.5 g/Nm^3	10-50 mg/Nm^3	1-80 mg/Nm^3	1-80 mg/Nm^3
Technology				
Updraft[a]	None[b]	WS + F	WS[b]	WS[b]
			WS + F	WS + F
			WS +ESP	WS +ESP
Downdraft	None[b]	C[b, e]	C[b]	C[b]
	C	C + F	2C[b]	2C[b]
		WS[b]	C + F	C + F
		WS + F	C + ESP	C + ESP
Fluidized Bed	2 C[b, c]	C + F	C + WS[b]	C + WS[b]
	C + WS[b]	C + WS[b]	C + F	C + F
	C + F	C + ESP[b, d]	C + ESP[d]	C + ESP[d]
	ESP[b, d]		[f]	[f]
Entrained Bed	similar to fluidised bed			

Key

C: Cyclone, 2C: two cyclones in series, F: fabric filter [baghouse], WS: wet scrubber, ESP: electrostatic precipitator

[a] cyclone not effective due to smaller particle size distribution and tar droplets – use wet scrubber to remove tars first if any clean up required.

[b] lower level of contaminants is acceptable – higher level would exceed limits

[c] assumes 50% of particulate is char and 90% burns in burner

[d] ESP is not as effective on particulates with high carbon content and may not be applicable

[e] cyclones are effective for this application but wet scrubbers are often used instead because gas cooling is also required. Also cyclone efficiency is affected by large turndown ratio required in some engine applications

[f] pressurised operation may restrict the size or applicability of gas cleanup equipment [particularly baghouses and ESPs]

Hasler and Morf summarised a very detailed study on the collection efficiencies of different gas cleaning options including sand filters, rotational particle separators, impingement filters included an extensive study into the recovery of particulates and tar and the results are summarised in Table 42 (172).

There are extremely limited reviews and data on the overall performance of gas cleaning unit operations as the expense involved in taking the necessary tar and particulate measurements to recognised standards can be significant.

Table 42. Collection Efficiencies for Selected Unit Operations [%]

Technology	Particulates	Heavy Tar	PAH	Water Solubles	Phenols
Sand bed Filter	70-100	48-95	68-96	77-93	98-99
Wash tower	60-100	10-25	40-60	63-78	0-33
Fabric Filter	70-95	0-45	0-70	30-70	13-30
Rotational Particle Separator	85-90	29-70	0-27	0-26	20-52
Tar adsorber	--	50-62	98-100	--	--

6.2 Wet technologies for physical tar removal

Wet and wet-dry gas cleaning cycles remove tar using physical methods:

- Gaseous tar condensation,
- Gas/liquid mixtures separations,
- Droplets filtration.

The specific energy consumption of wet gas cleaning system is indirectly proportional to the particle diameter (172). Both solid particulates and tar droplets are covered by the term "particles". The separation of small particles requires high specific energy inputs in the form of pressure drop over the filtration system.

6.2.1 Cooling towers and Venturi scrubbers

Cooling/scrubbing towers are usually used after cyclones as the first wet scrubbing units. All heavy tar components condense there. However, tar droplets and gas/liquid mists are entrained by gas flow thus rendering the tar removal rather inefficient. Venturi scrubbers are usually the next step. In venturi scrubbers, typically 2 kWh/1000 m^3 are consumed, corresponding to a pressure drop of approximately 7kPa.

According to Hasler et al. (172), the particle diameter must be below 10µm and the particle concentration must not exceed 50 mg/Nm^3 for IC engine applications, however, as can be seen later, this specification has been significantly tightened. For gas turbines, the corresponding values are 30 mg/Nm^3 and 5 µm. Any scrubber type discussed above can separate particles above 5µm with at least 90% efficiency. However, it has been found during combustion of wood that the mass fraction of flue gas particles with diameter below 1µm is in the range of 40-80% w/w [173]. In an open top gasifier, particles in the range of 0.7-2 µm have been identified [172]. If the same is true for other gasifiers and also waste pyrolysis systems, only venturi type scrubbers are expected to reach the overall particle separation efficiency up to 90% and then in combination with additional gas cleaning in secondary and possibly tertiary stages. For that case, the pressure drop will be in the range of 20 kPa. Fernandez (174) has shown that at a gas/liquid ratio of 1:1, particle concentrations at the exit of the venturi was lower than 10 ppmv.

The correct dimensioning and selection of the wet gas scrubbing system requires information of the particle size distribution in the gas. There are no reliable sets of tar droplets size distribution data from biomass producer gases given the difficulty in online measurement of a representative sample.

In all types of wet scrubbers, some moisture is condensed. As some of the biomass producer gas tars tend to condense even at temperatures of 300ºC, all wet scrubbers will also separate tars to a certain degree. However, very limited data on tar separation are to be found in the literature. Tar separation efficiencies have been reported ranging from 51-91% in a venturi scrubber used to purify the producer gas from a counter-current rice husk gasifier (172). The gasifier generates a gas with approximately 80g/Nm^3 of tars. Before the venturi scrubber, the raw gas is mixed with (clean) recycle gas at a ratio of approximately 20:1. With this dilution, the tar content at the entrance to the venturi decreases to 4 g/Nm^3 approximately. The gas velocity at the entrance is maintained at 56m/s. The pressure drop over the venturi is estimated to be 4 kPa. For the venturi scrubber investigated, the tar separation efficiency has been found for gas to liquids flow ratio [Q_g / Q_l] between 4000 and 8000 (172):

$$\eta_{tar} = 0.78\,\mathrm{Re}^{0.04}\, We^{0.57} \left(\frac{Q_g}{Q_l} \right)^{-0.43}$$

with:

η_{tar} tar separation efficiency in %

Re Reynolds No. $\mathrm{Re} = \dfrac{\rho u d}{\mu}$ (ρ = gas density in kg/m3, u = gas velocity in m/s, d = characteristic length in m, µ = gas dynamic viscosity in kg/ms)

We Weber no. $We = u\left(\dfrac{\rho d}{s}\right)^{0.5}$ (s = surface tension in kg/s^2)

Q_g volumetric gas flowrate in m^3/s

Q_l volumetric liquid rate in m^3/s

Data from the Biosyn gasifier runs show a tar retention of more than 90% at gas/liquid ratios of 1:1. For a venturi scrubber, the following solids collection efficiencies have been reported, as indicated in Table 43.

Table 43. Collection efficiencies

Particle size [µm]	Pressure Drop [" w.g.]	Collection Efficiency [wt%]
1	5	>80
1	10	>91
1	20	>98

Higher power consumption is needed to improve collection efficiency, reflected in a greater throughput of scrubbing media.

6.2.2 Sand bed and sawdust filter

In most cases, sand bed and sawdust filters are used as drop and tar separators after a gas quench system to remove residual particles and tar components. The tar separation efficiency is expected to be lower for a sand bed filter than for a sawdust filter since sand is a non-porous, inert material with a low specific surface area.

Such systems have been extensively tested both in India and in Switzerland for the IISc/DASAG open top gasifier (175, 176). With native wood, the particle separation efficiency has been found to be 80-85% whereas the tar separation efficiency is 60-95wt%. The phenols could be reduced by 95%. This deep-bed filtration mechanism is essentially based on impact separation phenomenon, which is enhanced by the sticky tar simultaneous removal.

In principle, both sand and sawdust filters can also be operated as dry cleaning systems. In this case, the filters have no previous quench but preferably a heat exchanger to reduce the temperature. Since sawdust starts to pyrolyse at temperatures above 110ºC, the gas temperature must be well below this point. However, it has been reported that "dry" sawdust cleaning units also produce condensates (172). Presumably, the temperature gap between gas moisture condensation (approx. 70℃) and the onset of sawdust pyrolysis (110℃) is too narrow to ensure a dry filter operation. Therefore sawdust filters are preferably used with a previous quench system. The quench also acts as a barrier for glowing particles from the gasifier. No experimental data has been found for the particle and tar separation efficiencies from both wet and dry sawdust filters. No experimental data has been found for sand bed filters either.

A general problem with sawdust and sand bed filters is the cleaning procedure of the filter unit. The Danish experience with the sawdust filter after the Martezo gasifier in Hogild showed that cleaning intervals are in the range of 200h operation. The cleaning requires very rigid safety precautions since the tar-loaded sawdust is toxic. Workers have to wear protective clothing and breathing apparatus while handling the filter unit. The sawdust must be treated as hazardous waste. Eventually the contaminated sawdust can be recycled as fuel back to the gasifier. Sand bed cleaning is viewed as being slightly less critical than sawdust filter cleaning. In principle, the sand bed filter system does not need uncovering since the bed can be washed with a soap solution. However, it is not yet clear which precautions have to be taken while handling the washing solution and what type of treatment is needed for the liquid.

Sawdust filters are sometimes stated as dry gas cleaning systems. However, all such filter systems found in the literature generate condensate inside the filter system as well as contaminated solids. The recycling of this tar containing biomass back to the gasifier can be envisaged.

6.2.3 Wet electrostatic precipitator

Electrostatic precipitators (ESP) operate on the principle of charging dust particles and liquid droplets with electrons from a generator electrode (corona discharge). The negatively charged particles are then transported in the electric field to the precipitation (or earthed) electrode. The particles are then discharged and remain on the precipitator surface. For dry electrostatic precipitators, the discharged particles are removed by a knocking mechanism whereas for wet electrostatic precipitators, the particles are removed by a continuously flowing liquid film. For the cleaning of biomass producer gas, only wet electrostatic precipitators should be considered since tar condensation on the precipitation electrode would disable the particle removal from a dry ESP's. With ESP's, particle efficiencies of more than 99% are possible for particles as small as 0.05µm. Due to the low filter temperature and the presence of a flowing liquid film, wet ESP's are considered effective for the separation of aerosols and some of the tar components. Before the wet ESP, a water quench system is used to reduce the gas temperature below its dewpoint. The quench is necessary to ensure wet precipitator surfaces in any operation condition. Partially dry surfaces will lead to disablement of the automatic particle discharge.

Hedden et al. (reported in (172)) have performed preliminary tests with a wet electrostatic precipitator to clean the producer gas from a co-current Imbert gasifier. The gas moisture after the ESP was 50-80 g/m^3 and the ESP was operated in the corresponding dewpoint temperature range from 38-46ºC. The particle separation efficiency was found as 99%, whereas much less tar could be removed. Tar separation efficiencies were determined between 0-60%. With the ESP, some operational problems have been encountered (spark-over, tar and solids deposition). Single test runs were made which lasted for several hours. The longest period of uninterrupted operation was 14 hours.

A wet electrostatic precipitator has also been used during long term gasification tests by Wellman process Engineering without operational problems. Good tar separation efficiencies have been obtained, although no data is available.

There has been a range of configurations of gas clean up systems employed at small scale to clean the gases up. Tests by BEL on a wet walled electrostatic precipitator have shown that tar removal efficiencies of over 88wt% can be achieved under very high gas flow conditions and over 95wt% when the gas flow is at design values (177).

Work carried out by Biomass Engineering Ltd on tar reduction and removal using a venturi scrubber and electrostatic precipitator has achieved problem tar reduction of 94-98wt% for C_3+ aromatic ring compounds (compounds including acenaphthylene and above) and over. Trials using an electrostatic precipitator have achieved tar removal efficiencies of at least 86wt% for similar compounds, as given in Table 44.

Table 44. Tar recovery in a venturi + ESP (VS+ESP) and ESP only gas cleaning system

Gas flowrate (nm^3/h)	396	754	973	1008
Gas cleaning system	VS+ESP	VS+ESP	VS+ESP	ESP
C_3 rings + tars at gasifier exit	222	477	820	207
C_3 rings + tars at system exit	5	22	34	25
% reduction	98	95	96	88

6.3 Dry technologies for physical tar removal

As mentioned, some processes, depending on the type and level of contaminants, may employ catalysts to crack tars and also use adsorbents to reduce acid gases (Sox, HCl, H_2SO_4, H_2S) to reduce the load on the collection system. If hot gas filtration and tar cracking and/or reforming conversion follows temperature should be as high possible. This is the case for physicochemical conversion to tar which is not covered here, as it does not typically apply to small-scale downdraft gasifiers. The collection efficiencies for various technologies are given in Figure 42.

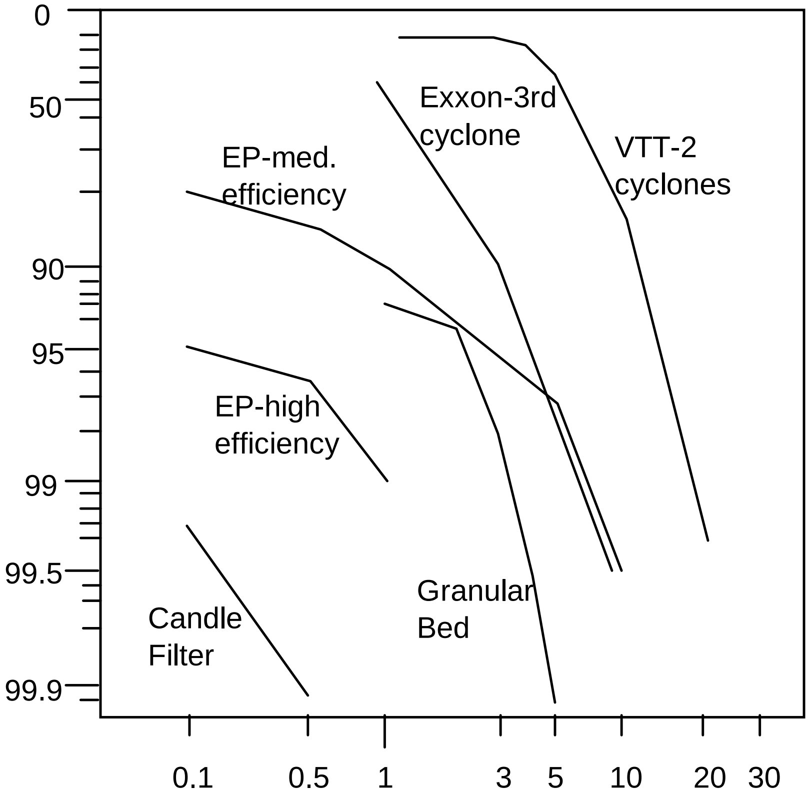

Figure 42. Collection efficiencies for various systems

All of these technologies have been used in pyrolysis and gasification and do have their respective advantages and disadvantages.

6.3.1 Use of filters for simultaneous particles and tar removal

Since most of the dry gas physical cleaning systems operate at lower temperatures, the gas must be cooled before entering the filter by using appropriate heat exchangers. In the case of filtration, inlet temperature is set by the filter type or filter material used and the properties of particles and tar components. Biomass tar tends to condense and/or polymerise at temperatures below 200-300ºC and tar condensation combined with particles can lead to sticky filter cakes that cannot be removed by simple mechanical means.

Therefore, any dry cleaning filter must be operated above a certain critical temperature if only the particles are to be removed and below another critical temperature if the tar is also targeted. The critical filter temperature is evaluated experimentally and depends on the amount of tar and particles generated in the gasifier as well as their nature. It would appear that ceramic filter candles can be used at over 600℃ to filter tar laden producer gas, however the candles do need to be preheated otherwise the initial flow of gas through the cold candle can lead to radpi blocking and hence destroy the candles. Precoat of the candles is one option, but carrying this out continuously on backflushed candles is a significant challenge and represents additional cost.

From experience in the UK, preheating of the filter vessel to 400℃ significantly increases candle lifetime, however, the gasification tars do accumulate in the matrix of the candle with time if the filter cake on the candle is not stably built up on its surface.

6.3.2 Fabric filter

Fabric filters are well-established filter units for flue gas dedusting from various combustion processes. However, in biomass gasification, only limited experience has been gathered so far. In the flue gas cleaning application, the separation efficiencies of fabric filters generally exceed 99.5% even for particles of less than 0.05µm diameter. The dust removal from the filtration surface is done by backflushing the (flexible) fabric filter elements with a pulsed jet of compressed air. For gasification applications, the dust removal must be made with an oxygen-free gas for safety reasons. Preferably, compressed producer gas is used. The preferred filter material today is PTFE (yngas) basis with a maximum filter temperature for continuous operation of 235ºC. Other materials such as Nextel™ and Siltemp™ are available. These fabrics essentially are ceramic fibre tissues and can be operated up to 600ºC. The separation efficiency of Nextel filter elements are expected to be slightly lower than for PTFE based materials. Nextel filter elements will not be destroyed by glowing fly ash particles, but PTFE fabrics can be severely damaged. Their resistance to the backflushing operations is not yet well known on a long-term basis.

Fabric filters have been tested both for circulating fluidised bed (CFB) gasifiers and for fixed bed gasifiers. The tars in the producer gas from the CFB gasifier tested were passed through a dolomite cracker before the fabric filter. The residual tar concentrations after the cracker are in the range 0.5-1 g/Nm3 and the particle concentrations are estimated to be in the order of 50 g/Nm3. No operational problems were encountered during a 200 hours test run and filter cakes could be removed easily and analogous to the flue gas application (Waldheim, reported in (172)). No information is available about separation efficiencies, operating conditions and filter materials used.

6.3.3 Ceramic filter

In contrast to fabric filters, ceramic filter elements have a rigid structure. Hence, the dust removal is more delicate and compressed gas consumption for the dust removal is higher. The ceramic filters can be operated up to 800ºC and in pressurised applications. The critical parameters for ceramic filters are material properties, sealing problems and temperature shock as across the filter element, especially during filter cake removal. Candle solids removal efficiency can be 100%.

6.3.4 Adsorption on activated carbon filters

As an alternative to sawdust, charcoal or activated carbon can be used as adsorbent for high boiling tar components. Charcoal or activated carbons are thermally stable up to 300ºC. Since conventional fabric filters are expected to exhibit a limited tar separation efficiency, an activated carbon filter can be installed after a fabric filter unit to remove high boiling hydrocarbons and possibly phenols. The filter is preferably made as a fixed bed with granular charcoal or activated carbon. The temperature should be as low as possible, e.g. 120ºC, but above the gas dewpoint. The tar-laden activated carbon can be recycled to the gasifier as extra feedstock. No information has been found for the tar adsorption characteristics of carbonaceous adsorbents from biomass producer gas.

6.3.5 Demister

Demisters are centrifugal flow units appropriately designed to coalesce mist droplets from a water bearing gas flow. They can resemble cyclones and hydrocyclones. Their design depends on mist liquid phase properties and gas flow loading. Although design data is proprietary and generally not available in the literature, such demisters and their operation have been reported (172). Tar and water are together removed from the producer gas at the exit of the second stage venturi scrubber. Wastewater containing tar is settled down for insoluble tar skimming then recycled back to the scrubbing loop.

6.4 Conclusions

Data from pyrolysis and gasification companies show that tar reduction efficiencies of 97-99wt% can be achieved in conjunction with solids content reductions of 91-99wt%. Gas cleaning systems are available with high recovery efficiencies, though there are usually 2 or more stages to increase efficiency.

There is a need for further data on collection efficiencies and the development of better design models for thermal conversion systems to account for the presence of non-condensable gases. The gas cleanliness requirements are predominantly driven by engine and turbine manufacturers. The number of non-fuel gas applications are limited to those of Choren Industries (178).

7. COSTS AND COMPARISON OF DIFFERENT TECHNOLOGIES

7.1 Comparison of thermal conversion technologies

Conversion And Resource Evaluation Ltd. has presented published cost data in the Tables above for the more developed or advanced pyrolysis technologies. There is reluctance by numerous companies to release cost data for a wide variety of reasons and this has restricted the amount of information presented on slow pyrolysis with power generation, given that only 8 companies have worked in this area has lead to a paucity of information.

According to the Fitchner Report (179) written in 2004 on the possibilities for thermal treatment of waste in the UK the total capital cost quoted for a 100,000 tonnes/year gasification or pyrolysis plant ranges between £23.5 and £30M. The operating costs are estimated to range from £1.8M/year to £2.2M/year (179). The cost for a plant based on grate combustion technology is estimated to be over £30M.

Due to the wide range of configurations of technologies available, plus the paucity of data in the public domain, it is very difficult to compare all technologies on a consistent basis. Conversion And Resource Evaluation Ltd. undertook a detailed technical and economic evaluation of a range of technologies and these are given below.

The major problem is the power generation or conversion device, as efficiency of engines and turbines is a function of scale and operating conditions, so a firm comparison is therefore not easy. Based on internal models and data we have correlated information on a range of systems and based on the available data, we've given the efficiency of electricity v's net electrical output.

Figure 43 presents the system efficiencies for 6 systems that were analysed at capacities between 1 and 20 MW_e. The efficiencies compared in Figure 43 are net efficiencies, defined as the ratio of net electricity output to the lower heating value of the total fuel energy delivered to the site. The total fuel energy includes energy in the auxiliary diesel fuel that is used to ignite fuel in the dual fuel diesel engine generators as used in the Fast Pyrolysis and Engine [FpyrEng] option.

The difference in sensitivity to scale of the four systems is noticeable. The engine-based generators are relatively efficient in smaller systems but their efficiencies do not improve much as the system capacity increases. In contrast the Integrated Gasification Combined Cycle [IGCC] and Combustion [Comb] system efficiencies improve significantly as system capacity increases. Thus the IGCC efficiencies rise give IGCC a clear advantage over the other systems at the larger capacities. The greater rate of change in the Combustion system efficiency also means that its poor performance at small scale rises to approximately the same performance as the engine systems at 20 MW_e.

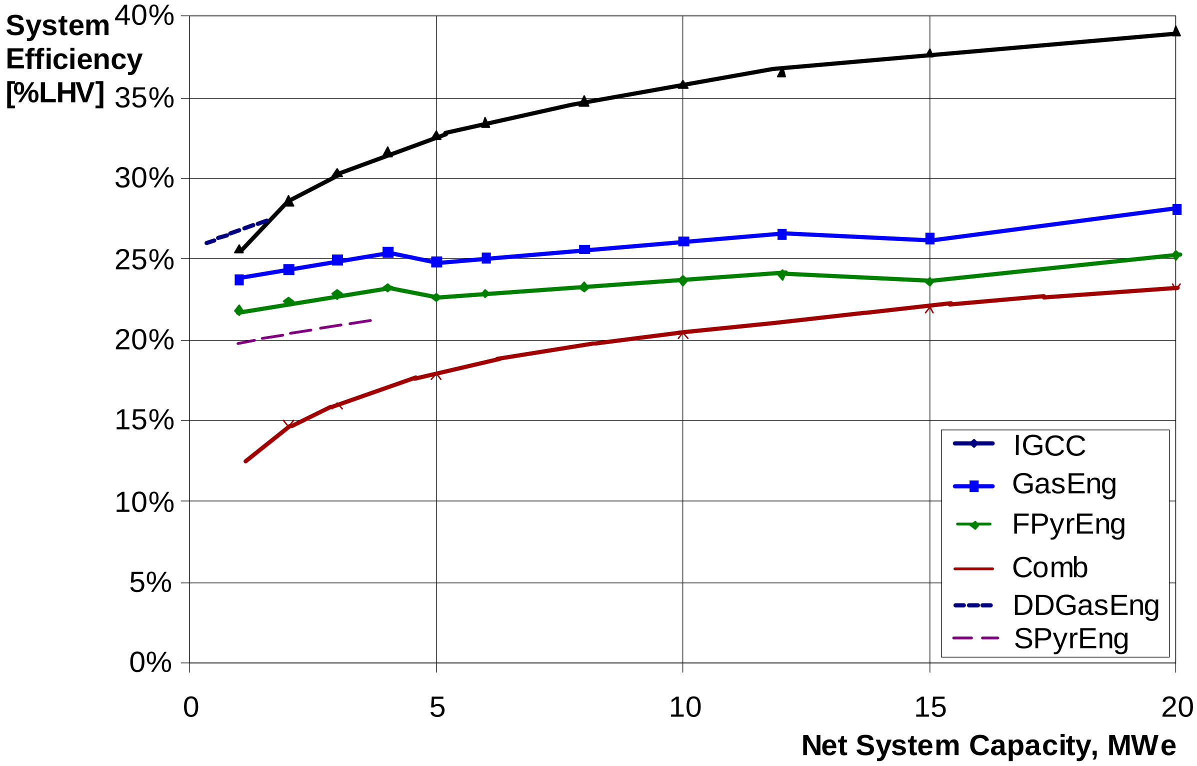

Figure 43. **System efficiencies for different technology configurations**

Codes:

IGCC	Integrated Gasification Combined Cycle
GasEng	Gasification and Gas Engine
FpyrEng	Fast Pyrolysis and Engine (dual fuelled with diesel)
Comb	Combustion + steam cycle [standard Rankine]
DDGasEng	Dondraft gasification and spark ignition engine
SpyrEng	Slow pyrolysis for char and spark ignition engine

The results of an internal economic assessment, using a wide variety of published and internal sources is represented in Figure 44. It can be seen that at small scale, downdraft gasification is the clear winner in terms of installed cost. Despite the lower efficiency of combustion it is the next clear choice due to the maturity of the technology and established track record. This is one of the reasons why the majority of new build plants in the UK for waste disposal are based on combustion.

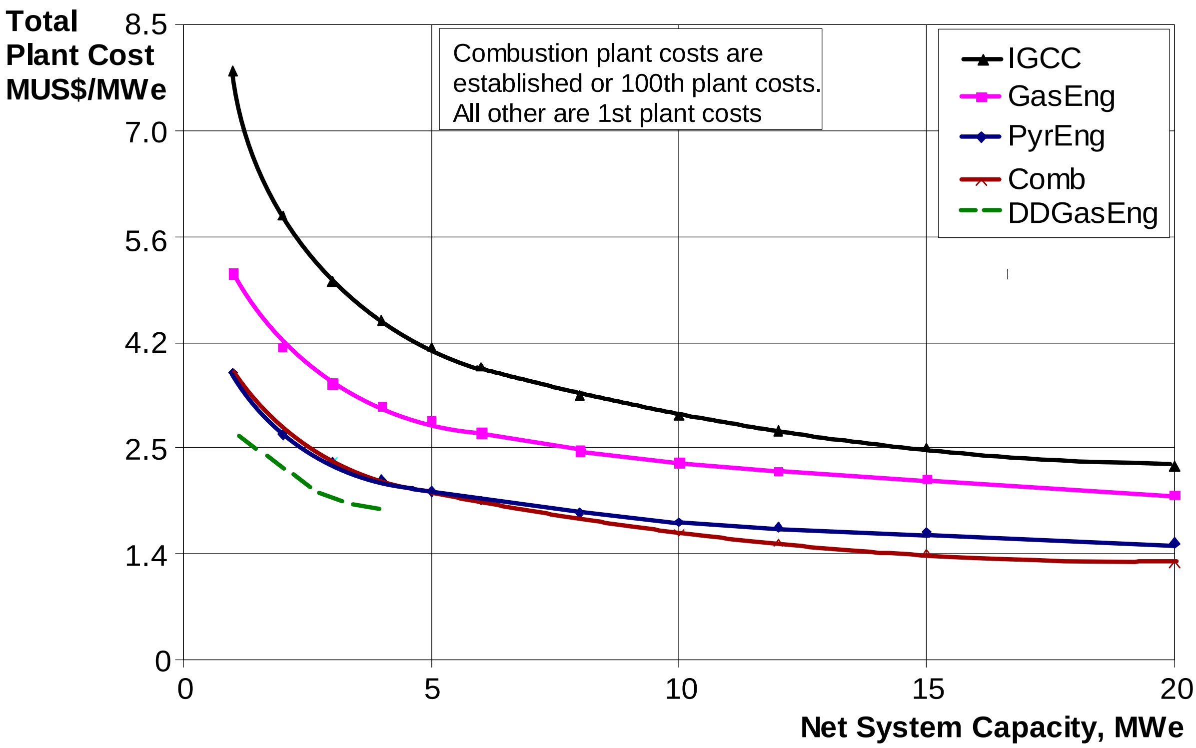

Figure 44. Installed costs comparison

7.1.1 Cost apportionment for slow pyrolysis coupled with power generation

The following approximate cost apportionment has been made for an integrated slow pyrolysis and char production process, as shown in Table 45, based on recent studies and internal assessments of the available technology.

Table 45. Overall Plant cost fraction for specific unit operations

	Unit cost	Cumulative
Pyrolysis kiln	1	1
Dryer & Feed System and bag filter	1.09	2.1
Gas Cleanup (tar cracking, filtration, scrub)	0.91	3.0
Engineering and Manufacture Labour	0.36	3.4
Instrumentation, electrical, controls, piping	1.29	4.6
Commissioning	0.60	5.3
Gas flare	0.27	5.5
Ancillaries	0.11	5.6
Options		
Char Conditioner/activator	0.5	6.2
Engines	4.0*	10.2

Note* new engines and includes piping costs

7.2 Competing biomass based energy conversion routes – combustion

The outputs of the IEA Tasks 19 and 32 [the successor to Task 19] and various other EC funded programs on biomass combustion and co-firing were consulted, in particular for detailed project profiles and ongoing activities. Research facilities are included where high quality output and data is available, but not all universities are covered. Countries are reviewed on an alphabetical basis. The different types of biomass combustor available are not reviewed, as detailed descriptions are readily available (e.g.180). The incentives for the development of biomass CHP in the EU have been recently assessed and are merely noted here (181). The reports on 21 co-fired projects, some of which are summarised below, can be downloaded for further information on specific co-fired plants only (182). There is an increasing trend for large biomass combustion plants, typically over 50 Mwe.

Cost data on a range of European biomass to electricity and bio-energy CHP projects were compiled by the OPET funded Combustion network, who published profiles on 21 bio-energy projects (183). Costs for a range of European projects were summarised by Utrecht University as shown in Table 46.

Table 46. Combustion plant survey results, Utrecht University (184)

Plant	Fuel (%wet)	Power MW_e[a]	Efficiencies, %LHV			Capital cost $\$_{1992}/kW_e$
			Boiler	Turbine	Overall	
Zurn Travelling grate	Wood (50%)	25	-	-	28	1200-1600
Delano I BFB	Ag, waste (24%)	27	86	35	29	-
McNeil Travelling grate	Wood (47%)	50	83	39	30	1800
Måbjergkærket CHP Vibrating grate	Straw, wood, MSW	34	89	36	30	2900
Händleöverket CHP CFB	Wood (50%)	46	89	38	32	1100[b]
Enköping CHP Vibrating grate	Wood (45%)	28	96	37	33	1900
Grenaa CHP CFB	Coal, straw	27	100[c]	37	35	2500
EPON co-fire Pulverised coal	Demolition wood	20	-	-	37	800[d]
WTE Pile grate	Whole trees (44%)	100	90	41	38	1500
ELSAM CFB	Coal, straw, wood	250	-	-	44	-

a *CHP capacities and efficiencies have been converted to give the expected performance in power only production*

b *Costs for CFB boiler and pretreatment only.*

C *Efficiencies are probably about 5-10% lower because of inaccurate data, this would lead to a electrical efficiency of 32-33%.*

D *Additional costs for additional investments for wood co-firing (pretreatment and burner)*

Utrecht University has a long track record of economic evaluation of such systems and their work on combustion technologies is summarised in Table 47.

Table 47. Breakdown of total project cost of FBC plants (185), US$

Component of total investment	Subcomponent	Ranges for conversion, retrofit, re-power, add-on and new plants		Examples for new plants ($/kWe)			
		Range of percentages of total investment (%)	Range of specific investment ($/kW)	13 Mwe BFB[a]	40 Mwe BFB[b]	18 Mwe CFB[c]	500 Mwe CFB[d]
	Boiler section	28–82	144–1436	538		1111	212
	Fuel handling	4–23	61–618				
	Steam turbine section	7–15	90–243				
	Instrumentation and control equipment	2–5	10–75				
	Emission control	2–6	30–60				
	Balance of plant	21–23	317				
	General plant facilities	10–15	141–486				
Total EPC		70–94	186–3045		1000	1500	1046
	Initial working capital	1					
	Contingency	6–12					
	Development fee	3–7					
	Start-up	1					
	Owner's cost						
	Initial debt reserve fund	9					
Total capital cost		86–94					
	Interest during construction	10					
	Financing fee	2					
Total project cost		100	1400–3200	1769	1300	1667	1692

Note: The presented ranges found in literature are collected separately for the different components; therefore they might not add up to 100% or to the totals for each sub section (total EPC, total cost of capital and total project cost). Moreover, the data is collected for different project types (conversion, retrofit, re-power, add-on and new plants). Both columns should thus be considered as an indication for specific investment cost for each component and emphasize the variation of investment cost for different plants and projects. The four columns from the right represent the plants.

[a] Forssan Energia Oy, Finland, 1996, main fuel: biomass

[b] Borås Energi AB, Sweden, 2005 main fuel: biomass

[c] Manitowoc Public Utilities, USA, 1991 main fuel: bit. Coal

[d] AES Puerto Rico Guayama, Puerto Rico 2002, main fuel: bit. Coal

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7.3. Costs for Advanced concepts for waste minimisation and power

Work by Bridgwater and Brammer compared the cost of four different conversion systems: fast pyrolysis to liquids + engine [PyrEng]; gasification + engine [GasEng]; Integrated Gasification Combined cycle [IGCC] and Combustion + steam cycle [Combust], all for biomass (186). Their results are summarised in Figure 45.

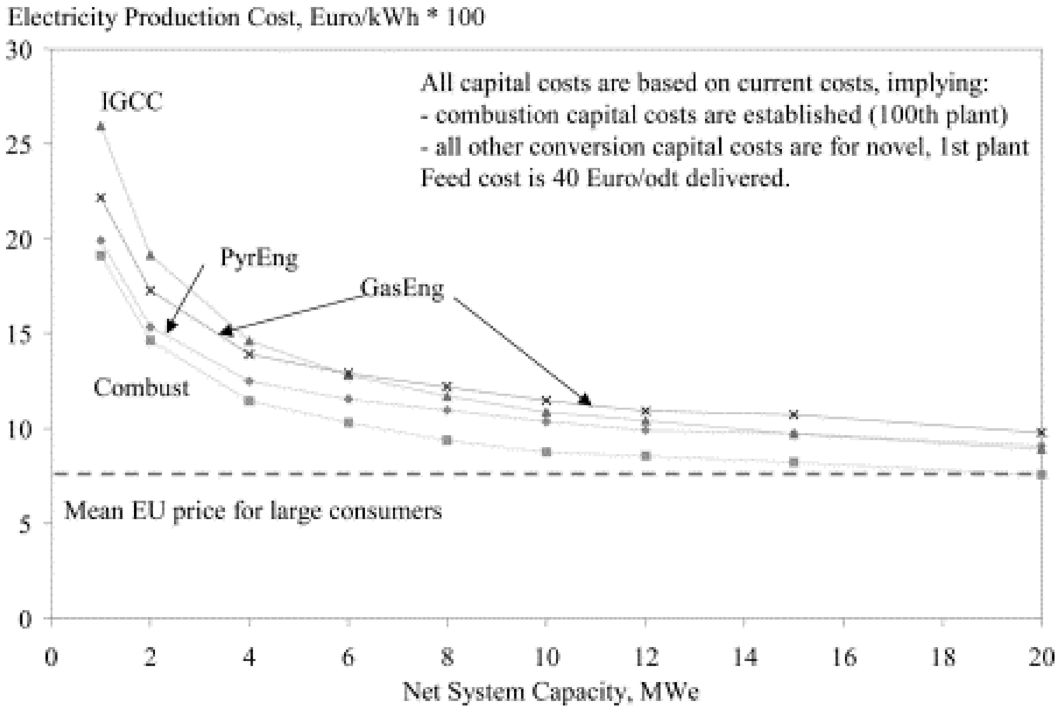


Figure 45. Comparison of electricity production costs for four biomass-to-electricity systems (186)

Their results show little difference in costs for the technologies above 10 Mwe, but combustion + steam cycle is the cheapest at all capacities, followed by IGCC and PygEng.

The recent tender assessment for waste disposal in California carried out by URS, USA collates data provided by a range of companies for facilities processing up to 100,000 t/y of MSW. These costs are summarised in Table 48. It can be seen that the cost range for disposal of 1 US ton of MSW vary from $35-289/ton or £20-165/t. The costs have also been converted to UK£, 2005 in Table 48. Additional cost information on other processes is given in Table 49, showing the wide range of disposal costs for the various technologies of $14-60/ton of waste.

Table 48. Cost comparison of various technologies (142). (adjusted and corrected to 2009, UK£ basis)

	Green Energy Corp., USA	GEM America, USA	Ebara Corporation, Japan	International Environmental Solutions Corporation, USA	Interstate Waste Technologies, Inc. [Thermoselect Process]	Ntech Environmental, Australia	Omnifuel Technologies, Inc., USA	Pan American Resources, USA	Primenergy, LLC, USA	Wastegen, UK	UK Pyrolysis company
Technology	Steam reforming pyrolysis	Pyrolysis	FB gasification	Pyrolysis	O_2 blown gasification	Pyrolysis+ gasification	FB gasification	Pyrolysis	Gasification	Pyrolysis	Pyrolysis
Capacity [t/y]	35917	27210	19192	48665	90700	29931	24383	49758	31745	90700	40,000
Capital Cost	9822112	12663641	45507520	22255947	72358778	18548459	6707784	9521380	14852949	57495288	9000000
Annual O & M	1446965	1984977	3440135	2231440	10337108	1709488	718691	2421204	1492003	3283939	1000000
Annual Capital Recovery	2090706	2219970	2731026	3807363	11746836	3216363	996585	823827	2475172	6995260	1800000
Annual Revenue Generated	1828350	1192395	314178	2878868	4245905	833107	821224	786789	1023320	2910699	112000
Net annual cost: [(O&M + Capital Recovery) – Revenues]	1709321	3012552	5856983	3159935	17838039	4092745	894052	2458242	2943855	7368500	2688000
Net disposal cost, £/t waste delivered	48	111	305	65	197	137	37	49	93	81	67

Table 49 Capital, Operating & Maintenance Cost Estimates, Normalised & Corrected [US$, 2004] (132)

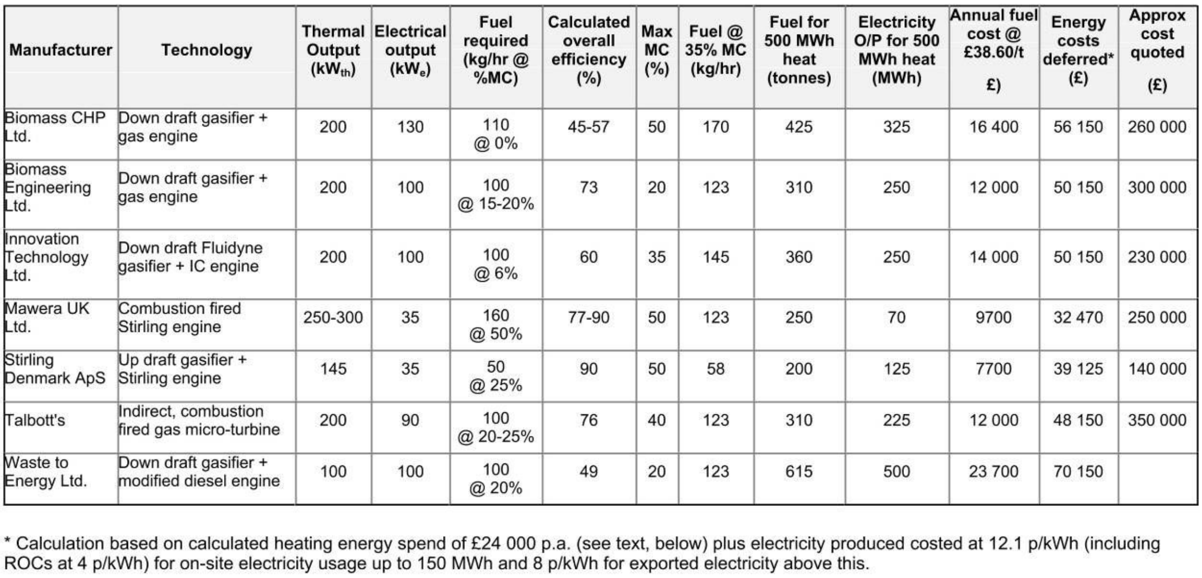
Feed Material	Gasifier Type	Feed Rate Plant (thousands of tonnes/yr.)	Size Plant (kW thermal)	Capital Costs, $/tpa	Size Plant, kWe	Capital Costs $/kWe	Conversion Efficiency, Percent (HHV)	O&M Annual Cost, Percent Capital	Total Ops. Cost, $/ton	Company
Coal	IGCC	0.611	530,504	752.7	200,000	2,300.0	37.7	2.5	18.8	
Coal	IGCC	1.206	1,047,120	636.7	400,000	1,920.0	38.2	2.5	15.9	Themista
Tyres	IGCC	0.233	289,996	732.0	74,500	2,290.9	25.7	2.5	18.3	Batelle
Tyres	IGCC	0.239	154,048	650.2	47,000	1,713.5	30.5	2.5	48.0	TPS
Tyres	Min	0.072	89,552	620.8	30,000	1,853.0	33.5	2.5	19.3	TPS
Tyres	Max	0.072	89,552	828.1	30,000	2,472.1	33.5	2.5	25.8	Alcyon
Tyres	Small scale	0.030	24,069	750.0	8,063	2,238.8	33.5	2.5	15.0	PI
Tyres	Small scale	0.030	24,069	720.0	8,063	2,149.3	33.5	2.5	14.4	Beven
Tyres	Medium	0.100	80,230	690.0	26,877	2,059.7	33.5	2.5	13.8	
Biomass	HPDGADT	0.125	155,512	712.7	56,000	1,588.0	36.0	15.1	61.7	
Biomass	HPDGGP	0.125	155,512	720.8	56,000	1,606.0	36.0	15.2	63.6	
Biomass	HPDGAUGT	0.267	332,494	678.4	132,000	1,371.0	39.7	15.9	61.6	
Biomass	LPIHGAUST	0.276	344,633	488.9	122,000	1,108.0	35.4	20.7	55.2	
Biomass	LPDGAUST	0.222	277,045	637.7	105,000	1,350.0	37.9	16.5	59.5	
	Average:	**0.258**	**256,738**	**687**	**92,536**	**1,859.0**	**34.6**	**7.6**	**35.1**	

Nomenclature for type of gasifier codes used above:

IGCC	Integrated gasifier with combined (Brayton and Rankine) cycle power conversion configuration.
HPDGADT	High-pressure directly-heated gasifier with aero-derivative gas turbine for power conversion.
HPDGGP	High-pressure directly-heated gasifier with "yngas field" plant with advanced utility gas turbine for power conversion.
HPDGAUGT	High-pressure directly-heated gasifier with advanced utility gas turbine for power conversion.
LPIHGAUGT	Low-pressure indirectly-heated gasifier with advanced utility gas turbine for power conversion.
LPDG	Low-pressure directly-heated gasifier with advanced utility gas turbine for power conversion.

Another independent study looked at several small scale suppliers of equipment in the UK and compared gasification with alternatives such as Stirling engines and indirectl fired gas turbines, as shown in **Table 50** (187). This is only for small-scale systems, but shows that most are looking at clean feedstocks and not wastes.

Table 50. Costs for small-scale gasification and combustion for power (187)



Manufacturer	Technology	Thermal Output (kW_{th})	Electrical output (kW_e)	Fuel required (kg/hr @ %MC)	Calculated overall efficiency (%)	Max MC (%)	Fuel @ 35% MC (kg/hr)	Fuel for 500 MWh heat (tonnes)	Electricity O/P for 500 MWh heat (MWh)	Annual fuel cost @ £38.60/t £)	Energy costs deferred* (£)	Approx cost quoted (£)
Biomass CHP Ltd.	Down draft gasifier + gas engine	200	130	110 @ 0%	45-57	50	170	425	325	16 400	56 150	260 000
Biomass Engineering Ltd.	Down draft gasifier + gas engine	200	100	100 @ 15-20%	73	20	123	310	250	12 000	50 150	300 000
Innovation Technology Ltd.	Down draft Fluidyne gasifier + IC engine	200	100	100 @ 6%	60	35	145	360	250	14 000	50 150	230 000
Mawera UK Ltd.	Combustion fired Stirling engine	250-300	35	160 @ 50%	77-90	50	123	250	70	9700	32 470	250 000
Stirling Denmark ApS	Up draft gasifier + Stirling engine	145	35	50 @ 25%	90	50	58	200	125	7700	39 125	140 000
Talbott's	Indirect, combustion fired gas micro-turbine	200	90	100 @ 20-25%	76	40	123	310	225	12 000	48 150	350 000
Waste to Energy Ltd.	Down draft gasifier + modified diesel engine	100	100	100 @ 20%	49	20	123	615	500	23 700	70 150	

* Calculation based on calculated heating energy spend of £24 000 p.a. (see text, below) plus electricity produced costed at 12.1 p/kWh (including ROCs at 4 p/kWh) for on-site electricity usage up to 150 MWh and 8 p/kWh for exported electricity above this.

A more recent report focusing on the UK and surveying a range of technologies for biomass and wastes is available and has summarised manufacturers costs for their technologies (188). Costs for RDF gasification, provided by ITI Energy give a "generic" cost of £1M/Mwe installed for plants over 1Mwe, though the overall scope of supply was not stated. A range of technology providers are also reviewed.

7.4 Conclusions

Costs for waste to energy systems are very project specific and needed to be treated with great care. The costs given above should be viewed as indicative, but it can be seen that the net disposal costs for wastes can be very high – see Table 48, thus deterring investment in advanced thermal conversion technologies.

Detailed cost information needs to be obtained on a project by project basis with the technology developer and the process boundary carefully defined and the scope of supply clearly stated.

8. ENGINE SPECIFICATIONS FOR PRODUCER AND SYNGAS

8.1 Engine Specification developments

Over the past 10 years, there has been a tightening of the demands for tars and particulates removal prior to the use of syngas or producer gas in SI engines.

The efficiency and the maximum capacity of the IC engine power generator increase with the lower heating value of the gas [189]. For a given producer gas composition, the LHV can be increased either by gas compression or by gas cooling. For small-scale systems, gas compression before the IC engine generally is not applied.

Tar condensation in the compressor may lead to corrosion and wear. Nevertheless, turbo-charging is considered a promising technique for IC engine applications since investment costs per kW of engine power can be drastically reduced. Most of the small-scale waste gasifiers and pyrolsyers use wet gas cleaning systems with additional moisture condensation to upgrade the producer gas quality. The gas cooling to ambient temperature is favourable in terms of maximum power efficiency. Furthermore, gas drying by moisture condensation increases the LHV of the gas and has a positive influence on the combustion efficiency.

Gas turbines are fuelled with pressurised gas. With respect to overall efficiency, it is favourable to use temperatures and pressure as high as possible. Producer gas temperatures of co-current biomass gasifiers are in the range of 400-800ºC and are not critical for the combustion chamber of the gas turbine. The lowest known gas turbine operation pressure is 7 bar, e.g. for the 2.7 Mwe model 501-KB3 from Allison Engine Co. in the USA. Any small-scale biomass gasifier available operates at normal pressure and hence producer gas compression may lead to severe corrosion and wear problems in the compressor. Therefore, it is assumed that the acceptable tar level in the producer gas is comparable for gas turbines and IC engines, as least for atmospheric gasifiers. Gas compression is regarded as part of the power generator and therefore is not discussed here.

In general for synthesis gas applications, the requirements are much stricter than for power generation applications, thought there is a lack of published data to confirm this. It is the intention of process developers to utilise the producer gas and syngas in engines and turbines. There is little long-term experience in the UK on the operation of engines on producer gas, but this is improving and very little with syngas and engines. Some indication of the possible levels of contaminants in the final gas prior to the gas turbine use are summarised in Table 51, Table 52 and Table 52 based upon manufacturers recommended limits, operational experience and theoretical calculation from 10 years ago, though these specifications are now largely obsolete, however, some companies do work to them, rather erroneously and this can lead to major issues with regards to warranties and basic operation.

Table 51. Gas Quality Requirements for Gas Turbines (190)

Particulate	30	mg/Nm^3
Particulate size	5	µm
tar	<50-100	mg/Nm^3
Alkali metals	0.24	mg/Nm^3
Ash [2-20µm: 7.5% and 0-2 µm: 92.5%]	2	ppm
Alkali [Na, K]	0.03	ppm
Calcium	1	ppm
Heavy metals [Pb, V]	0.05	ppm
Sulphur containing compounds	20	ppm
Halogens [HCl, HF]	1	ppm

Other requirements for engines and turbines have been made by General Electric for their LM2500 turbine and are given in Table 52.

Table 52. Calculated maximum allowable concentrations in producer gas (191)

Solids [d < 10µm]	5	ppbw
Solids [10µm < d< 13 µm]	30	ppbw
Solids [d > 13 µm]	3	ppbw
Lead	100	ppbw
Alkali metal sulphates	60	ppbw
Calcium	200	ppbw
Vanadium	50	ppbw
Na + K + Li	20	ppbw

Table 53. Gas requirements for gaseous fuels for the ABB Single Burner (192)

LHV range	2.2-4	MJ/kg
Particulates [d < 5µm]	2	ppm
Other metals	0.2	ppm
Calcium	0.2	ppm
Tar and naphthalene	0.5	ppm
Na + K	0.05	ppm

There appears to be little consensus in the gas quality requirements for gas engines. A more extensive review by Stassen for the IEA reports results for a range of engine and turbine systems (193).

Based on discussions with pyrolysis and gasification companies, the following specifications are now required, depending on the engine provider. Jenbacher have issued no definite tar limits but have reported problems with undefined tars at concentrations of 15 to 25 mg//Nm^3. They have also reported problems with condensation of naphthalene in engine gas inlets. GE Jenbacher specifications are given in Table 54. Guascor have set a number of limits for the allowable tars in the gas going to their FBLD 480 engine as shown in Table 55. One of these limits was 10 mg/Nm^3 of tars with three rings or heavier, the first 3-ring compound being acenaphthylene.

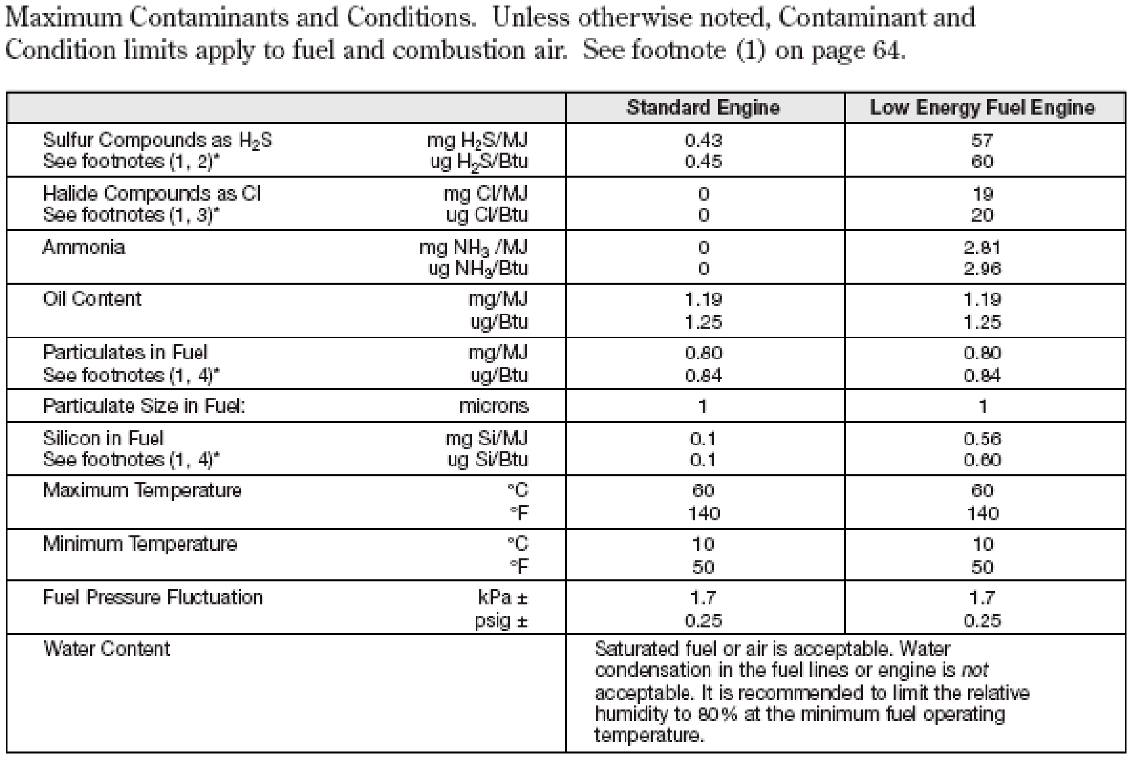
Table 54. Gas requirements for gaseous fuels for Jenbacher engines (194, 195)

			Notes
LHV range	1-3	kWh/nm^3	
	3.6-10.8	MJ/$_n$m^3	
Thermoselect gas	2-3	kWh/nm^3	
	7.2-10.8	MJ/$_n$m^3	
Fluctuation	2	%/30s	
Gas pressure fluctuation	10	mbar/s	
Particulates	>3	µm	Gas filter with engine is not a process filter
	<50	mg/10kWh	
Gas humidity	< 80	%	Must be guaranteed
Gas temperature	10-40	ºC	Min/Max
Total Si	0.02	ppm	
Total Sulphur	≤200	mg/10kWh	With CO catalytic converter
	≤700	mg/10kWh	without catalytic converter
	≤2000	mg/10kWh	without catalytic converter, limited warranty
Total Halogens Cl + 2*F	≤20	mg/10kWh	With catalytic converter
	≤100	mg/10kWh	without catalytic converter
	≤400	mg/10kWh	without catalytic converter, limited warranty
C_2H_2	≤0.2	vol%	
COS	≤0.2	vol%	
Ammonia	< 50	mg/10kWh	
HCN	- -	mg/10kWh	Not defined level at present
Tar ($C_xH_yR_z$) dew point			Min 5℃ below gas temperature
Condensate or sublimate	0		

Table 55. Gas requirements for gaseous fuels for Guascor engines (196)

Parameter	Value	Units	Notes
Lean syngas	4.6-7.0	$MJ/_{n}m^{3}$	
Rich syngas	7.0-14.0 8	$MJ/_{n}m^{3}$	
LHV variation	1	%/min	Relative to carburetion point – absolute value. Electronic carburation
Methane Number	>75		
Gas pressure			Subject to type of carburetion system used
Gas humidity	<60	%	Gas temperature at fixed values below 25℃. and/or >15℃ above wet gas dewpoint
Gas temperature		ºC	Min/Max
Total Sulphur [as H_2S]	70	mg/MJ	No catalytic converter
O_2	<2	vol%	
	±1	Vol%	At carburetion point
H_2	<25	vol%	
C_4+'s	<2	vol%	
Total Si	0.2	mg/MJ	
Total Halogens	3.5	mg/MJ	Maximum as equivalent of Cl^-
Cl^-	<3.5	mg/MJ	Organic and inorganic forms. No catalytic converter
F	$=2xCl^-$	mg/MJ	
Br	$=0.5Cl^-$	mg/MJ	
I	$=0.25Cl^-$	mg/MJ	
Ammonia	1.5	mg/MJ	
Tar	3	mg/MJ	No catalytic converter. No condensable vapours
Solids [1-5µm]	3	mg/MJ	No catalytic converter. Solids must be < 5µm

Table 56. Gas requirements for gaseous fuels for Caterpillar engines (197)



Maximum Contaminants and Conditions. Unless otherwise noted, Contaminant and Condition limits apply to fuel and combustion air. See footnote (1) on page 64.

		Standard Engine	Low Energy Fuel Engine
Sulfur Compounds as H_2S See footnotes (1, 2)*	mg H_2S/MJ ug H_2S/Btu	0.43 0.45	57 60
Halide Compounds as Cl See footnotes (1, 3)*	mg Cl/MJ ug Cl/Btu	0 0	19 20
Ammonia	mg NH_3 /MJ ug NH_3/Btu	0 0	2.81 2.96
Oil Content	mg/MJ ug/Btu	1.19 1.25	1.19 1.25
Particulates in Fuel See footnotes (1, 4)*	mg/MJ ug/Btu	0.80 0.84	0.80 0.84
Particulate Size in Fuel:	microns	1	1
Silicon in Fuel See footnotes (1, 4)*	mg Si/MJ ug Si/Btu	0.1 0.1	0.56 0.60
Maximum Temperature	°C °F	60 140	60 140
Minimum Temperature	°C °F	10 50	10 50
Fuel Pressure Fluctuation	kPa ± psig ±	1.7 0.25	1.7 0.25
Water Content		Saturated fuel or air is acceptable. Water condensation in the fuel lines or engine is *not* acceptable. It is recommended to limit the relative humidity to 80% at the minimum fuel operating temperature.	

Efforts were made to obtain data on other gas specifications for Perkins and M.A.N. engines; however the information was not available for this report.

8.2 Conclusions

Engine manufacturers have clearly shifted all liability for the gas to the technology providers with stricter specifications and tolerances on tars, particulates and moisture. This has lead to a limited development on the use of pyrolysis for wastes to power via syngas and a preference for companies to view it as a waste minimisation technology, followed by combustion of the raw gas for heat and then power generation through a steam cycle.

Gasification processes have considerably more experience with engines, with a wide range of success and failures, however technology providers have and are making improvements to their gas cleaning systems to meet engine requirements as the prices paid for "green" electricity also increase, justifying the additional expenditure.

9. OVERALL CONCLUSIONS

9.1 UK and Ireland waste gasification and pyrolysis technolgies

17 pyrolysis and 19 gasification companies and developers, agents and licensees were reviewed within the context of being active in the UK and Ireland mainly in the past 5-10 years. There has been a mixed degree of success and the vast majority of efforts has focused on using wood and clean wood wastes for power generation. There have been rather limited developments in waste gasification and pyrolysis, though this is slowly changing, in favour of the use of pyrolysis for th advantages that it offers over gasification.

There are several technologies being offered purporting to be "pyrolytic gasification", "2-staeg pyrolysis and gasification", or a variant thereof. These processes are generally just staged combustors as the main producer gas or syngas product is not cleaned to a standard suitable for use in a prime mover – it is simply combusted raw for heat and may be used to heat the process or raise steam for power generation. The recent issues over the Energos plant on the Isle of Wight with excessive dioxin emissions highlights that air is used to burn the gases, causing the formation of dioxins. There is a need to carefully look at the technology and assess its true nature.

9.2 Gas cleaning for engines and turbines

Data from pyrolysis and gasification companies show that tar reduction efficiencies of 97-99wt% can be achieved in conjunction with solids content reductions of 91-99wt%. Gas cleaning systems are available with high recovery efficiencies, though there are usually 2 or more stages to increase efficiency. Final gas conditioning may also be required to meet engine manufacturers precise requirements, including the use of final fabric filtration and ensuring the gas is significantly above its dewpoint.

There is a need for further data on collection efficiencies and the development of better design models for thermal conversion systems to account for the presence of non-condensable gases. The gas cleanliness requirements are predominantly driven by engine and turbine manufacturers. The number of non-fuel gas applications are limited to those of Choren Industries for liquid fuels by FT synthesis.

9.3 Emissions Compliance

Processes are generally in compliance with WID and data presented above shows this clearly. There is a need for companies to expend significant effort in the acquisition and CEM compliance which will also instil more confidence in the end users and improve the overall image of waste thermal conversion technologies.

9.4 Costs

Costs for waste to energy systems are very project specific and needed to be treated with great care. The costs given above should be viewed as indicative, but it can be seen that the net disposal costs for wastes can be very high, thus deterring investment in advanced thermal conversion technologies.

Detailed cost information needs to be obtained on a project by project basis with the technology developer and the process boundary carefully defined and the scope of supply clearly stated. The costs for some technologies are dropping and as landfill taxes increase, more interest will be shown in waste pyrolysis and then possibly waste gasification.

9.5 Power Generation

Engine manufacturers have clearly shifted all liability for the gas to the technology providers with stricter specifications and tolerances on tars, particulates and moisture. This has lead to a limited development on the use of pyrolysis for wastes to power via syngas and a preference for companies to view it as a waste minimisation technology, followed by combustion of the raw gas for heat and then power generation through a steam cycle.

Gasification processes have considerably more experience with engines, with a wide range of success and failures, however technology providers have and are making improvements to their gas cleaning systems to meet engine requirements as the prices paid for "green" electricity also increase, justifying the additional expenditure.

APPENDIX A: PROFILES: COMMERCIAL COMPANIES BURNING SYNGAS FOR POWER GENERATION

Short profiles of those companies outside of those reviewed above who have some experience in burning syngas in engines is given.

BEST Energies, Australia	
Technology	Paddle pyrolysis process
Feedstocks used	Green waste, poultry litter, papermill sludge, cotton trash, wood chip
Products derived	Syngas for power generation, char for non-energy uses
Capacities of known plants	300 kg/h, Gosford, Australia
Power generation experience	Yes – combustion of syngas in a dual fuel engine since 2006
Performance data available	No
Last known operational date	Current
Status	300 kg/h demonstrator in operation 2-4 t/h systems offered
Related process	Heated kilns
Contact	Robert Downie BEST Energies Australia Pty, Ltd 56 Gindurra Road Somersby NSW 2250 Australia Phone: 61 2 4340 4911 Fax: 61 2 4340 4878 info@bestenergies.com.au http://www.bestenergies.com/
Notes	Technology is being offered commercially at 2 and 4 t/h
References	None
Cost data	None

Energos UK [Waste Gas Technology Ltd. process]	
Technology	Rotary kiln
Feedstocks used	MSW, RDF, wood, plastics, dried sewage sludge, car tyres, chicken litter, straw, etc.
Products derived	Syngas for power generation [22-30 MJ/nm^3]
Capacities of known plants	50 kg/h [test unit] 500 kg/h Nash [Welsh Water], Wales
Power generation experience	Yes – 55 kWe test engine for > 5 years [Romsey]
Performance data available	Only from company
Last known operational date	2001 – 500 kg/h Nash plant, Wales
Status	Active
Related process	Noell, Technip-Pyropleq, Siemens, Takuma
Contact	Contract Heat and Power Ltd ENER·G House Daniel Adamson Road Manchester M50 1DT UK T: +44 (0) 161 745 7450 F: +44 (0) 161 745 7457 E: efw@energ.co.uk ENERGOS AS Vikelfaret 4 7054 Ranheim Norway T: +47 73877314 F: +47 73877301 E: efw@energ.co.uk W: www.energos.com See website:http://www.energ.co.uk/?OBH=809
Notes	WGT Ltd. bought by ENERGOS in 2002. No commercially operating plants known
References	"An assessment of UK systems for the thermal conversion of waste", ESTU B/RR/00434/REP, Tebodin (UK) Ltd., for ETSU, Crown Copyright 1997.

Klean Industries Inc., Canada	
Technology	Batch processor Continuous processor Different configurations available
Feedstocks used	Various wastes including plastics and biomass
Products derived	Char and syngas
Capacities of known plants	5 t/d, Japan, 2.5 t/d, Okayama, Japan, plastics 16 t/d, Odo, Japan [2000], tyres 32 t/d, Zarnovica, Western Slovakia [2007], tyres Modules of 4, 8, 12, 16 and 20 t/h offered
Power generation experience	Japan project 220 kWe in gas engine. No data given
Performance data available	Emissions data available
Last known operational date	Current
Status	Active
Related process	Batch processes [Beven]
Contact	Klean Industries (UK) Ltd. P.O. Box 5038, Hove, East Sussex Great Britain BN3 6YG Telephone: +44.(0)795.630.7692 Fax: +44.(0)709.223.7758 http://www.kleanindustries.com/s/Home.asp
Notes	Various agents around the world Conrad Industries operate a KleanAir pyrolysis process
References	Search company website for information
Cost data	None

PKA Umwelttechnik GmbH & Co. KG , Germany	
Technology	Heated kiln
Feedstocks used	MSW, industrial waste, including shredded tires, plastic waste
Products derived	Syngas and char
Capacities of known plants	0.4 t/h pilot [1994] 9000 t/y, Bopfingen, Germany 28,000 t/y, Aalen, Germany [since 2001] 31,000 t/y, Freiberg, Germany [2001]
Power generation experience	Yes – but no details available
Performance data available	Yes – data on emissions
Last known operational date	2004
Status	Closed down
Related process	Rotary kilns
Contact	No details http://www.toshiba.co.jp/about/press/1997_12/pr1602.htm
Notes	Tokyo--Toshiba Corporation in 1997 announced a technology collaboration agreement with PKA Umwelttechnik GmbH & Co. KG (PKA), which gave Toshiba exclusive rights to market waste processing plants in Japan based on PKA's technology.
References	Malkow, T., "Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal", Waste Management, Elsevier Ltd., 2004, 24, p. 53-79.
Cost data	None

APPENDIX B: BEL ASSESSMENT OF 250 KWE GASIFICATION PLANT

DEVELOPMENT OF A 250 KWE DOWNDRAFT GASIFIER FOR CHP

B/T1/00800/00/REP
URN NUMBER

Contractor

Biomass Engineering Ltd.

The work described in this report was carried out under contract as part of the DTI Technology Programme: New and Renewable Energy, which was managed by Future Energy Solutions. The views and judgements expressed in this report were those of the contractor and do not necessarily reflect those of the DTI or Future Energy Solutions.

First published 2005

EXECUTIVE SUMMARY

The primary objective of the work was to design, construct and operate a nominal 250kWe [net] downdraft biomass gasifier for the production of electricity with full environmental compliance. Secondary objectives included a full techno-economic assessment, life cycle analysis and detailed tars and particulates analysis of the producer gases before and after filtration.

To date there has been limited development of downdraft gasification systems in the UK, and even in Europe, due to perceived problems of "tars" in the gas. This has led to very slow development of the technology to a commercial reality, with only 5 gasifiers under 150kWe in operation on a continuous or semi-continuous basis. Biomass Engineering Ltd. have worked to develop a gasification system which reduces the "tars" to acceptable levels for an internal combustion engine or a gas turbine.

The development of dry filtration systems has met with very limited success in the UK, due to high tar levels in the producer gas - a problem virtually eliminated by the Biomass Engineering Ltd.'s design, as evidence in independent test work carried out by CRE [now a division of EMC Environmental Engineering Ltd.] demonstrating levels of <13mg/Nm^3 tars and <50mg/Nm^3 particulates in the raw gas from the gasifier. Prior work by Power Gasifiers International tried a back-pulsable filtration unit, but was impeded by gasifier problems, after modifications made to an imported System Johansson gasifier [160kWe] from South Africa in the early 1990's. Biomass Engineering Ltd. tested a back-pulsable system for 6 months, with good results and has operated an Iveco engine [60kWe] on the producer gas satisfactorily.

Based on their operational experience in Northern Ireland [> 2500 hours], and work at their own facility on a 55-65kWe unit, using a back-pulsable filtration unit, Biomass Engineering Ltd. developed the capability to scale-up their design to a 250kWe, utilising a dry gas cleaning system to obviate the need for water for gas scrubbing. To this end a 250kWe demonstration unit was the next logical step in the development of the technology. By using a dry gas cleaning system, the operating costs can be reduced by over 10% as the candles were back-pulsed by using the cleaned producer gas and therefore it was a regenerable system with no reagent requirements or water requirements or generation of a wastewater. Detailed measurement of the 'tars" and particulates in the gas, before and after the hot gas filter would demonstrate the effectiveness of the filter and provide data for engine companies to assess the gas for their engines.

Biomass Engineering Ltd. designed, built and operated a nominal 250kWe [net] wood based downdraft gasification system from wood reception in the form of logs through to grid export of the produced electricity. It was originally intended that prepared woodchip would be purchased for the gasifier; however, due to the lack of available chips in the required form, Biomass had to take the step of making their own woodchip on site to their specifications for the gasifier. This has given Biomass increased flexibility for the process by allowing them to source roundwood for the chipper, which tends to be more readily available than oversize woodchip.

The gasifier was built by Biomass Engineering Ltd. and the hot gas filtration system was supplied by Caldo Environmental Ltd. The only other components in the gas train were the hot gas cooler, a demister column to remove the water droplets, a gas fan and gas buffer tank prior to the fabric filter on the gas engines. It had originally been intended that Iveco would supply one normally aspirated gas engine; however, due to the limitations on their engine ranges, two turbo-charged, intercooled compressed natural gas engines were supplied.

The first onsite production of gas started in July 2004, with wood throughputs of over 200 kg/h rapidly achieved and clean gas flared successfully. The unit was operated for 800 hours prior to power generation, which started in early February 2005. The operation of the system for power export was delayed due to considerable delays in the grid connection being completed and delays in the modification of the gas engines to allow 500-600 Nm^3/h of producer gas to be fed to the engines. Despite discussions on the grid connections being initiated at the start of the contract, Core Utilities, who were contracted to do the grid connection constantly delayed the development of this part of the project, with the result that 18 months were required to get a connection in place. Wood chip production started in December 2004 and wood drying was integrated into the wood hopper by using diluted engine exhaust gases. Integrated wood drying was completed in early February 2005.

A carbon balance and mass balance was made on the system, showing that over 97wt% of the carbon could be accounted for and an air:fuel ratio of 1.55:1 was achieved. This shows that the gasification system was performing to expectations.

Based on the tar and particulate sampling performed under contract by ECN, the Netherlands, organics chemicals totalling 1-3 g/Nm^3 were measured, condensable down to –40°C. Although the level of organics chemicals measured appears very high, the actual quantity of these organic chemicals which may form "tar" were approximately 20 mg/Nm^3, as confirmed with ECN. Over 99.7wt% of the organic vapour, dominated by benzene, toluene, xylene and naphthalene [over 80wt% of the organic vapours] were passing straight through the gas conditioning system to the engines. No deposits have been found in the engine manifolds or inlets. The very high tar destruction level also meant that the gas CV was typically 5-5.2MJ/Nm^3 [LHV basis]. Particulates in the clean gas after the ceramic filter was zero. The contract started in March 2003 and with a short time extension, ended on 30th July 2005. The complete gasification system has been operated and in fact, the scope of the project had increased to include wood chip preparation.

Prior to the end of the contract, over 2200 hours operation on the engines have been obtained and over 1400 hours on the operation of the gasifier to clean producer gas only since August 2004. Planning permission and authorisation under LA-PPC has been obtained. The net electrical output of 250kWe was achieved and the gas engine gas train modified to allow higher flows of producer gas and achieve the desired power outputs.

A life cycle assessment of the process was carried out using commercially available software. Analysis of the Biomass Engineering Ltd. data demonstrated that the one emission requiring catalytic abatement on the engines was carbon monoxide. The net CO_2 emissions were calculated to be 4kg/MWh and compare very favourably to coal which was typically 900-1100kg/MWh. A techno-economic assessment of the process was also made based on the process performance. Net electricity generating costs for a feedstock at £25/t dry basis were calculated to be 5.5p/kWh [£1300/kWe installed capital cost, feedstock cost £25/t] for a 250kg/h system, generating over 270kWe net output. Cost savings can be made if the excess heat from the process can be sold and CO_2 allowances/offsets were taken into account.

The main conclusions from the work were:

- Biomass Engineering Ltd. have clearly demonstrated that their gasification technology, can and has been scaled up to 250kWe output. The main hindrance in the project has been the issues of suitable wood chip supply [now resolved], grid connection [an ongoing issue for the industry] and suitable gas train for the gas engines. Further development work in the case of the gas train was required.
- An extensive monitoring campaign was carried out on the process emissions and tar sampling of the gases showed that although high levels of organic compounds were present in the clean gas at 2000-300 mg/Nm^3, only 20mg/Nm^3 would be classed as "tar" liable to form deposits. These "tars" have been successfully removed prior to the engine in a simple cleanable mesh filter. Jenbacher has subsequently stated that it will guarantee its engines based on the Biomass Engineering Ltd. results.
- The gasification system was relatively simple, uses a dry gas cleaning system which obviates the need for water scrubbing of the gases and hence reduces emissions. Over 2200 hours on clean gas production has been obtained. Only 1400 hours of engine operation were obtained due to massive delays in the grid connection and changes required to the gas train of the gas engines. Electrical outputs of over 250kWe have been achieved.
- A heat integrated system was feasible with chipping of wet wood on site and its subsequent drying with the engine exhaust gases, which significantly enhances the flexibility of the process and improves the overall thermal and electrical efficiency.
- Some work was still required on the engine CO emissions in terms of selection of a suitable catalyst- work was ongoing.
- Productions costs were calculated at 5.5p/kWh [£1300/kWe installed capital cost, feedstock cost £25/t] for the demonstration unit, higher than expected due to the use of 2 engines and the significant costs involved in the first grid connection. These were expected to drop by over 20% for subsequent projects as part of the "learning" curve.
- The process met the project requirements, although more sustained engine operation would have been preferred.

The following technical and non-technical recommendations were made:

- Subsequent projects need to discuss grid connection at the very outset and agree a timetable of works and scope of supply with agreed deliverables to prevent excessive lead times in projects. The electricity companies need to be more aware of the needs of small-scale generators who want to export to the grid.

- Further work on engine catalysts was required for the Iveco engines, as they so not supply such a system for their engines. Costs and suppliers need to be further developed for the UK market to ensure full emissions compliance.
- Onsite chipping of wood logs has proven to be a better option than sourcing wood chips. This will be replicated on future projects. Only FSC graded wood to be used.
- True CHP options have a significant effect on the process economics and more opportunities for heat use should be investigated. Sale of heat for 1p/kWh reduces the net electricity-generating price to 3.5p/kWh.
- Continuous operation of the system was preferred to reduce thermal cycling and improve the lifetime of some plant components, notably the ceramic filter.
- A start-up fan with a gas throughout similar to the main gas fan would reduce start-up times and also improve restarting the system from a temporary shutdown. Any restarting always needs to bypass the hot gas filter to avoid filter damage by "tars" accumulation.

CONTENTS PAGE

1. INTRODUCTION

Biomass gasification in the UK has met with limited success at large scale and with more moderate success at small-scale with several small commercial and R&D units operating at capacities less than 150 kWe.

Biomass Engineering Ltd. have demonstrated that their downdraft gasification technology was capable of producing very low tar levels in the producer gas, as independently measured, and have several gasifiers in operation as indicated in Table 57.

Table 57. Biomass Engineering Ltd. Gasification systems

Client/ Location	Plant capacity	Feedstocks	Fuel use	Hours of operation	Status
Ballymena ECOS Centre, Northern Ireland	55-65 kWe 55-65 kWth recovered	Willow, pine, spruce, poplar, bark strips, sawmill wastes	• Power generation and heat recovery for building	> 3500	Operated over winter season
Biomass Test unit Newton-le-Willows, England	80 kg/h Maximum 80-85 kWe 160-200 kWth	Spruce, poplar, willow, papermill sludge, demolition wood, leather wastes, buffing dust, palletwood, beech, RDF	• Particulate filtration trials • Capstone C-330 testing • Gas engine testing • Scrubber trials	> 2000 on power generation > 2500 on feedstocks	Available for testing
British Leather Corporation, Leeds, UK	50 kg/h 100 kWth boiler use	Leather dust Sludge cake	• Boiler use • Cr III metal recovery from char/ash	>450	Dormant
Mossborough Hall Farm, Rainford, England	250 kWe 250 kWth for drying	Mixed conifer, poplar	• Power generation	> 1000	Operational
Jepsons, Culcheth, England	85 kWe 170 kWth	Mixed woods	• Power generation		Awaiting grid connection

Biomass Engineering Limited has succeeded in developing a downdraft gasifier capable of producing a very low tar, low particulate gas of consistent high calorific value [> 5MJ/Nm^3 for wood feedstocks]. The company has successfully coupled an 80kg/h test unit to two engines [Perkins 1000 series modified diesel and an Iveco G.E.8061SRi25 [130 kWe on natural gas]] and a micro-turbine (198). Biomass Engineering Ltd. has demonstrated the capability to generate consistent, guaranteed levels of heat and power with one commercial unit working in a public building in Northern Ireland with [2500 hours operation since May 2000] (199). A 50kg/h R&D leather waste gasifier [>450 hours] has also recently been tested with the British Leather Corporation. Further commercial systems up to 3MWe were under discussion.

Prior work on the gas quality was very high with tar levels less than 12mg/Nm^3 in the raw gas, readily suitable for engine use as a single fuel, as evidenced by over 2500 hours on an installation in Northern Ireland and over 2000 hours operation on their test unit at Newton-le-Willows (199). To further develop their system and build on their operational experience, Biomass Engineering Ltd. concluded that a 250kWe was technically and economically feasible using a dry gas cleaning system for the removal of the particulates and trace tars from the gas (199). The development of a dry filtration system had been supported by test work on a 50Nm^3/h test ceramic filtration unit which demonstrated the technical feasibility of the system (200). To date, there has been little published in the UK on the use of dry filtration systems for downdraft gasification systems, with only Power Gasifier International (UK) Ltd. in the mid 1990's using ceramic filtration on a System Johannson gasification unit – there was no published data on the performance of the unit.

Biomass Engineering Ltd. were interested in scaling up their technology to a module size of 250-300kWe in order to improve the overall economics of the technology. To this end, an application was made to the DTI for a demonstration project to design, build and operate a system with a net electrical output of 250kWe. As shown by Biomass Engineering Ltd., the correct design of gasifier could give very low tar levels in the producer gas, thus avoiding the need for a wet gas cleaning system and allowing a dry gas system to be used, which would greatly simplify the system. This report details the system, its operation, the features of the system and the plant performance.

The scope of the project was to design, build, install and operate a 250kWe net downdraft biomass gasification system. Biomass Engineering Ltd. was responsible for the complete system, with connection of the unit to the electricity grid for export of the 250kWe. Heat recovered from the engines would be used to dry wood as required. The objectives and deliverables of the project were:

- Achieve 3500-4000 operational hours with the gasifier coupled to the gas engine to provide data for a commercial system, operating on a variety of wood residue fuels, including recycled wastes, industrial clean wood wastes and energy crops where available.
- Demonstrate environmental compliance by extensive monitoring programme for the emissions [solids (char and ashes), condensate (from the cooled producer gas) and engine exhaust gases (COx, NOx, O_2, H_2O, VOCs)] and ensure environmental compliance to local authority pollution prevention and control [LA-PPC] requirements.
- Demonstrate a low cost, high efficiency gas engine with an overall net conversion efficiency of 26-30% [wood energy to electricity].
- Techno-economic assessment of the system to determine installed plant costs and net electricity production costs.

The duration of the project was from March 2003 to April 2005. The project was extended by 3 months to allow further operational experience on power generation to be obtained and detailed tars and particulates testing to be done on the system.

2. SYSTEM CONFIGURATION

The system flowsheet was shown in Figure 46 with the respective equipment codes in Table 58. Wood was delivered to site and stored under a open sided store. Biomass was lifted into the vibratory feeder/hopper [D01], which also acts as the wood dryer as diluted engine exhaust was ducted to D01. The dried wood dropped off the vibratory feeder on the belt conveyor [C01] and was transported to the feed hopper on top of the gasifier [V01]. The fuel was then gasified under a slight negative pressure and the hot gases during start-up were drawn through the start-up fan [F02] to a flare [S04] with solids removal in a cyclone [S03].

Char and ash, which fall through the gasifier grate, were removed by an augur [C02] to a char/ash storage bin [V02]. Char from the ceramic filter was recovered in a storage drum for mass balance purposes, but it can be removed in the common screw from the base of the gasifier to a storage bin. When the desired producer gas flowrate has been reached, the start-up fan was stopped and the main gas fan [F01] started and it ramps up to either a programmed gas flowrate over a defined period or a specified delivery pressure to the gas engines. The hot producer gases were passed through a back-pulsable ceramic filter [S01] and the remaining gases were then cooled in a water-cooled shell and tube heat exchanger [H01]. Cooling water was supplied from an evaporative cooling tower [F05]. The cooled gases were passed through a demister [V03] and then boosted by the main gas fan [F01] to the gas buffer tank [V04]. Prior to the engines being brought on line, the producer gas was flared [S05] until the desired flowrate was reached from F01. The ceramic filters were back-pulsed using the clean producer gas, delivered by a gas compressor [F03] to a small pressure vessel [V05]. The gases were passed through a final safety filter [S02]. The gas engines [E01 and E02] were brought on line and started solely on producer gas. The principal plant components were described in detail below.

Table 58. Codes for the unit operations and equipment in Figure 46

Code	Description	Code	Description
C01	Wood Feed Conveyor	S01	Hot gas filter
C02	Char/ash conveyor	S02	Fabric filter
D01	Wood dryer/hopper	S03	Start-up cyclone
E01/02	Gas engines	S04	Start-up flare
F01	Main Gas Fan	S05	Main flare
F02	Start up fan	V01	Downdraft Gasifier
F03	Producer gas compressor	V02	Char/Ash Storage Bin
F04	Dilution air fan	V03	Demister tank
F05	Cooling tower and fan	V04	Gas Buffer
H01	Producer Gas Cooler	V05	Producer gas buffer tank
P01	Quench recirculation	V06	Char /ash bin
P02	Cooling tower pump		

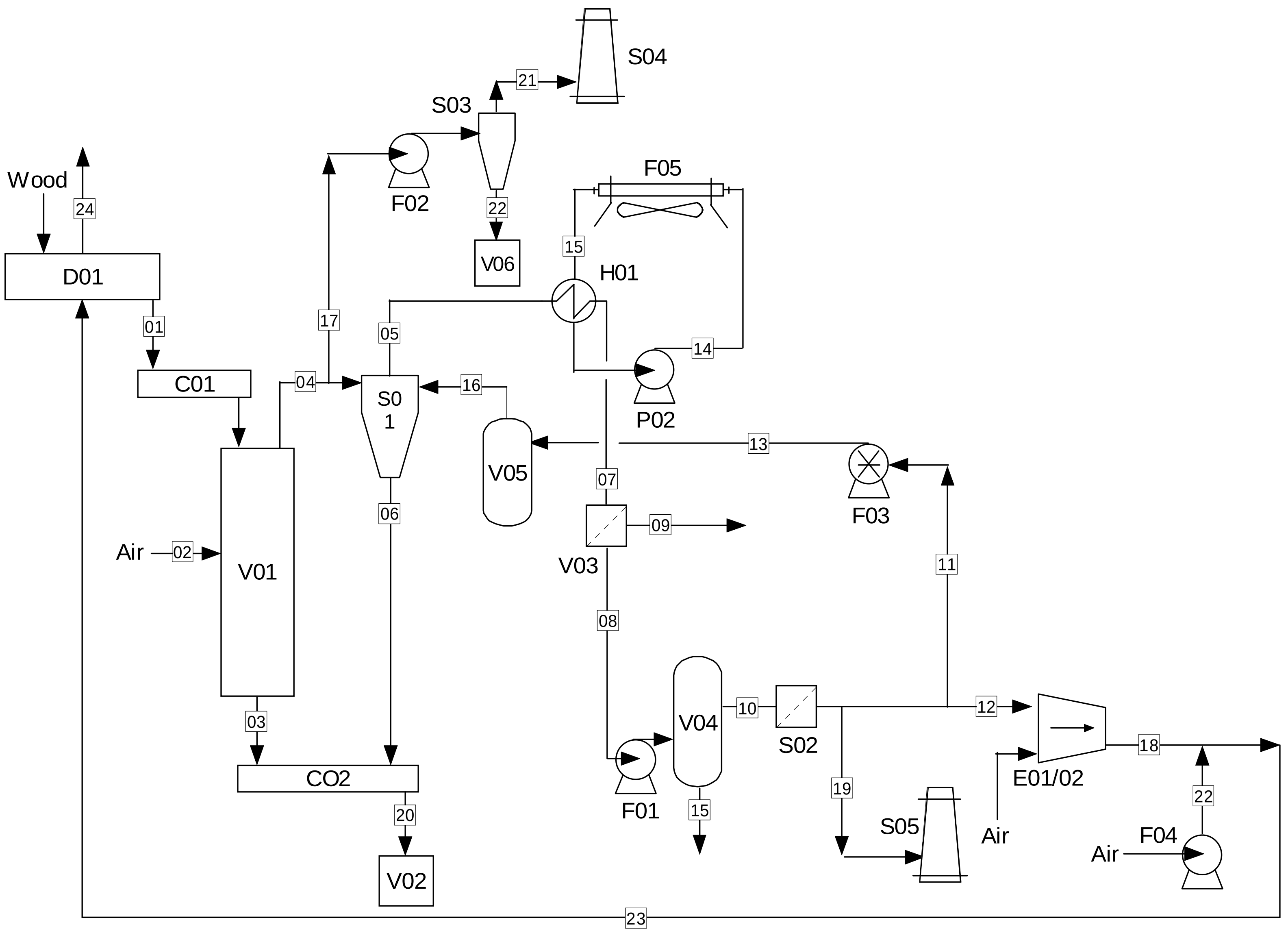


Figure 46. Biomass Engineering Ltd. 250 kWe [net] configuration

2.1 Biomass Supply and Preparation

As the machine takes whole logs, these were sourced and purchased from two suppliers [one Forest Stewardship Council [FSC] grade timber, the other non FSC grade timber] in Cumbria as no local supplier could meet the present weekly demand of 20t [dry basis].

2.2 Biomass Feeding and Feedstock Supply

For the purposes of the project, purchased wood chip was to be used as the fuel. This has proved to be one of the most problematical parts of the project, as discussed in Section 3.1. The biomass in the forms of logs up to 9" in diameter was delivered to site, chipped onsite and stored under cover where it was then scooped up in a tipper and dropped into a vibratory feeder/hopper which also acts as the fuel dryer [D01]. The vibratory feeder can hold up to 2-3t of chipped material. The chipped material was then fed along the vibratory hopper to a standard belt conveyor that then conveys the material up to the top hopper. There was a level sensor in the top hopper, which starts the conveyor when it reaches low level and opens the top slide valve. When the high level sensor was reached, the conveyor and vibratory feeder/hopper stop and the top valve closes. The bottom valve of the feed hopper opens and the wood chip was dropped into the gasifier. The top hopper was refilled every 10-20 minutes depending on the feedstock and the plant operational capacity.

2.3 Biomass Gasification

The gasifier was of a throated downdraft design, with air distribution by means of equally spaced and sized tuyeres. The air was drawn into the tuyeres by means of the start-up gas fan [F02] and then during full load operation the main gas fan [F01]. The pressure drop through the gasifier was monitored and the grate was moved when the setpoint was reached to drop char and ash into the gasifier base. The char and ash were screw conveyed to a sealed bin [V02], which was removed and emptied every week. The char and ash was spread on the land of the farm for use as a potash fertiliser.

During start-up, the initial gases were sent via the start-up fan [F02] to a gas flare. Once the maximum output of the start up fan has been reached [300m^3/h, maximum temperature of 300ºC] after a programmed start, the main gas fan was started on a programmed sequence to ramp up to the desired producer gas flowrate [600-750Nm^3/h], as measured downstream of the main gas fan. The hot dusty producer gases exit the gasifier at up to 600ºC after switchover from the start-up fan.

2.4 High Temperature Gas Cleaning

Biomass Engineering Ltd. have moved from using wet gas scrubbing to dry hot gas cleaning, as there were cost and operational advantages. The advantages in moving to a dry gas conditioning system were:

- Avoidance of use of wet scrubbing, generating a significant quantity of dilute waste requiring treatment
- Gasifiers, which have very low "tar" production, were more suited to a dry gas conditioning system as the main contaminant to be removed was char and ash particles.

- System can be automated for continuous cleaning of the filter elements, reducing labour requirements and solids handling problems.
- System can operate in more extreme climates of low temperatures as no water required.
- The capital costs were reduced by 5%.

The hot gases passed through a ceramic filter unit [S01]. The filter unit holds standard CERAFIL^{TM} ceramic filter elements, 1m long, 60mm o.d.. The candles were back-pulsed using the clean pressurised producer gas, which was taken from the gas buffer tank and compressed to 5-6 bar g. The candles can be back-pulsed either in timed sequence of each row, or on the basis of pressure drop. One row was back-pulsed every 5 minutes. The number of candles was significantly more than what would be expected, however the supplier wanted to allow for higher gas flowrates and more process flexibility. The quantity of char and ash fines would be carried over to the filters was an unknown. The pulse frequency, duration and pressure can be modified to meet process requirements. For the initial trials, the char and ash from the base of the ceramic filter were being recovered separately in a storage bin to determine how much was being carried through to the filer and allow subsequent designs to take account of the actual solids loading from the system. For future use, a common screw conveyor for the ceramic filter and the materials from the base of the gasifier will be augured into a common vessel. The recovery rate was about 2-3kg/h of char and ash from the filter. The char and ash were free flowing with no sign of tar deposition. The specification of the filter was in Table 59.

Table 59. Hot gas filter specification

Number of elements	214
Total filter area	40 m^2
Filtration medium	10mm thick, vacuum formed ceramic fibres
Maximum gas flow	up to 2000 Am^3/h at approximately 600ºC
Maximum face velocity	4.0 cm/s

After commissioning of the unit and operation of the complete system, a comprehensive monitoring program was carried out to determine tar levels in the producer gas as it enters and exits the ceramic filter system. This was carried out by ECN, the Netherlands following the EU "tar" protocol (201) and discussed later.

2.5 Gas Cooling And Moisture Removal

The hot cleaned gases from the ceramic filter were then passed through a water-cooled shell and tube exchanger. The heat exchanger was very compact as rippled tubes were used which increase the tube side heat transfer coefficient and therefore allows for a smaller exchanger. The water was supplied from a standard evaporative cooling tower, which has an automatic chemical doing system and water top up. The gases enter the exchanger at 400-550ºC and leave at 30-40ºC, depending on the local conditions. The demister vessel subsequent to the heat exchanger removes the over 96wt% of the water aerosols. Condensate production rates have been as expected and the demister was removing 30-35kg/h of condensate recovered for every 250kg/h of wood gasified. The demister vessel was automatically drained and the condensate sent to drain. The condensate has been extensively analysed as discussed later. As there was no foul sewer on the site, the condensate was currently being tinkered offsite for disposal. The heat exchanger removes 128kWth for cooling the producer gas from 500ºC to 35ºC.

The producer gas was then boosted to ~3kPa in the gas buffer tank by the main gas fan [F01]. A small amount of water was condensed in the buffer tank, approximately 100g/h. A separate line was taken off the gas buffer tank [V04] for the back-pulsing of the ceramic filter elements. The gas compressor [F03] operates for a few seconds every 5 minutes to restore the back-pulse vessel pressure to 5bar g on the hot gas filter [S01]. A small fabric filter was used as a "police" filter to protect the gas engines if a filter candle fails.

2.6 Power Generation

The cleaned and dried producer gas was then passed to two Iveco engines, model GE8210 SRG85, which were compressed natural gas [CNG] combined heat and power [CHP] engines, at 3-5kPa. The engines were delivered with their CNG gas trains, which had a maximum gas flowrate of 125Nm^3/h, which would give a gross electrical output of just over 110kWe, which was less than 50% of the required 250kWe net output. Engine electrical efficiency was expected to be in the range of 34-36%. Each engine was in an acoustic enclosure and fully independently controlled from separate MAGE panels in the plant control room. The electricity from the engines was exported to the grid. A complete transformer and grid connection control room was also installed for the export.

2.7 Heat Integration

To improve the overall thermal efficiency of the process, the engine exhaust gases were diluted on exit from the exhaust with ambient air and ducted to the wood hopper. This allows the wood fuel to be dried to the required moisture content in the range of 15-25wt%, dry wood basis.

2.8 System Control

The gasification system was controlled from a PLC and this allows the process from the wood hopper through to the grid connection to be controlled remotely. By using appropriate control loops, the gasification system was allowed to produce gas at a consistent flowrate and deliver the gas at a positive pressure to the gas buffer tank and consequently the gas engines. The dynamic response of the engines ensures that slight fluctuations in the gas flow to the gas engines were moderated and the gasification system was not affected. The use of programmable logic control [PLC] ensures that operator attendance can be reduced and hence reduce labour costs. Photographs of the main plant components were at the end of this report.

3 ONSITE OPERATION AND SYSTEM DEVELOPMENT

3.1 Biomass Resource

As noted earlier, the original intention of the project was to purchase wood ship locally to the desired specification for the gasifier. This was to avoid Biomass having to deal with an additional processing step for the demonstration plant. Mersey Forest were involved in the project to identify sources of wood for the project and therefore avoid the additional processing step of preparing the wood chip. Mersey Forest identified a very wide range of wood sources of all types in the area. The results of their survey were summarised in Figure 47. Despite contacting over 20 firms in the UK, mostly locally, but up to 200 miles away, none were able to supply a wood chip to meet the specification of Biomass Engineering Ltd.. The assistance of Mersey Forest gave details of local suppliers of wood chip, but all the chip types were small and typically less than 25 mm in size. Fuels sourced from several companies were of such poor specification that most could not be used in the gasifier.

None of the contacted suppliers from the Mersey forest survey were able to meet the required quantities or specification of large chips, commonly called oversize. Several companies supplied some materials and others up to 200 miles away contacted to see if they could supply wood chip to the required specification. Although several companies initially said that the specification wouldn't be a problem, delivered test samples were never close to the provided specification. Samples provided by 5 companies were unsuitable. Biomass Engineering Ltd. were therefore forced into sourcing a suitable chipper to meet their required fuel specification.

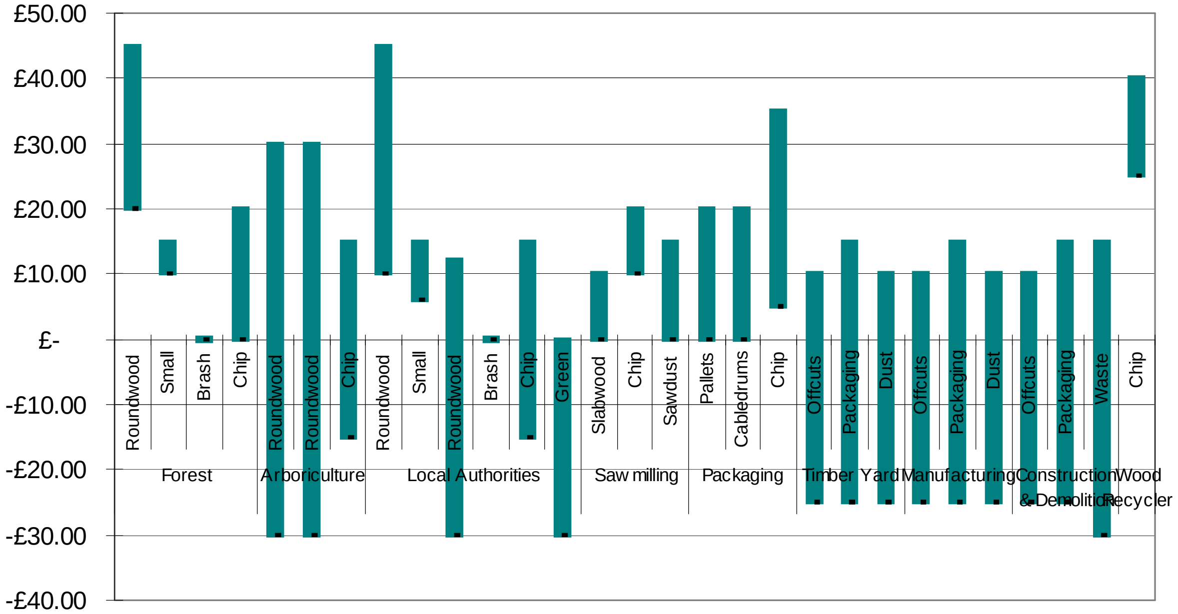


Figure 47. Mersey Forest wood sources review and costs

3.2 Biomass preparation

As noted, Biomass Engineering Ltd. had to resort to sourcing their own roundwood or slabwood and a suitable chipper to make large, uniform woodchip. Most commercially available wood chip was typically produced with a cone shaped blade which gives thin "slices" of woodchip which were roughly 4 cm x 4 cm x 1-1.5 cm maximum and in most cases the material was in the forms of pins and slices. Wood chippers configurations fit into three types where the wood was cut across the grain:

- Disc chipper [material cut by the action of knives]
- Drum chipper [material cut by the action of knives]
- Screw chipper [material cut by a continuous knife formed in the shape of a spiral cone, ie "screw".

From prior work and sample specifications form suppliers were assessed, the screw type chipper was found to be the unit which would give wood chips of fairly uniform shape and little fines production. A screw chipper was sourced from Fuelwood (Warwick) UK Ltd. The model chosen was the Laimet HP25, which upon trials with timber strips was found to give the required wood chip specification with minimal fines production. The typical characteristics of the machine were given in Table 60. The rotating screw blade also functions as a feed unit so that a separate feed was unnecessary. The feed conveyor and upper feed roller (available as accessories) significantly increase chipping productivity. The chipper was powered on site from the PTO drive of a tractor and has proved to be satisfactory in operation.

Table 60. Laimet HP25 specification

Type	Laimet HP-25
Total weight	1800kg
Rotating mass	800kg
Chip production	40-120m^3/h
Max log diameter	200mm/9"
Power requirements	100-150kWe [manual feed] 120-200kWe [machine feed]
Feed rate	0.4-0.8 m/s
Blade type	1/160 [chip size 60-100 mm]

In practice, the power requirement of the chipper was considerably less than that stated for processing at its maximum capacity. An equivalent of 55-65kWe was typical using the tractor.

3.3 Gasifier Specification

The basic gasifier design started in April 2003 after the basic mass and energy balance was completed. The basic derivation for the mass balance was given below. Ideally, each 1kg of wood at 15wt% water, upon gasification gives 2.8Nm^3/h of wet gas, 2.64Nm^3/h of dry gas, LHV of ~5.1MJ/Nm^3.

For each 1kg of wood at 25wt% water, upon gasification gives 2.63Nm^3/h of wet gas, 2.48Nm^3/h of dry gas, LHV of 4.9MJ/Nm^3. This assumes a gasifier efficiency of 84% – in practice 75-80% has been achieved, so the gas output volume was about 5% less than these values. In practice, each 1kg of wood at ~20wt% will give ~2.5-2.6 Nm^3/h of producer gas with an LHV of ~ 5MJ/Nm^3. Wet wood reduces the gas heating value as gasification efficiency drops, so drier wood of 15wt% water was preferred. An engine has a variable electrical efficiency curve, depending on its load. For the Iveco 8210SRG engine, the efficiency with engine capacity was given in Table 61 for 1500rpm in peak efficiency operation.

Table 61. Iveco 8210SRG efficiency with load

Load	50%	75%	100%	110%
Efficiency	30.1	33.1	34.7	35.4

Engine manufacturers prefer their engines to be run at 80%, so the engine efficiency to be ~33.3%, although a conservative value of 30% was taken as the engines might be operated at a lower load and at the time the final engine specification wasn't yet known. Assuming running the engine at 80% load, at 33.3% efficiency, the amount of gas and hence wood can be calculated. Each 1 kg/h of wood gives ~2.6Nm^3/h of producer gas with a LHV of 5MJ/Nm^3. Therefore amount of power generated per hour was:

$$\frac{5MJ/Nm^3 * 2.6Nm^3/h * 33.3\%}{3600s} * 1000 = 1.2025\text{kWh}$$

Equation 1

Therefore for 250kWh requires:

$$\frac{250}{1.2} = 207.9 \text{ kg/h wood} \text{ or;}$$

Equation 2

207.9 kg/h * 2.6Nm^3/kg = 540.5Nm^3/h of producer gas

Equation 3

which corresponds to a measured gas flowrate of:

$$540.05 * \frac{318K}{293K} * \frac{1bar}{1.03bar} = 570m^3/h$$

Equation 4

for a gas temperature from the fan of 45ºC [273K + 45 =318K] and a fan discharge pressure of 30mbar [0.03 bar].To calculate how much gas was required for each kWh, it has been shown that 2.6 m^3/h gives 1.2025kWh, therefore to give 1kWh:

$$= \frac{2.6}{1.2025} = 2.16\text{Nm}^3\text{/kWh}$$

Equation 5

The typical mass balance for the process was shown in Figure 48. It was accepted for a unit of this size, that to carry out a full mass balance was very difficult, as the wood was dried in the hopper and continuously fed to the gasifier, so weighing of the fuel input to the gasifier was not practically feasible.

Detailed product analyses were performed and the mass balance based on the work carried out in June 2005 was given overleaf in Figure 48. This was possible form detailed analysis of the process streams and the data obtained from the "tar" measurement work on the 28-29th June 2005. The gasification system has been operated with higher throughputs of wood giving overall electrical outputs to 270kWe.

3.4 Gasifier Commissioning and Preliminary Operation

The gasifier was constructed at Biomass Engineering Ltd. and components fabricated and fitted on skids as appropriate. The gasifier, hot gas filter and conveyors were delivered to site in early 2004 and one of the major delays was in the engine delivery. The installation of the system was completed in June 2004 and hot commissioning of the gasifier commenced in late July 2004. The first gas was produced on 16th July 2004 and after a few days; producer gas throughputs of over 700 m^3/h were obtained. The first fuels to be used in the gasifier were rather poor quality wood chips, which contained a large proportion of bark, mainly in the form of long strips, which were liable to cause bridging in the fuel hopper on the gasifier. Most of these had to be removed to prevent bridging. The bark content of the fuel was 8wt%, dry basis. The moisture content of the fuel was 19wt%, dry fuel basis, which was within the acceptable range for the gasifier.

Minor problems were found with the three start-up burners, which were PLC controlled so that the gasifier can be ignited remotely. The condensation of moisture in the burner tubes after a day's operation could cause one or more burners to fail on occasion during the next days startup. Retraction of the burners back into the refractory lining of the gasifier largely solved this problem.

In order to avoid the use of pokers inside the gasifier, the gasifier has a tube inside to ensure that the potential for the wood chips to build was greatly reduced, however this reduces the amount of wood the gasifier can hold and therefore the feed hopper and valve system needs to operate every few minutes to ensure that the gasifier remains full of wood.

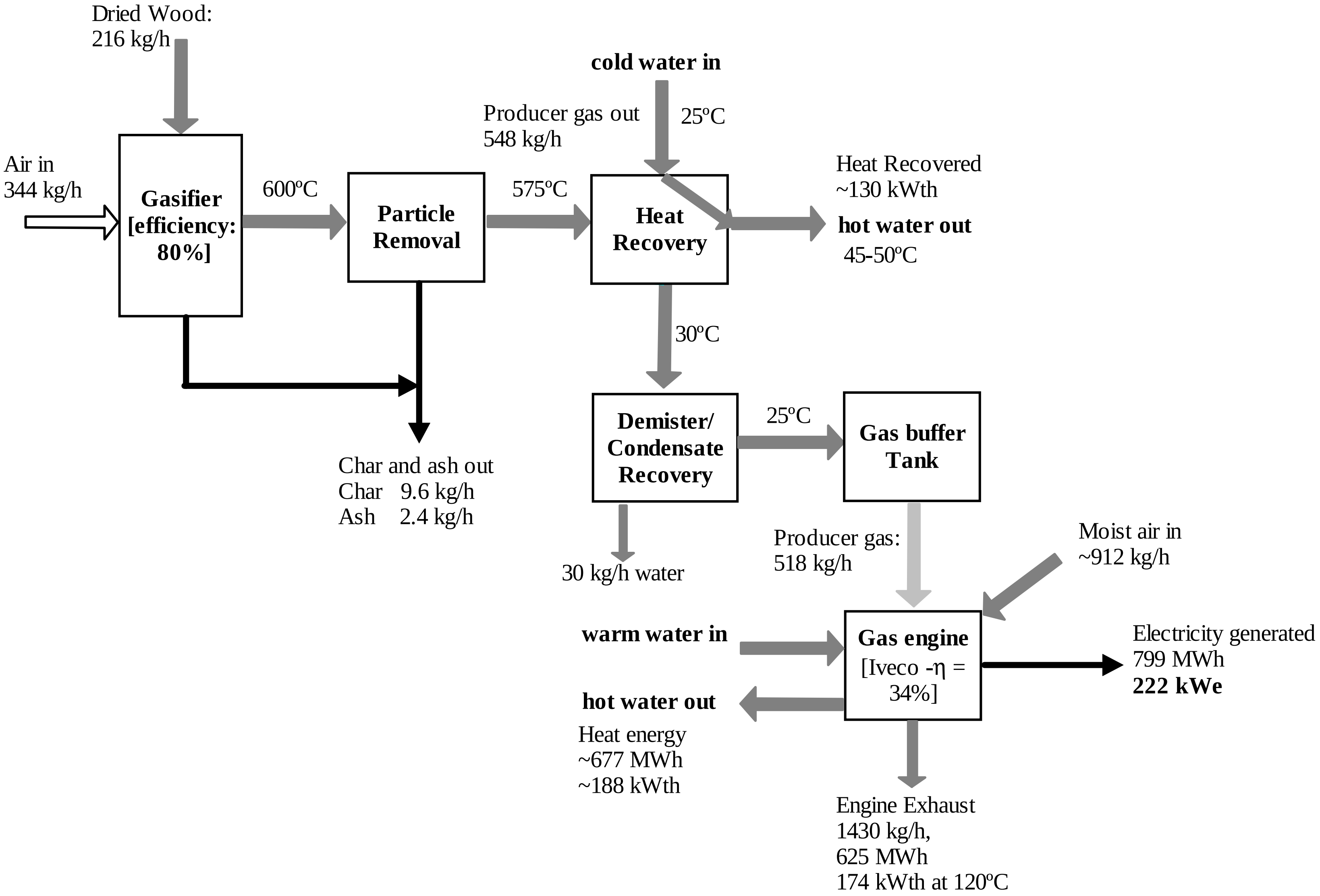


Figure 48. **Process Mass and Energy Balance – June 2005**

3.5 Gasifier operation and gas production to flare

From August 2004, Biomass Engineering Ltd. regularly operated the gasifier, with the gas being flared while operational experience was obtained. A summary of minor operational issues and how they were resolved were given in Table 62. There have been no major issues and the majority of the unit operations have met the requirements of the system.

Table 62. Minor operational and commissioning problems

Operational Issues	Resolution
Bridging problems in fuel hopper	• Modification to fuel hopper design • Improved fuel specification by producing own woodchip • Hoppers to be replaced
Condensate in F02	• Drain fitted to fan
Preferential gas flows through gasifier due to position of air and gas inlets	• Second air inlet installed • Modifications made to gas outlet
Start-up burner ignition problems	• Retraction of burners after initial start-up
Start-up fan seals not satisfactory	• High temperature seals fitted and condensate drain fitted on fan
Grate distortion	• Selection of higher temperature refractory casting for grate and improved support
Wear on filter candles due to lack of gas baffle plates in filter box	• Fitting of gas baffles to divert gas flow
Restricted gas flows through engines of 125Nm^3/h	• Removal of zero pressure governors, backpressure regulators to increase flows to over 275Nm^3/h per engine.

The various issues listed in Table 62 have been resolved and the unit was operating 12 hours a day, 5 days a week.

3.6 Gasifier operation and integration to the gas engines

The gasifier has performed well meeting the requirements for gas production to generate 250kWe. Based on the gas flows achieved to date, electrical outputs of up to 300kWe were possible. The only minor issues with the gasifier has been that the addition of a second air inlet to prevent preferential air flow through the unit, better choice of refractory for the grate and slight repositioning of the gas outlet.

3.7 Gas cleaning, cooling and delivery to the engine

The ceramic filter system [S01] has performed well, with the filters removing 100% of the entrained char and ash particles. The back-pulsing of the elements with the cleaned producer gas has been very efficient, with only small traces of vapour deposition on the clean side of the unit, due to thermal cracking of some organic components on the filters.

One problem with filter damage by the entrained solids has been resolved with the addition of a deflector plate inside the unit. Several elements had been damaged after 6 months by erosion by the ash particles.

The heat exchanger [H01] has performed to its specification, cooling the gases down to 30-40℃. The cooling tower [F05] coupled to the heat exchanger has also met expectations and has an integral cleaning system, serviced by an external contractor. The demister tower [V03] has proved very effective in removing the water vapour, with less than 2wt% remaining in the gas after the demister. The main gas fan [F01] has been problem free and has proved very capable of delivering gas flows over 700m^3/h to the main flare and gas engines. The fabric filter [S02] has also trapped the residual condensate organics in the gas phase prior to the engines. These were the 20mg/Nm^3 of "tars", which were not recovered in the condensate, but pass through the system to the gas engines.

3.8 Gas engines and power generation

It was originally intended that the gasification system would operate with only one engine to reduce costs, however Iveco could not confidently provide a single gas engine to meet the net requirement of 250 kWe. One factor was that the deration of the engines was an unknown to Iveco, but Biomass Engineering Ltd. had provided a specification with an engine deration of 45% early in the project. Biomass Engineering Ltd. therefore had no choice but accept two gas engines, which meant that additional costs would be incurred and operation on two engines would require 2 controls, extra pipework and more maintenance. The two gas engines supplied by Iveco were the 8210SRG85.10 A 70E turbo-charged, intercooled compressed natural gas [CNG] engines. As such, the engines were supplied in 2004, but with the wrong gas train.

The supplied gas train was for CNG, with a delivery pressure of 6bar and a maximum flowrate through the zero pressure governor of 125Nm^3/h, 30 mbar pressure, which was insufficient to meet the projects objective of an electrical output of 250kWe.

Despite visits to site by Iveco engineers and requests to Iveco UK, no modifications were made by Iveco and consequently, Biomass Engineering Ltd. were forced to simplify the gas train to remove virtually all of the flow restrictions and ensure that sufficient producer gas could be delivered to the gas engines. The other issue with the gas engines was that the air inlet for the engine was specified for natural gas. Producer gas requires less air per m^3 than natural gas: consequently the air consumption was higher than would be preferred. Biomass Engineering Ltd. have had to modify the gas/air mixing system to reduce the air consumption to the engines. The electrical output of the engines has benefited from the modifications made by Biomass Engineering Ltd. and electrical outputs of over 150kWe per engine have been obtained. Unfortunately no gas emission data from the engines have been obtained. The engine deration has been reduced to less than 20%, due to the intercoolers and turbo-charging of the engines. The engine efficiencies were 33-34%, which were in line with expectations.

3.9 Grid Connection

The two gas engines export heat and electricity. The export of the electricity to the grid was a key feature of the project, as there were very few small-scale gasifiers operating in the UK, which were connected to the grid. Biomass Engineering Ltd. initially contacted Scottish Power to arrange for export of the electricity to the grid, however, they were not prepared to buy or take the electricity under the terms of the Renewables Obligation Order [2002].

Biomass Engineering Ltd. made arrangements for GreenEnergy to take the electrical output from the project, however a grid connection was still required. With regards to the electricity connection and installation, Scottish Power advised Biomass Engineering Ltd. that to connect to the Grid, they would only agree to their wholly owned subsidiary, Core Utilities, making the installation.

Repeated efforts by Biomass Engineering Ltd. over a period of 18 months continually met with delays and inconsistent responses from Core Utilities. One major problem was that Core utilities would not provide a firm quotation for the work, nor the scope of supply. In the end, Biomass Engineering Ltd. had to employ specialist contractors to construct a grid supply control room and install a new transformer and lay an armoured underground cable to the nearby electricity lines. The grid connection was finally completed in March 2005, which left Biomass Engineering Ltd. with little time to operate the gas engines and demonstrate the complete system. Biomass Engineering Ltd. kept FES/DTI fully informed of this problem during the contract, hence the request for a short extension to the contract to allow more operational hours to be obtained on the unit.

This issue of grid connection was a major obstacle to the development of small-scale renewables, and represents a unquantifiable variable in such projects, which will deter potential clients from using small-scale biomass gasification as it may represent a significant project cost. The experiences of Biomass Engineering Ltd. will allow them to mitigate some of the delays and costs involved with grid connections.

3.10 Overall Assessment of the System

Up until the end of the contract in July 2005, Biomass Engineering Ltd. achieved the following:

- Design, construction and operation of the gasifier from wood feeding to clean gas outlet for over 2200 hours
- Operation of the gasifier for wood feeding to power generation for over 1400 hours with electrical outputs of over 270kWe on the two engines.
- Integration of heat recovery from the engine exhaust gases to the wood dryer for 200 hours.
- Analysis of the product char, gas and condensate [see Section 5]. The main emission not measured was the engine exhaust.

4. PRODUCT ANALYSIS

All of the products streams from the gasifier have been extensively analysed and have helped assess the overall performance of the gasification system. The products and materials analysed were:

- Char and ash recovered from the hot gas filter char bin
- Char and ash recovered from the bottom of the gasifier [recovered from the char/ash bin]
- Producer gas from the gasifier and after the hot gas filter
- Condensate from the process recovered in the demister column.
- "Tars" and particulates in the hot producer gas pre and post the hot gas filter

Detailed analytical results were given below.

4.1 Byproduct Char

The initial chars formed in the process were very high in ash, typically over 60wt%, as shown in Table 63 which was due to very long residence times in the gasification zone. The initial materials were also high in bark [> 7wt%], which has a much higher ash content than clean wood [0.5-1wt%]. With a move to increased throughputs and slightly reduced pressure drops in the gasifier, this dropped to 20-30wt%, but still represents over 95wt% carbon conversion of the starting biomass.

Table 63. Initial char compositional analysis: July 2004

	C	H	O$^{\#}$	N	Ash
Char from auger	37.33	1.06	7.14	0.1	54.37*
Char from ceramic filter	27 3			0	75.27*
		.			
		4			
		6			
Fly ash from start-up cyclone	12.90	4.03	0.59	0	82.49*

Note: # by difference

* high ash due to oxidation of the reduced metals in air

The elemental analyses of the char fines recovered from the ceramic filter, the char screw conveyor and the char pot on the start-up cyclone have slightly different compositions, as the ash particles tend to be finer, i.e. highly reacted and were lower in density and were entrained to the hot gas filter. The char and ash samples contain reduced metals, which when ASTM methods for ash content were applied have shown mass increases in the ash due to subsequent oxidation of the metals in the ash. The char fines from the cyclone char pot were very high in ash as the charcoal used initially in the gasifier was high in ash and was carried through shortly after start-up. The oxygen values in the char were therefore not particularly reliable. Further analyses of the chars from the process have been analysed and these were shown in Table 64.

Table 64. Byproduct char compositional analysis: June 2005

	C	**H**	**O#**	**N**	**S**	**Ash**
Char from auger	71.88	0.51		0.10	0.102	9 *
Char from ceramic filter	82.87	0.50	5.44	0.10	0.1	11*

Note: # by difference
* high ash due to oxidation of the reduced metals in air

Due to the position of the gas outlet from the gasifier being moved to ensure a more uniform flow of producer gas down through the gasifier and out to the hot gas filter, the finer ash particles were carried over to the hot gas filter and the larger particles drop down into the augur. The high ash levels in the resultant char, even allowing for some oxidation during the ashing process, the carbon conversion of the gasifier exceeds 95wt%, which was extremely efficient.

4.2 Producer gas

From the initial commissioning through to the end of the contract, gas samples were regularly taken and analysed by Aston University for a full range of gases. Typical results were given in Table 65 below. These results were typical of downdraft biomass gasification systems.

Table 65. Producer gas compositions [vol%, 20°C, 10 1235 Pa]

	Date taken, Feedstock and moisture content		
	July 2004 Pine [8wt% bark] 18.5 wt% H_2O	May 2005 Mixed conifer NK	June 2005 Mixed conifer 24.5 wt% H_2O
CH_4	1.80	1.67	2.05
CO_2	14.32	12.75	11.82
C_2H_4	0.45	0.33	0.48
C_2H_6	0.05	0.02	0.03
H_2	15.49	14.67	15.38
C_3H_6	0.03	0.00	0.01
C_3H_8	0.00	0.05	0.00
CO	17.68	17.53	21.24
n-C_4H_{10}	0.01	0.00	0.00
Organics	NK	NK	0.07
N_2	50.16	52.98	48.97
HHV [MJ/Nm^3]	5.28	4.3	5.39
LHV [MJ/Nm^3]	4.88	4.0	5.03

Notes: NK – Not Known

4.3 Condensate

The process of gasification generates water, no matter how dry the feedstock to be gasified. For every 250 kg/h of dried wood gasified, 35 kg/h of condensate were recovered, virtually all from the demister column. A small amount was recovered in the gas buffer tank, but as the water vapour pressure was significantly below it saturated vapour pressure, the amount accumulated in one day was less than 1 kg. Elemental analysis of the condensates have also been made and also on the "tars" recovered from the condensate. These were shown in Table 66.

Table 66. Condensate analysis: June 2005

	C	H	O#	N
Condensate	1.51	11.3	87.1	0.1
Recovered "tars" from condensate	70.06	10.67	19.28	0

The approximate molar composition of the water insoluble "tars" was $CH_{1.83}O_{0.21}$, which was what would be expected for gasification products, which were tertiary compounds. The condensate was analysed in April 2005 by Environmental & Management Services Limited. A full range of polyaromatic hydrocarbons [PAHs], phenols and other likely chemicals were analysed for and the results were shown in Table 67 and the phenolics and other compound were in Table 68. The feedstock used during the testing was chipped conifer.

Table 67. Analysis of process condensate [April 2005] – US EPA 16 PAHs

Chemical	Value	Units
Acenaphthene	20.2	µg/l
Acenaphthylene	1280	µg/l
Anthracene	16.2	µg/l
Benzo (a) Anthracene	2.34	µg/l
Benzo (a) Pyrene	3.39	µg/l
Benzo (b&k) Fluoranthene	9.35	µg/l
Benzo (g,h,i) Perylene	2.43	µg/l
Chrysene	4.85	µg/l
Dibenzo (a,h) Anthracene	< 0.5	µg/l
Fluoranthene	41.7	µg/l
Fluorene	5.50	µg/l
Indeno (1,2,3,-cd) pyrene	1.82	µg/l
Naphthalene	3040	µg/l
Phenanthrene	185	µg/l
Pyrene	36.3	µg/l

The PAHs present in the condensate were in relatively small quantities. Based on a condensate recovery rate of a maximum of 35 kg/h, the amount of PAHs present was 0.16

g/h, which was relatively insignificant. The phenols recovered in the liquids dominate the chemicals present in the condensate, as given in Table 68.

Table 68. Analysis of process condensate [April 2005] – Phenols and other compounds

Chemical	Value	Units
Pentachlorophenol	<0.5	µg/l
2,4,6 Trichlorophenol	<0.5	µg/l
Phenol	173000	µg/l
2-Methylphenol (o-Cresol)	3640	µg/l
3-Methylphenol (m-Cresol)	14400	µg/l
4-Methylphenol (p-Cresol)	5150	µg/l
2- Chlorophenol	1.97	µg/l
2,4-Dichlorophenol	<0.5	µg/l
2,6-Dichlorophenol	<0.5	µg/l
3,5-Dimethylphenol	630	µg/l
4-Chloro-3-methylphenol	<0.5	µg/l
2,4,5-Trichlorophenol	<0.5	µg/l
2,3,4,6-Tetrachlorophenol	<0.5	µg/l
2-Nitrophenol	<0.5	µg/l
4-Nitrophenol	<0.5	µg/l
2,4-Dintriophenol	<0.5	µg/l
3,4- Dimethylphenol	104	µg/l
2,3 & 2,6- Dimethylphenol	87.1	µg/l
2,4- Dimethylphenol	160	µg/l
2,5- Dimethylphenol	149	µg/l
Chemical Oxygen Demand (COD)	642	mgO_2/l
Biological Oxygen Demand (BOD)	163	mgO_2/l
pH	8.8	

As can be seen from the analysis, the most predominant components were phenol and its derivatives. The total emission level of PAHs was 4.6mg/l of condensate and 197mg/l of phenolics. The majority of the phenols were phenol, the ortho-, meta- and para-cresol forms.

As the site at the Mossborough Hall Farm does not have a foul sewer for disposal of the condensate, in conjunction with the porous nature of the local geology and wells, which were used on site, the condensate was currently being tankered off site for disposal. There were no benzene, toluene and xylenes [BTXs] measured in the condensate, which has positive implications as discussed below.

4.4 "Tars" and Particulates

One of the crucial aspects of the work, as this was a scale-up of the Biomass Engineering Ltd. technology, was the measurement of the "tars" and particulates. Tars were in parenthesis, as there was some debate in the gasification community about the applicability of the EU "tar" protocol to biomass gasification as although high levels of organic chemicals may be measured, they do not have a negative impact on the quality of the gas, in fact they can increase the heating value of the gas.

In June 2005, after CRE Casella were unable to meet the requirements of the measurement campaign, ECN of the Netherlands, who were the co-ordinators of the recently funded EU Network on the development of the "tar" protocol for the testing of gasification systems, were contracted to carry out a full assessment of the gases, before and after the hot gas particle filter. The results were given in Table 69 for two different gas flowrates over two days of testing.

Table 69. Sampling parameters on the biomass gasifier

	June 28			June 29		
Sampling point (SP)	SP1	SP2	SP3	SP1	SP2	SP3
Sampling point temperature [℃]	500	380	300	600	570	430
Sampling point pressure [mbar]	-50		-80	-50		-100
Dried clean wood chips feedstock rate [kg/hr]	~125			~250		
Product gas flow rate upstream buffer tank [m^3/hr]	270			540		
Outlet pressure product gas [mbar]	+50			+50		
Outlet temperature product gas [℃]	35			40		

Sample point location:

SP1: gasifier outlet SP2: ceramic filter inlet SP3: ceramic filter outlet

The measured values given in Table 70 and Table 71 show that benzene, toluene and naphthalene comprise over 80wt% of the organic chemicals at 275m^3/h nominal flow and over 72wt% of the organics at 550-575m^3/h flow.

Table 70. "Tar" measurement results June 28th –29th, 2005: identified compounds

Sampling code and location →		SP1 28-06-05 14:30	SP2 28-06-05 11:02	SP3 28-06-05 11:22	SP1 29-06-05 14:27	SP2 29-06-05 11:05	SP3 29-06-05 11:06
Chemical Compound ↓		**Outlet gasifier 28-06**	**Inlet ceramic filter 28-06**	**Outlet ceramic filter 28-06**	**Outlet gasifier 29-06**	**Inlet ceramic filter 29-06**	**Outlet ceramic filter 29-06**
Benzene	mg/m_n^3	1482.9	1531.0	1401.0	3001.1	1839.7	2206.0
Toluene	mg/m_n^3	225.6	240.3	213.6	503.9	349.2	414.3
Ethylbenzene	mg/m_n^3	1.8	2.1	1.8	11.2	11.2	15.3
m/p-Xylene	mg/m_n^3	17.3	18.0	16.2	38.5	28.8	34.3
o-Xylene+Styrene	mg/m_n^3	62.0	69.3	59.6	182.6	134.6	158.5
Phenol	mg/m_n^3	24.9	24.1	17.3	163.9	108.6	124.1
o-Cresol	mg/m_n^3	1.4	1.1	0.7	17.9	9.8	8.2
Indene	mg/m_n^3	35.5	29.7	3.2	239.4	91.1	40.3
m/p-Cresol	mg/m_n^3	6.7	5.4	6.2	54.4	31.0	27.3
Naphthalene	mg/m_n^3	234.4	262.3	231.9	669.3	383.8	478.4
Quinoline	mg/m_n^3	< 1	0.6	< 1	2.2	1.3	1.6
Isoquinoline	mg/m_n^3	< 1	< 1	< 1	2.3	1.5	1.3
2-methyl-naphthalene	mg/m_n^3	19.0	20.9	12.3	64.2	44.9	48.8
1-methyl-naphthalene	mg/m_n^3	14.4	15.5	10.3	42.9	28.4	32.1
Biphenyl	mg/m_n^3	11.8	13.5	12.3	31.3	20.2	26.4
Ethenyl-naphthalene	mg/m_n^3	4.6	5.1	2.6	18.5	12.6	12.8
Acenaphthylene	mg/m_n^3	55.4	65.5	39.3	259.4	134.0	139.1
Acenaphtene	mg/m_n^3	< 1	< 1	< 1	9.4	5.0	5.6
Fluorene	mg/m_n^3	5.8	5.8	0.5	55.5	17.8	10.6
Phenanthrene	mg/m_n^3	19.6	33.5	30.2	107.6	57.7	76.9
Anthracene	mg/m_n^3	2.7	6.0	6.0	25.6	13.7	16.0
Fluoranthene	mg/m_n^3	6.1	12.4	11.6	48.5	22.9	32.3
Pyrene	mg/m_n^3	5.9	12.4	11.6	49.0	22.0	30.8
Benzo(a)-anthracene	mg/m_n^3	< 1	2.0	2.4	10.4	7.3	7.1
Chrysene	mg/m_n^3	< 1	0.8	1.6	2.0	2.7	4.7
Benzo(b)-fluoranthene	mg/m_n^3	< 1	< 1	< 1	3.5	2.7	4.7
Benzo(k)-fluoranthene	mg/m_n^3	< 1	< 1	< 1	1.2	0.8	1.8
Benzo(e)-pyrene	mg/m_n^3	< 1	< 1	< 1	1.4	1.0	1.9
Benzo(a)-pyrene	mg/m_n^3	< 1	< 1	0.8	2.0	1.8	2.7
Perylene	mg/m_n^3	< 1	< 1	< 1	< 1	< 1	< 1
Indeno(123-cd)-perylene	mg/m_n^3	< 1	< 1	< 1	< 1	< 1	< 1
Dibenz(ah)-anthracene	mg/m_n^3	< 1	< 1	< 1	< 1	< 1	< 1
Benzo(ghi)-perylene	mg/m_n^3	< 1	< 1	< 1	< 1	< 1	< 1
Coronene	mg/m_n^3	< 1	< 1	< 1	< 1	< 1	< 1

A range of organic chemicals were also measured by the same methods, but could not be specifically identified beyond a certain class or "group" of chemicals. These were given in Table 71.

Table 71. "Tar" measurement results June 28th –29th, 2005: not identified compounds

Sample code -→		SP1 28-06-05 14:30	SP2 28-06-05 11:02	SP3 28-06-05 11:22	SP1 29-06-05 14:27	SP2 29-06-05 11:05	SP3 29-06-05 11:06
Chemical Compound ↓		**Outlet gasifier 28-06**	**Inlet ceramic filter 28-06**	**Outlet ceramic filter 28-06**	**Outlet gasifier 29-06**	**Inlet ceramic filter 29-06**	**Outlet ceramic filter 29-06**
Unknowns-1	**mg/m$_n^3$**	37.9	51.5	160.1	264.2	187.4	178.4
Unknowns-2	**mg/m$_n^3$**	14.6	22.0	23.2	177.3	106.6	87.9
Unknowns-3	**mg/m$_n^3$**	4.7	13.9	8.6	77.8	36.2	31.7
Unknowns-4	**mg/m$_n^3$**	< 1	1.1	3.6	28.7	9.5	7.4
Unknowns-5	**mg/m$_n^3$**	< 1	0.9	2.6	< 1	1.4	< 1
Total GC-FID tar excl benzene	**mg/m$_n^3$**	812.1	936.0	890.0	3165.9	1887.2	2063.3
grav tar	**mg/m$_n^3$**	39.0	257.5	787.2	536.9	431.3	403.9
dust	**mg/m$_n^3$**	1117	1053	0	5994	3714	0

Notes:
Unknowns-1: compounds in the boiling point range benzene - naphthalene
Unknowns-2: compounds in the b.p. range of naphthalene - phenanthrene
Unknowns-3: compounds in the b.p. range of phenanthrene - pyrene
Unknowns-4: compounds in the b.p. range of pyrene - benzo(e)pyrene
Unknowns-5: compounds in the b.p. range of benzo(e)pyrene - coronene
Total GC-FID tar excl. benzene: sum of all individual compounds including the unknowns and excluding benzene

As can be seen from the condensate analysis in Table 68, the single aromatic ring compounds such as benzene remain in the gas phase and do not precipitate as liquids or solids. If all of the chemicals, all of which have a boiling point over 80℃ condensed out, then there would be 2.15 kg/h depositing in the condensate for a producer gas flow of 550m^3/h. From the analysis of the condensate given in and taking a condensate production rate of 35 kg/h, the recovery rate of all the organic chemicals was 7.1g/h, demonstrating that over 99.7wt% of the organics were not being recovered at 30℃ in the condensate or in the pipework.

No chemical deposits have been observed in the pipework although a few grams of "tars" were recovered after 50,000 m^3 of producer gas in a plastic mesh filter after the main gas fan. This demonstrated that the BTXs and naphthalene were passing to the gas engines and being combusted.

Comparing specifically the US EPA 16 PAHs, their recovery in the condensate was 0.16g/h: the production rate after the hot gas filter was 448g/h. It was readily apparent that over 99.6wt% of the PAHs were going to the gas engines. Further clarification on the nature of the chemical class was obtained from ECN:

> "In general tars can be classified according to the following classes:
> Class 1: GC undetectable tars that include the heaviest tars that condense at high temperatures even at very low concentrations
> Class 2: Heterocyclic compounds (eg phenol, pyridine, cresols). These were compounds that generally exhibit high water solubility

> Class 3: Small 1-ring aromatic compounds that were not important in condensation and water solubility issues
> Class 4: Light polyaromatic hydrocarbons that only condense at relatively high concentrations and intermediate temperatures
> Class 5: Heavy poly-aromatic hydrocarbons (4-7 ring compounds) that condense at relatively high temperature at low concentrations
>
> In general, the class 1 and class 5 tars were responsible for condensation problems. Class 1 tars cannot be determined easily. The tars from class 5 that have been identified in the measurement contain pyrene and larger compounds, including the unknowns 4 and 5. It should be noted that their concentration level was very low (well below 20mg/m^3)."

From subsequent discussions with ECN, their view was that allowing for the organic chemicals most likely to form "tars", approximately 20mg/Nm^3 would be of form of condensed "tars", i.e. prone to forming deposits including the unknown group 5 chemicals. This would be consistent with the observations made at Mossborough hall during regular operation. The results demonstrate that the Biomass Engineering Ltd. gasifier was capable of giving a gas that was suitable for use in an engine.

4.5 Carbon balance

Based on the analyses of the fuel, char, condensate and the producer gases from the unit, a carbon balance can be made which will allow the amount or wood processed to be estimated and the process efficiency determined.

The chemicals in the condensate were approximated by the composition given in Table 67. By then calculating the amount of carbon in the residual ash from the char augur on the base of the gasifier and from the hot gas filter; the amount of carbon in the condensate and in the dried producer gas, the carbon balance can be completed.

It can be determined that each m^3 of producer gas contains 0.14kg of C and 0.499kg of N/Am^3 of producer, accounting for the organic vapours present in the gas at 0.003kg/m^3 of producer gas and a residual trace of water vapour. This allows the air consumption to be estimated and hence the equivalence ratio, which will allow an assessment of how close to ideal gasification stoichiometry the gasifier was working at. From the mass flow of material, approximately 1.6kg of air was being consumed. The carbon balance analysis was summarised in Table 72.

The errors were due to slight fluctuations in producer gas flow and the errors in the measurement of the mass of char and ash in the bins, as there was some system holdup.

Table 72. Carbon balance for the gasification process

Process stream	**Flow**	**units**	**Carbon in [kg/h]**	**Carbon out [kg/h]**
Dried wood fuel in	214.4	kg/h	88.71	
Dry air in	344.3	kg/h		
Flowrate of producer gas	~550	m^3/h		76.85
Bin char flowrate	4.5	kg/h		3.73
Filter char flowrate	4	kg/h		2.88
Condensate flowrate	35	kg/h		0.45
		Total	88.71	83.91
		Carbon closure	97.0%	

The equivalence ratio [mass air/mass dry wood] was 1.55, which was reasonable given that not all of the carbon was converted and some was present in the residual char from the hot gas filter, the bottom of the gasifier and in the condensate. As a check the ash balance can be estimated, however as noted, the ash was reduced during the gasification process and this can only be an estimate. This was estimated at 2.1kg/h ash in, 2.2 out, due to oxidation of the ash in the analytical procedure.

5. COSTS OF BIOMASS GASIFICATION SYSTEMS

Biomass Engineering Ltd. has previously presented work on the techno-economics of downdraft gasification systems, both for engines and for micro-turbines (198). The techno-economics presented here takes a more commercial approach from the costs derived for the Mossborough Hall farm installation and how much the electricity production cost would be from the unit.

Due to the commercial sensitivity of cost data for the various components within the gasification system and the overall production cost of the system itself, only the variation of electricity production costs with throughput and feedstock cost will be presented. Costs for power only and combined heat and power systems will be given. The basic mass flow data leading to net electrical production were given.

5.1 Methodology

Costs associated with the production of electricity produced by biomass gasification comprise an annual cost of capital (assuming all of the capital was loaned), to which were added the annual operating costs of the plant. The operating costs comprise feedstock cost, labour, utilities, maintenance and overheads. The cost of electricity was obtained by summing the production cost elements, and dividing by the total annual production of electricity and also the variant of combined heat and power, taking into account revenues from the sale of heat. The methodology for calculating each of the production cost elements was described in the following parts.

5.2 Capital Cost

Capital cost was calculated as a total plant cost, which includes both direct costs [installed equipment] and indirect costs [engineering, design, supervision, management, commissioning, contractor's fees and interest during construction, contingency].

The validity of any model can only be confirmed by comparison with actual cost data for installed plants. Unfortunately, there were few operational small-scale biomass gasifiers in the UK, which were not specifically built for the application and the comparison of costs on a consistent basis was always very difficult. The supplementary information included engineering, design, management and estimate of commissioning costs, with detailed engineering drawings for the entire plant and a basis for the labour costs and man hours involved in the project from conception to completion. The mass balance used as the basis for the cost estimation was given in Figure 48.

5.3 Total Plant Cost

Total plant cost *[TPC]* was built up in the following manner:

The delivered cost of each process unit as purchased or fabricated by Biomass Engineering Ltd. was obtained and the final installation cost based on the costs expended by Biomass Engineering Ltd. on the system hardware calculated.

Various items related to installation were then added to the equipment cost *[EC]* by Biomass Engineering Ltd. to give the direct cost for each process unit. This was done using direct cost factors published by the UK Institution of Chemical Engineers (202). The factors can take the form given in Equation 6:

$$F = c(aEC^{b}) \qquad \text{Equation 6}$$

where *a* and *b* were constants for a given factor, and *c* was a multiplier to be included if unusual or atypical conditions pertain. Factors were applied for piping, instrumentation, lagging, electrical, civils, structures and buildings. The direct cost [*DC]* was then given by equation 7.

$$DC = EC(1 + \sum F) \qquad \text{Equation 7}$$

The direct costs were added to give the direct plant cost *DPC*. Indirect costs were then added to give *TPC*. All costs were on a 2004 basis. The basic economic data was given in Table 73.

Table 73. Calculation factors used in the techno-economic assessment

No of plant replications	1
Life of project [years]	20
Interest rate [%]	8%
Inflation rate [%]	3%
Labour rate [£/y]	20000 per person
No. of shifts	1
Overheads [%CC/y]	4%
Maintenance [%CC/y]	4%
Availability	90%

5.4 Operating Cost Calculations

For the operation of the system, it was assumed that two staff would be employed to maintain the system during the day and ensure adequate supplies of wood were available after drying and for continuous feeding to the gasifier. The components of the operating cost were: annual cost of capital, labour, utilities [electricity and water], maintenance and overheads. The development of the unit has the aim of sufficient degree of automation that the site owner only has to ensure that the wood hopper was filled twice a day with prepared material and that the system startup, if done on a daily basis, takes less than 1 hour.

5.4.1 Capital Amortisation

Capital was amortised using the standard relationship given below. This was a simplification since the equipment used was likely to have different working lives and some items may need replacing during the life of the project. Capital amortisation was the money required to pay back the loan on capital required to set up the plant. It was calculated by the using equation 8.

$$\text{Fixed charge, €k/y} = TPC \times i \times \frac{(1+i)^l}{(1+i)^l - 1} \qquad \text{Equation 8}$$

where TPC: Total plant cost, k£
i: annual nominal interest rate, %
l: length of project, years (assumed to be the same as the loan period)

This fixed charge was constant in nominal terms and must therefore be adjusted to real terms for consistency with all other production costs. The cost in real terms of capital amortisation can be calculated for each year of the project by applying Equation 9. An average of the annual charges was used to give the approximate cost of capital amortisation in real terms.

$$\text{Annual charge, k£/y} = \frac{1}{(1+f)^n} \qquad \text{Equation 9}$$

where n_x project year
f: annual rate of inflation, %

It was expected that the gasification would have an operational life of 20 years, with major engine overhauls subject the manufacturers' specification and replacement of plant components such as ceramic filter elements and pumps and fans. Unfortunately Biomass Engineering Ltd. do not have any plants running yet for 20 years which could supply this data. The 55-75kWe unit in Northern Ireland has not had any components replaced in 5 years.

5.4.2 Utilities

Only utility requirements for continuous operation were taken into account; any start-up requirements were ignored. The two utilities considered were electricity and water and these were based on the operational experience at Biomass Engineering Ltd.

5.4.3 Electricity

In a complete electricity production plant, the electrical power necessary to operate the plant would be taken from the gross output from the generator terminals prior to the point of connection to the customer.

The power consumption of fans and pumps was calculated from the known flow rates and pressures using in-house data. The power consumption of the conveyors and motors was taken from manufacturers data and scaled appropriately. The maximum parasitic load was 10%, but typically was 5% or less of the gross electrical output at 250kWe.

5.4.4 Water

Water requirements were for make-up water for the cooling tower. A water price of £0.15/m^3 was taken for replacement of cooling water losses from the cooling tower.

5.4.5 Maintenance and overheads

Maintenance and overheads were both included as a fixed percentage of TPC per annum. A typical value of 4% was used.

5.5 Electricity production cost

Based on the data presented and the cost factor approach described, then using the net electricity generated, and the annual operating cost of the plant, including the amortised capital and all other costs, then the net electricity cost can be calculated. As required, based on the ability to recover twice as much heat from the system as electricity [gas cooling, engine cooling system and engine exhaust], then as appropriate, the effects of income from the sale of heat from the system can be assessed, as discussed later. The calculated net electricity production costs were given in Figure 49.

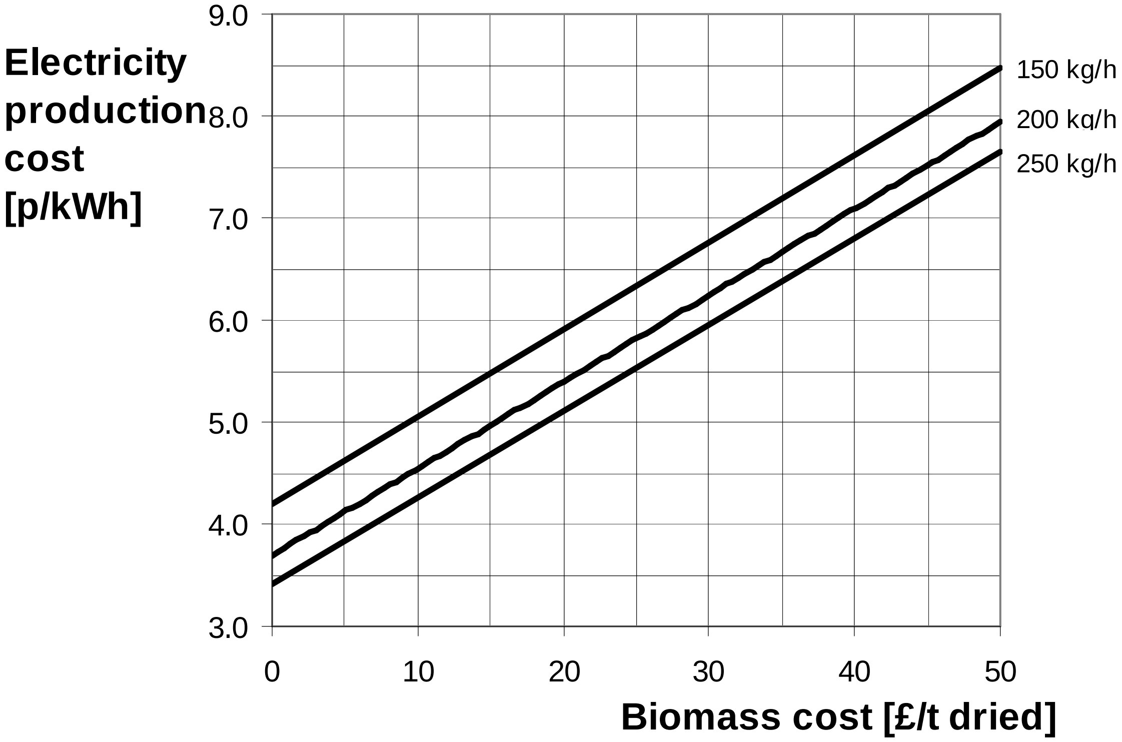


Figure 49. Net electricity production cost at varying plant throughputs and feedstock cost

The electricity production cost ranges from 3.4p/kWh at zero feedstock cost for the 250 kg/h unit [~300 kWe output] to 7.65p/kWh for a feedstock cost of £50/t. As the plant size was reduced, it can be seen that the net electricity production cost increases due to reduced electricity revenue. Biomass Engineering Ltd. were currently purchasing material at a cost from £20-25/t delivered.

5.6 Combined heat and power production costs

Using a gasifier allows it to be operated purely as a "power" gasifier, generating electricity with heat being used to dry the feedstock, or supply space heating for onsite use. The other option, which may become of more interest, was the combined heat and power system, where recovered heat was exported for commercial benefit and sold to a local user. Some cost for the dry system were carried out, assuming an income of 1p/kWth. The results were given in Figure 50. The sale of heat can reduce the net electricity production cost by 25% by 293kWe output and a zero cost feedstock, which was a significant improvement and this reduces to a 16% reduction for a £50/t feedstock cost.

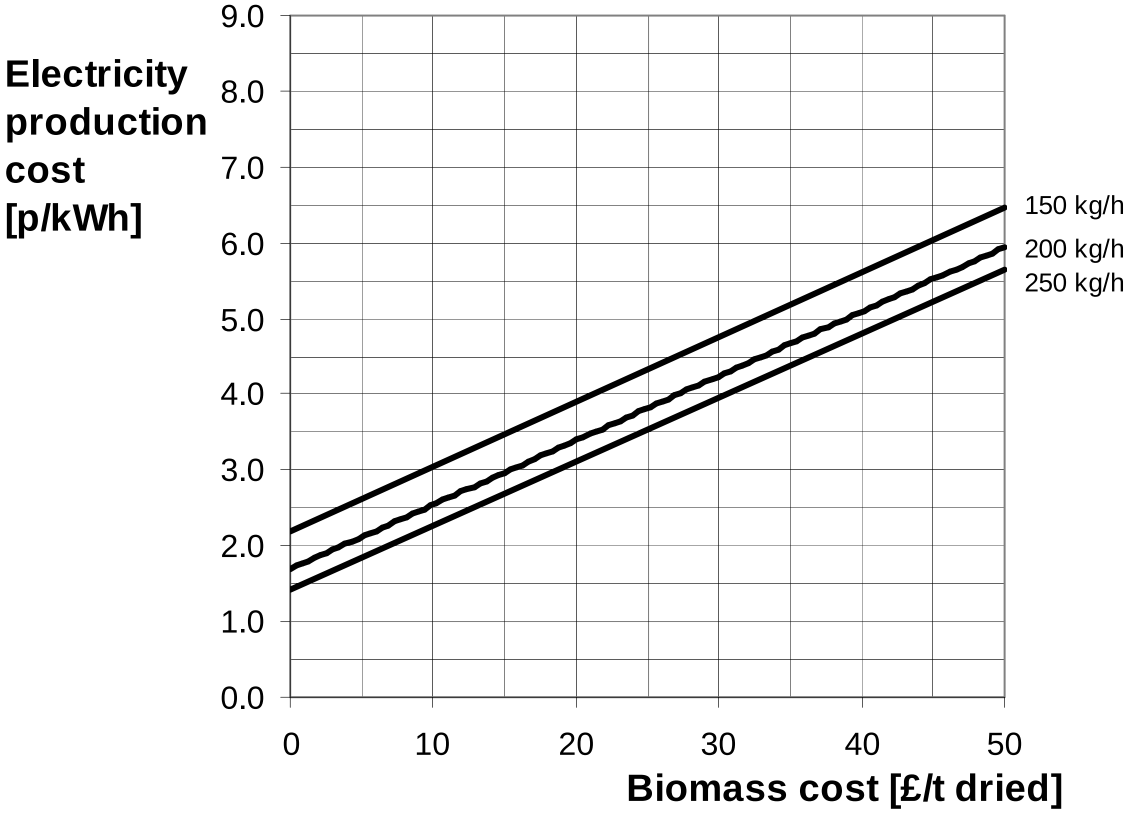


Figure 50. Net electricity production costs for CHP system: variation with feedstock cost and plant throughput

CHP therefore has the strong potential to make a significant cost impact and more opportunities for such systems need to be identified. Based on the data presented, the Biomass Engineering Ltd. can be built economically and used in the CHP mode to provide a reliable system for a range of biomass types. Net electricity production costs were therefore reduced by 2 pence per kilowatt hour [p/kWh] for the CHP options, making gasification an attractive alternative to fossil fuels.

The costing of biomass gasification systems was difficult, as there were usually site-specific costs which cannot always be allowed for in the determination of generic costs for small scale biomass gasification systems.

6. LIFE CYCLE ASSESSMENT [LCA]

6.1 LCA software

Part of the project requirements was an assessment of the life cycle analysis of the gasification process. After careful consideration of the available LCA packages, the GEMIS package developed by Öko-Institut and Gesamthochschule Kassel was selected. The GEMIS package has extensive databases on biomass gasification, which can be altered to accommodate user input data. This allowed the most flexibility and therefore model the system more accurately. GEMIS was a life-cycle analysis program and database for energy, material, and transport systems (203).

GEMIS includes the total life-cycle in its calculation of impacts – i.e. fuel delivery, materials used for construction, waste treatment, and transports/auxiliaries. The GEMIS database covers for each process:

- efficiency, power, capacity factor, lifetime
- direct air pollutants (SO_2, NOx, halogens, particulates, CO [carbon monoxide], Non-Methane Volatile Organic Compounds [NMVOC])
- greenhouse-gas emissions (CO_2, CH_4, N_2O, SF_6, all other Kyoto gases)
- solid wastes (ashes, overburden, FGD residuals, process wastes)
- liquid pollutants (absorbable organic halogens [AOX], biological oxygen demand, [BOD_5], chemical oxygen demand [COD], N, P, inorganic salts)
- land use.

GEMIS software can also analyse costs - the respective data were implemented for fuels and energy systems. Furthermore, GEMIS allows also to value results by aggregated indicators: resources into Cumulated Energy Requirement [CER] and Cumulated Material Requirement [CMR], greenhouse gases into CO_2 equivalents, air pollutants into SO_2 equivalents and ozone-precursor equivalents, as well as external costs.

6.2 Input data and simulation

The basic user input data was modelled for a short rotation coppice [SRC] wood system to a downdraft gasifier coupled to a spark ignition engine. The data was based on the process emissions detailed in this report. The user location data was given in Table 74.

Table 74. User location data for LCA

Location: United Kingdom
Technology: powerplants-motors-gas
Technology status: Best Available Technology (BACT)
Reference year: 2000
Sector: 40.11 Production of electricity
SNAP Code: 1.1.5 Stationary engines
Input gasifier FB+cleaning\gas-wood-forest (ICE/GT)-2020-Biomass Eng. Ltd.

The basic consumption of concrete and steel for the basic civil engineering works were given in Table 75.

Table 75. Raw materials for civil engineering

Product	Delivering process	Demand	
steel	metal\steel-D-mix	$20.0000*10^3$	kg/MW
Cement	Non-metallic minerals\cement	$200.000*10^3$	kg/MW

The electrical output was specified at 250kWe and the recoverable heat ratio taken at 1.8 times the electrical output. The basic process values as input to the model were given in Table 76. A labour rate of two persons was assumed, although in practice this will be less due to the high level of automation of the system.

Table 76. Basis process input data

Power		250	kWe
Operating time		8000	h/a
Life time		20	years
Land use		50	m²
Employees		2	Persons
Efficiency		34	%
Fuel	woodgas-FB (SRF-poplar)		100%

The calculated process emissions were given in Table 77. The stack height was set at 15 m and the primary emissions were from the engine exhaust.

Table 77. Process Direct emissions

Base for emission data	5	%	O_2	
	18.46	%	CO_2	
Flue gas volume flow	1209.85	Nm³/h	$457.06*10^{-3}$	Nm³/MJ
Stack height	15	m		
Emission control systems	Catalyst-3way-noCost			

By running the LCA, a range of emission outputs can be calculated and their reduction either within the engine or by the use of other catalytic or sorbent control was possible. For the biomass gasification system, the only additional reduction technology specified was a three way catalytic oxidation system for the gas engines to reduce CO emissions. The CO and CH_4 will be largely oxidised in the engine and will also then be catalytically reduced. The data and gas concentrations were given in Table 78. The engine exhaust from the process had not been measured at this time, so the emissions were based on other engine work and an lambda ratio of 1.4. A small amount of SO_2 was allowed for from the engine oil, as has been observed on the Ballymena ECOS Centre gasifier engine. The amount was relatively insignificant.

The transport of the wood was incorporated into the model by allowing the material to be transported 25miles to site, which has a slight impact on the LCA. A deCO catalyst was assumed for the engines at no additional cost, ie it would be incorporated into the overall cost of the gasification system and would not be an additional cost item. The deCO catalyst operating at 75% efficiency still gives a high exit level of CO: this was a conservative estimate and work was ongoing to obtain and test a suitable catalyst.

Table 78. Input and Gas outputs of the gas engines

Raw gas SO_2	0.140	mg/Nm^3
Inherent control SO_2	0.140	%
Raw gas NOx	57	mg/Nm^3
Inherent control NOx	25	%
Reduction NOx	95	%
Raw gas Particulates	2	mg/Nm^3
Raw gas CO	140000	mg/Nm^3
Inherent control CO	98.5	%
Reduction CO	75	%
Raw gas NMVOC	5	mg/Nm^3
Reduction NMVOC	70	%
Raw gas CO_2	365035	mg/Nm^3
Raw gas CH_4	18000	mg/Nm^3
Reduction CH_4	60	%

From the engine exhaust, which was the largest plant emission, comprising over 95wt% of all the process emissions, the various pollutants can be assessed and these were given in Table 79. The exact values from the model do not correspond to the engine emissions as emissions from the transport of the wood to site were also taken into account. All of the emissions except the CO emission were acceptable. Biomass Engineering Ltd. were currently undertaking work to fit a suitable deCO catalyst to the engines to bring the level down to 50ppm.

Table 79. Pollutant Emissions: SOx, NOx, VOCs, CO_2, CH_4

Emission	Quantity	Units	Quantity	Units
Clean gas SO_2	0.140	mg/Nm^3	$47.884*10^{-3}$	ppm
Clean gas NOx	2.1375	mg/Nm^3	1.04	ppm
Clean gas Particulates	0.002	mg/Nm^3		
Clean gas CO	525	mg/Nm^3	419.8	ppm
Clean gas NMVOC	1.5	mg/Nm^3	1.28	ppm
Clean gas CO_2	365035	mg/Nm^3	$184.633*10^{3}$	ppm
Clean gas CH_4	36	mg/Nm^3	50.17	ppm
Emission rate SO_2	$169.78*10^{-6}$	kg/h	1.36	kg/a
Emission rate NOx	$2.5861*10^{-3}$	kg/h	20.69	kg/a
Emission rate Particulates	$24.197*10^{-6}$	kg/h	$193.58*10^{-3}$	kg/a
Emission rate CO	$635.17*10^{-3}$	kg/h	$5.08138*10^{3}$	kg/a
Emission rate NMVOC	$1.8148*10^{-3}$	kg/h	14.518222	kg/a
Emission rate other particulates	$24.197*10^{-6}$	kg/h	$193.58*10^{-3}$	kg/a

From the results in Table 79, the ambient air concentrations can be assessed. These were given in Table 80, compared to model background data for the UK. The results show that the effects on background concentrations were negligible.

Table 80. Process Emissions: residual air concentrations

Ambient air concentration SO_2	$50.933*10^{-6}$	µg/m^3	Average	$382.00*10^{-6}$	µg/m^3	Peak
Ambient air concentration NOx	$775.82*10^{-6}$	µg/m^3	Average	$5.8186*10^{-3}$	µg/m^3	Peak
Ambient air concentration Particulates	$7.2591*10^{-6}$	µg/m^3	Average	$54.443*10^{-6}$	µg/m^3	Peak
Ambient air concentration CO	$190.55*10^{-3}$	µg/m^3	Average	1.4291374	µg/m^3	Peak
Ambient air concentration NMVOC	$544.43*10^{-6}$	µg/m^3	Average	$4.0832*10^{-3}$	µg/m^3	Peak
Ambient air concentration other particulates	$7.2591*10^{-6}$	µg/m^3	Average	$54.443*10^{-6}$	µg/m^3	Peak

From the data presented in Table 79 and Table 80, the emissions can be calculated as a emission in terms of kg/MWh, which allows comparison across different power generation technologies to be made. The results were given in Table 81. The CO_2 equivalent of 4kg/MWh was a very positive result, given that coal based power generation was of the order of 900-1100kg/MWh. The CO emission was the only high one and as noted, was based on a system at 75% efficiency.

Table 81. Summary of output emissions: mass equivalent

SO_2 equivalent	$7.8813*10^{-3}$	kg/MWh
CO_2 equivalent	4.0070292	kg/MWh
SO_2	$679.11*10^{-6}$	kg/MWh
NOx	$10.344*10^{-3}$	kg/MWh
Particulates	$96.788*10^{-6}$	kg/MWh
CO	2.5406888	kg/MWh
NMVOC	$7.2591*10^{-3}$	kg/MWh
CH_4	$174.22*10^{-3}$	kg/MWh
Ash	$7.3015*10^{-3}$	kg/MWh
PAH (liquid)	0.0059	kg/MWh
Sorbents use	none	
Catalyst-3way-noCost	0.000	kg/MWh

The LCA results show that biomass gasification was an environmentally compliant technology and that the main emission of concern was the CO emission. Biomass Engineering Ltd. were undertaking work with a US company to fit a suitable deCO catalyst to the engine exhaust to abate the emission to acceptable levels.

7. CONCLUSIONS

- Biomass Engineering Ltd. have clearly demonstrated that their gasification technology, can and has been scaled up to 250-300kWe output. The main hindrance in the project has been the issues of suitable wood chip supply, grid connection and suitable gas train for the gas engines. Further development work in the case of Iveco was required.
- An extensive monitoring campaign was carried out on the process emissions and tar sampling of the gases showed that although high levels of organic compounds were present in the clean gas at 2000-300 mg/Nm^3, only 20mg/Nm^3 would be classed as tar liable to form deposits. These have been successfully removed prior to the engine in a fabric filter. One engine company has subsequently stated that it will guarantee its engines based on the Biomass Engineering Ltd. results.
- The gasification system was relatively simple, uses a dry gas cleaning system which obviates the need for water scrubbing of the gases and hence reduces emissions. Over 2200 hours on clean gas production has been obtained. Only 1400 hours of engine operation were obtained due to massive delays in the grid connection and changes required to the gas train of the gas engines. Electrical outputs of over 270kWe have been achieved.
- A heat integrated system was feasible with chipping of wet wood on site and its subsequent drying with the engine exhaust gases, which significantly enhances the flexibility of the process and improves the overall thermal and electrical efficiency. Other heat can be recovered from the hot gases from the ceramic filter as required, subject to site requirements.
- Some work was still required on the engine CO emissions in terms of selection of a suitable catalyst- work was ongoing.
- Wastewater from the unit can be sent to foul sewer for treatment as required.
- Productions costs were calculated at 5.5p/kWh [£1300/kWe installed cost] for the demonstration unit, higher than expected due to the use of 2 engines and the significant costs involved in the first grid connection for a feedstock cost of £25/t delivered dry. These were expected to drop by over 20% for subsequent projects as part of the "learning" curve.
- Wood cost has a significant influence on the electricity production costs and where possible, long term supply contracts for suitable roundwood should be negotiated to ensure that optimal pricing was obtained.
- The process met the project requirements, although more sustained engine operation would have been preferred.

8. RECOMMENDATIONS

The following technical and non-technical recommendations were made:

- Subsequent projects need to discuss grid connection at the very outset and agree a timetable of works and scope of supply with agreed deliverables to prevent excessive lead times in projects. The electricity companies need to be more aware of the needs of small-scale generators who want to export to the grid.
- Further work on engine catalysts was required for the Iveco engines, as they so not supply such a system for their engines. Costs and suppliers need to be further developed for the UK market to ensure full emissions compliance.

- Onsite chipping of wood logs has proven to be a better option than sourcing wood chips. This will be replicated on future projects. Only FSC graded wood to be used.
- True CHP options have a significant effect on the process economics and more opportunities for heat use should be investigated. Sale of heat for 1p/kWh reduces the net electricity-generating price to 3.5p/kWh.
- Further work on filtering of the condensate with the by-product char was required to further reduce emissions.
- Continuous operation of the system was preferred to reduce thermal cycling and improve the lifetime of some plant components, notably the ceramic filter.
- A start-up fan with a gas throughout similar to the main gas fan would reduce start-up times and also improve restarting the system from a temporary shutdown. Any restarting always needs to bypass the hot gas filter to avoid filter damage by "tars" accumulation.

9. ACKNOWLEDGEMENTS

Biomass Engineering Ltd. would like to acknowledge the financial support of the DTI which has enabled this project to be carried out.

Photographs

Photograph 1. Wood reception and chip storage

Photograph 2. Wood hopper and integral dryer

Photograph 3. Gasifier and Hot filtration unit

Photograph 4. Demister, Gas fan and Gas buffer tank [engines in background]

Photograph 5. Iveco gas engines in acoustic enclosures and exhaust gases dilution fan and duct

Photograph 6. Transformer and control room for grid connection

APPENDIX A.
TAR AND PARTICULATE SAMPLING METHODOLOGY

A.1 Sampling set-up

Figure 51 presents a photograph that shows the specially designed ECN sampling probe. This probe was connected to the gasifier system via 3" BSP sampling ports. Biomass product gas has been sampled from the gasifier outlet (sampling point 1, SP1) and from the inlet and outlet of the ceramic filter (sampling points 2, SP2 and 3, SP3). The probe consists of a bend sampling tube, a thermo-couple and a high temperature valve. Due to the width of the channels only sampling point 1 allowed for measurements exactly in the middle of the gas duct. For the other two sampling points the channel width was too large and the samples were taken nearer to the wall of the hot gas filter. During sampling the probe was heated up to 350 ℃ with trace heating. Ideal isokinetic sampling conditions could not be reached due to the differences in gas flow characteristics of the product gas.

Figure 51. Special ECN tar and particulate sampling probe

A.2 Hot dust filter

The Stainless steel filter holder was made at ECN and Schleicher & Schuell glass fiber soxhlet thimbles (Filterhülsen aus Borosilicatglasfasern) type: 603GH, 30 X 77 mm were used to recover the particles. Filter (made at ECN) temperature during sampling = 350℃

Figure 51 and Figure 52 present the standardised sampling set-up for tars and particulates that has been used during the measurement campaign. Table 82 gives the actual sampling conditions during the measurement campaign.

Table 82. Impinger sequence of the standardised tar and particulate sampling set-up

Impinger	Isopropanol	Temperature	Frit	Temperature control
1	100 ml	+ 40℃	no frit	Water bath
2	50 ml	+ 40℃	G1	Water bath
3	50 ml	- 20℃	G3	Glycol bath
4	50 ml	+ 40℃	no frit	Water bath
5	50 ml	- 20℃	G3	Glycol bath
6	50 ml	- 20 ℃	G3	Glycol bath

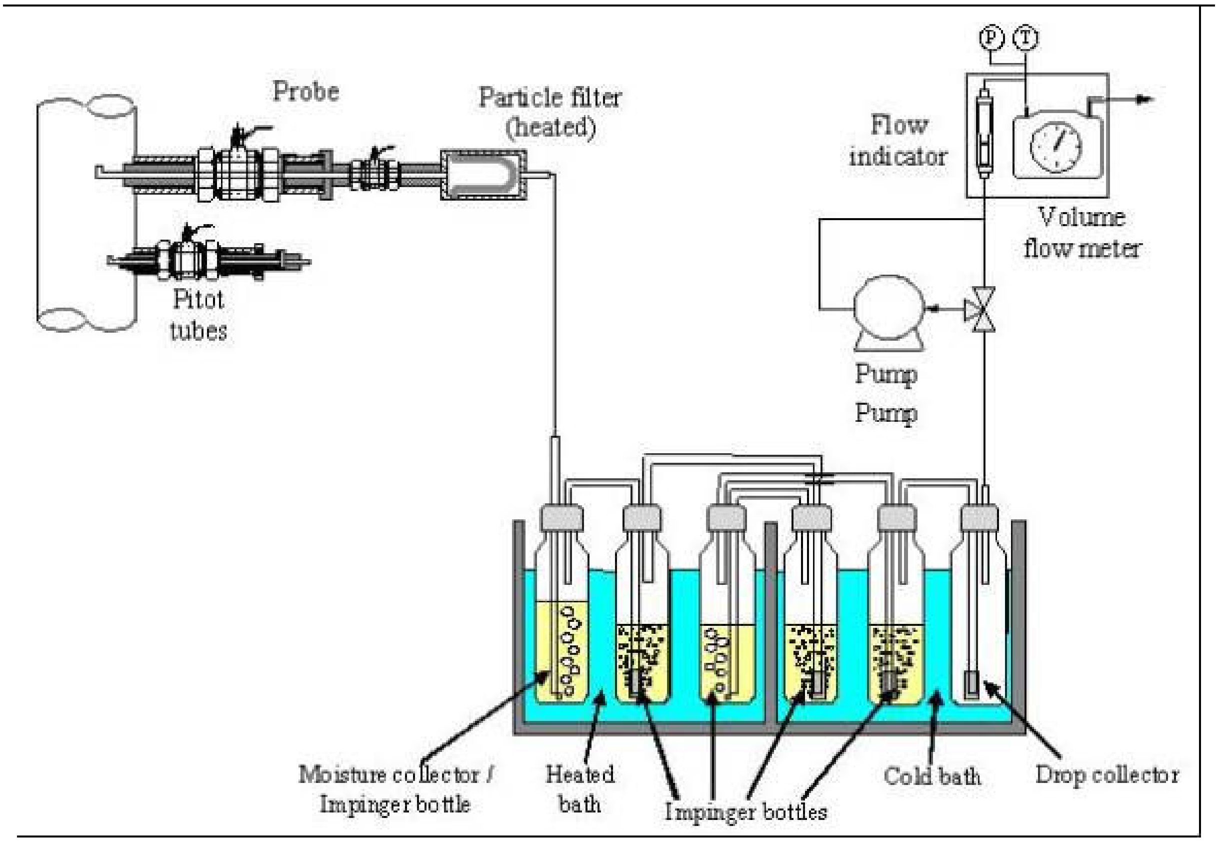


Figure 52. Standardised sampling set-up for tars and particulates

The sampling set-up of the tar measurement standard consists of an atmospheric and isokinetic sampling train for tar and particulates in biomass product gas with a removable probe and Pitot-tubes for flow measurement.

Sampled tar and dust was subsequently analysed off-line in the laboratory with gravimetry, gas-chromatography and/or mass-spectrometry according to standard procedures.

Table 83. Sampling conditions

Date	Sampling Position	Start time	Stop time	Sampled producer gas volume (m_n^3)	Sample flow (l_n/min)	Bulk weight solution (kg)	Dust weight filters (mg)
28/06/2005	SP2	11:02	12:32	0.285113	3.17	0.6737	300.10
,,	SP3	11:22	12:38	0.204051	2.68	0.6013	0.00
,,	SP1	14:30	15:44	0.247843	3.35	0.5953	276.79
29/06/2005	SP2	11:05	12:37	0.266478	2.90	0.6499	989.64
,,	SP3	11:06	12:40	0.181689	1.93	0.6100	0.00
,,	SP1	14:27	15:47	0.207778	2.60	0.5918	1245.40

Note:

SP1 = outlet gasifier
SP2 = inlet ceramic filter
SP3 = outlet ceramic filter
m_n^3 = dry gas at 273 K and 1 atmosphere

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