Programme Area: Bioenergy

Project: Energy From Waste

Title: AEA – Advanced Thermal Technologies Technology Landscape Review

Abstract:

This document is Appendix B3 (of 3) of the Energy from Waste UK Benefits Case (Deliverable 2 of 2 in Work Package 4).The ETI commissioned AEA to provide an up-to-date assessment of current development and demonstration activities in EfW technologies, including both Advanced Thermal Treatment (ATT) and Anaerobic Digestion (AD) technologies. This document is the review of Advanced Thermal Treatment technologies.

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

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Energy from Waste Technology Landscape Review

Advanced Thermal Technologies

A Report for the Energy Technologies Institute

AEA in Confidence
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Title
Energy from Waste Technology Landscape Review

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1. Introduction and Methodology

1.1 Project Context and Scope

This review is part of a wider Energy from Waste (EfW) project, in which the Energy Technologies Institute (ETI[1]) is seeking to examine the technology development and demonstration needs required to allow a wide range of wastes to be used for energy production purposes. This Flexible Research Project (FRP) is currently being delivered by a Caterpillar-led consortium that includes Cranfield University, The Centre for Process Innovation (CPI), EDF Energy and Shanks Waste Solutions. Hereafter, the commissioner of this report is referred to as the Consortium.

1.2 Purpose and Structure of This Review

The Consortium's requirement for this project was to provide an up-to-date assessment of current development and demonstration activities in EfW technologies, with reference to NASA's Technology Readiness Level scheme (see Section 1.3), which assigns a score from 1-9 to reflect the maturity of each technology.

The full scope of the project included reviews of both Advanced Thermal Treatment (ATT) and Anaerobic Digestion (AD) technologies. During the course of the project, it became clear that these two groups of technologies are at quite different levels of development, and that their reviews should accordingly focus on different aspects. For that reason, it was decided to write two parallel reports – one each on ATT and AD – and an overarching summary report pulling together conclusions and findings from the two technologies. Accordingly, this report focuses on ATT technologies.

Through discussions between the Consortium and AEA, it emerged that the key requirements for the review were:

+ to create a "long-list" of all major "enterprises" (including companies, suppliers, distributors, technology providers, research institutes and universities) involved in EfW technology;
+ to determine criteria that could be applied to the "long-list", in order to obtain a short-list of about 20 enterprises to review in detail;
+ to make good use of AEA's extensive body of public and private resources (including project reviews, journals, papers, conferences, reports, site visits and supplier publications) in assessing the individual enterprises;
+ to assess the current TRLs of the key unit operations that constitute the processes used by the enterprises; and
+ to conclude from the information provided the key opportunities and threats associated with ATT as an EfW technology.

To deliver these outcomes, the rest of the document is structured as follows:

+ the remainder of this section provides more detail on the information sources AEA used to support the analysis, and explains the short-listing process;
+ Section 2 presents reviews of the three short-listed "successful" projects;
+ Section 3 presents reviews of the nine short-listed "unsuccessful" projects;
+ Section 4 presents reviews of the eight short-listed future technologies that could effect a step-change in the performance of ATT technologies;
+ Section 5 draws conclusions from review performed, and recommends some next steps.

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[1] http://www.energytechnologies.co.uk/Home.aspx

1.3 The Technology Readiness Level scheme

Technology Readiness Levels (TRLs) were developed by NASA, and the original definitions only included seven levels, though this was later expanded to nine levels. As might be expected, the NASA definitions have a clear bias to space technology, so Table 1 below presents the definitions that AEA used for this study.

Table 1: AEA's Technology Readiness Level Definitions

Phase	TRL	Description
I	1	Basic principles observed and reported
	2	Technology concept and/or application formulated
	3	Analytical and experimental critical function and/or proof of concept
II	4	Component validation in laboratory environment
	5	Component validation in industry environment
	6	Subsystem model or prototype demonstrated in industry environment
III	7	Full system prototype demonstrated in industry environment
	8	Actual system qualified through test and demonstration in industry
	9	Actual system proven through successful operation

1.4 AEA's Body of Evidence

AEA is the UK's leading provider of technical environmental advice and support to UK Government, and is a trusted advisor to local government and the private sector. We have been operating in the UK, Europe, US and China for over 40 years and employ over 1,000 staff, many of whom are world-leading experts in their fields. AEA was voted Number One Consultancy for Climate Change and Renewables by our peers in the prestigious Edie Awards in 2006, 2007, 2008 and 2009.

AEA has worked on technology development, procurement, evaluation and delivery in both the thermal and biological areas for over 30 years, supporting developers, financiers, users and their contractors in designing solutions for waste treatment. We have assisted Government Agencies in evaluating new technology delivery, and in reviewing technology development and providing technical support to grant programmes designed to support technology advances.

Our team's technical and process technology expertise is underpinned by a thorough understanding of both the energy and waste markets, and associated data (e.g. feedstock availability and characteristics). Our market knowledge of new technology development was critical to the successful delivery of this assignment, enabling us to cut through the marketing literature on each technology and focus on their strengths and weaknesses, in order to short-list appropriate technologies on a robust evidence base. We know many of the technology providers and are in touch with numerous technology start-up companies and universities, having undertaken similar research assignments for several clients in the last two years. This insight has ensured that our scores and commentary are based on real evidence and visibility of the operations in question and not on the promotional literature available on the web.

That said, however, much of our work in the recent past has been on confidential studies, on topics such as feedstocks, technology options and process efficiencies for private sector clients including Hills, Shanks, Biossence, and Dairy UK. In addition, some of our on-going work for the International Energy Authority (IEA), DECC, Defra and WRAP is currently confidential. Although these studies are not publically available and so cannot be presented within this report, we have taken the lessons learned and the perspectives of the key technical staff who have worked on these projects to inform our technology appraisals. To give an idea of the extent of this body of evidence, the electronic "research" library within our system folder for this project contains almost 300 files, including reports, case studies and presentations.

Some examples of recent projects that have been utilised to inform our position on specific technologies include:

- **Task Leader of the International Energy Agency's Bio-Energy Agreement Task on Integration of Energy into Solid Waste Management.** Leadership of an international grouping charged with the coordination of National R & D efforts and dissemination of the state of the art in this area.
- **Evaluation of Energy from Waste Options for Hills Waste Solutions (2009).** A critical evaluation of current and near future thermal treatment technologies .
- **CHPQA -** DECC CHP quality assurance programme to annually validate and audit the performance of 1300 CHP sites including several EfW and biomass sites and proposed technologies such as plasma gasification.
- **Analysis of Renewable Technologies Growth to 2020 for DECC (2010).** A review of renewable energy (including AD, liquid biofuels/bioethanol and energy from waste) deployment and projected development in the UK.
- **An assessment for waste technology investment opportunities for Shanks Waste Management (2009/10).** A study to inform their five-year investment plan.
- **UK and Global Bioenergy Resources and Prices, DECC (2010).** A study of the availability of bioenergy feedstock (including waste) in the UK.
- **Bio-energy Review for the Environment Agency (2008).** Examination of the development of bio-energy in England and exploration of likely future development.
- **Design of a Renewable Heat Incentive for DECC (2009-10).** Quantitative and qualitative cost benefit analysis to support the development of the Renewable Heat Incentive.
- **An assessment of waste technology options for Essex Waste Partnership (2009/10).** As part of their PFI funded residual waste treatment procurement project.
- **Management of two databases on behalf of DECC (current):** RESTATS, the UK's Renewable Energy STATisticS database, and REPD, the Renewable Energy Planning Database project that tracks the progress of new projects from inception to operation.
- **Ofgem** - Development of Syngas metering & sampling methodology for RO 2009 for use when assessing how a generating station should meter syngas and calculating its ROCs allocation.
- **NNFCC Suitability of UK-Derived Biomass Feedstocks for Energy Generation** – Assessment of the biomass, energy crops and agricultural residue applicability to combustion technology and prime mover options
- **Bioenergy Capital Grants Scheme** – Technical application reviews including gasification, ORC, CHP and AD applications.
- **Evaluation of Opportunities for converting indigenous UK wastes to fuels and energy** – Review of UK waste arisings and technology options available to use various waste fractions as feedstock.
- **Welsh Assembly Government** – Modelling of Impacts for Selected Residual Waste Plant Options using WRATE, specifically modeling EfW technology options including gasification, slow pyrolysis, fast pyrolysis and combustion for projected waste arisings, with and without CHP.
- **DECC EfW Workshops for Local Authorities** – Authoring and presentation of EfW options providing understanding of their operation and performance.

1.5 ATT Landscape Review Methodology

It was agreed that a landscape review of ATT technologies would be carried out in three phases:

1. A system-level review – to get a broad understanding of the various biomass and waste based systems available globally, and to highlight sites of particular interest.
2. A site-level review of 20 agreed sites – to further examine project that were deemed to be successes, failures or of technological interest.
3. A unit operations peer review to provide AEA's opinion of the status of operations / characteristics that have contributed to making some projects successful and causing others operational difficulties.

This three-phase approach highlighted technical areas where there is scope for significant advances in overcoming current technical barriers, increasing feedstock flexibility or increasing the thermal / conversion efficiency of the feedstock to energy process.

1.5.1 System Level Review

AEA collected basic data on 150 processes or organisations known to have been involved or currently involved in the area of ATT. Also included were specifically chosen organisations or processes that are not active within the ATT sector but who have developed or are developing technologies that may be relevant to ATT processes. The full list is provided at the end of this document, in Annex I.

It was beyond the scope of this project to review all the processes in much detail, so, with guidance from the ETI Consortium, AEA selected three categories to assist with the short-listing process:

- projects that are currently successful (“Successful Projects”);
- projects that AEA considers have not met the original expectations, from which valuable conclusions can be drawn (“Unsuccessful Projects”); and
- technologies that may overcome the current barriers to the development of ATT processes for energy from waste (“Future Developments”).

1.5.2 Site Level Review

20 sites were reviewed in detail to get a specific understanding of the technology, the nature of the organisations supporting the project and any remarkable features. This was carried out by using information in the public domain, AEA’s own knowledge bank and discussions with staff who have a good knowledge of the projects.

1.5.3 Evaluation of Unit Operations.

The unit operations for each site were assessed against TRL definitions in Table 1. Each process was considered according to the following functional groups of operations:

1. Pre-treatment of feedstock
2. Conversion process
3. Post treatment / Clean up
4. Power generation
5. System integration

2. ATT Successes

A preliminary screening exercise to identify successful processes was undertaken by applying the criteria below. Table 2 presents the processes / organisations we selected for review.

- the processes needed to be operational, ideally with several examples.;
- sufficient information should be readily available to carry out the review.

Table 2: Selected Successful Projects

	Process Name	Process Description	Reactor type
1	Ebara	Innovative twin internally circulating fluidised bed. Known to have lower pre-treatment requirements	Close coupled combustion
2	Scotgen	Batch slow pyrolysis with low level air injection	Close coupled combustion
3	Thermoselect	Updraft gasifier, wet scrubbing, wet ESP, syngas supplied to gas engines or steel manufacture	3 stage combustion

2.1 Ebara – Kawaguchi-city Asahi Tokyo Waterfront Recycle Power

Process Category	Close coupled combustion	**Reactor Type**	Twin internal circulating fluidised bed
Primemover	Steam Turbine	**CapEx**	Unknown
Fuel/feedstock	Residual MSW	**Throughput**	135,000 tpa [*]
Development Stage	Proven	**Operating hours**	nda
Design capacity	11.7 MW [*]	**Availability**	>90% [*]

[*] Ebara has 200 plants. These figures are from their plant in Tokyo

Ebara Corporation is an organisation based in Japan with more than 25 years' experience in delivering waste management, energy recovery and resource recycling technology using fluidised bed furnace designs. Ebara has at least 14 Twin Rec reference plants known to be operational and they were responsible for the development of the innovative twin internally-circulating fluidised bed furnace design that lowers the feedstock pre-treatment requirements. Ebara typically uses close-coupled gasification / combustion, mated to open steam cycles with high-pressure super-heated steam at 400˚C. These systems are designed to operate at high furnace temperatures capable of melting the ash (in particular fly ash) generated and producing a clean but low GCV syngas that is then combusted, although they vary their designs according to the anticipated feedstock.

2.1.1 Estimation of electrical output

A calculation was carried out to estimate the operational average electricity output from the Ebara process at Kawaguchi. The calculation went as follows:

Estimation of Energy Input

Ebara's stated typical waste NCV	13	MJ/kg
Tonnage capacity	420	tonnes
Fuel Input	63.19	MW

Estimation of Fuel Used for Steam Generation

Steam to recycling & public bath	35	te/hr	Ebara stated steam supply
Steam to recycling & public bath	28	MW	Assumed 1 tonne /hr steam = 0.8 MW
Assumed Saturated Boiler efficiency (NCV basis)	85%		
Fuel used for heat	32.94	MW	

Estimated Operational Electrical Output

Fuel used for power generation	30.25	MW	Difference between energy input and energy used to generate steam.
Assumed condensing steam turbine efficiency (NCV basis) excluding generator losses and parasitic loads	25%		
Operating electrical output (accounting for generator losses 10% & parasitic load 10%)	6.06	MWe	

Comments

AEA believes that Ebara has demonstrated significant success in waste utilisation for energy and materials recovery. They have adapted their design twin circulating fluidised bed to suit various markets. Their twin internally circulating fluidised bed process is designed to operate with high levels of feedstock and operational flexibility. They use a steam cycle and a close coupled gasification and combustion arrangement; the initial gasification occurs at 580°C allowing metals and recyclables to be physically separated from the bed materials. The secondary chamber operates at 1300°C. As a result, fly ash / dust melt to form a slag, which is probably the best configuration for maximising both energy and materials recovery.

Figure 1: The evolution of the Ebara fluidised bed technology

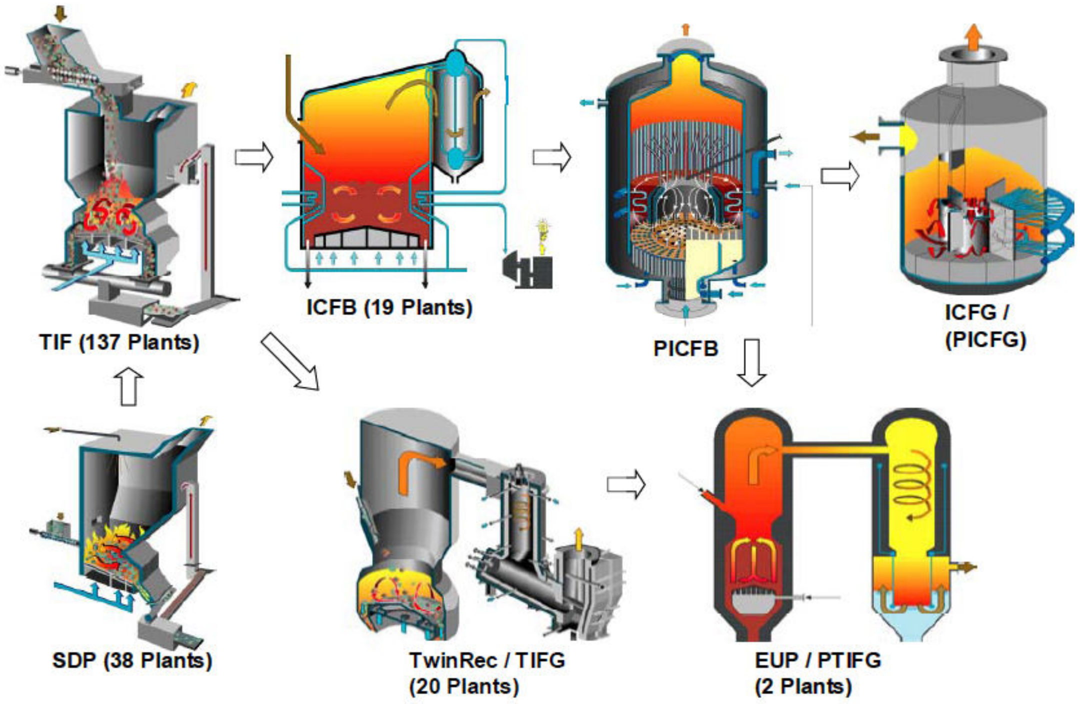

Table 3: Ebara – Kawaguchi-city Asahi Tokyo Waterfront Recycle Power TRL

Unit Operation	TRL	Justification
Pre-treatment	9	The Ebara process uses a twin internally circulating fluidised bed which is stated as capable of handling black bag waste inserted directly into the reactor vessel, therefore the conversion process. As the reactor feeding mechanism is operational at several example plants, this aspect of the plant is fully developed.
Conversion process	9	
Post Treatment	9	The high reactor operating temperatures produce molten slag which is recovered by quenching in a water bath. The flue gas is then cleaned up using the established approach of bag filters and absorption units (electrostatic precipitation is not explicitly mentioned and is thought that it is probably too costly at the 11 MW_e scale of the plant).
Power generation	9	The syngas proceeds to high temperature combustion and heat recovery raising steam for an open steam cycle (which is a well established approach to generating power in energy from waste plants).
Integration	9	The Ebara design is the result of ongoing development and the delivery of several plant of increasing sophistication and integration. There is no specific mention of any innovative integration features and in AEA's opinion integration is no greater than we would expect of a modern incinerator.
Overall TRL	9	The Tokyo water front Recycle power plant was completed in 2002 and to our knowledge has operated continuously.

Data Sources

Evaluation of Emissions from Thermal Conversion Technologies Process Municipal Solid Waste and Biomass Vanivara, University of California June 21, 2009.

Fluidised-Bed Gasification and Slagging Combustion System H.Fujimura, T. Oshita, K Naruse Ebara Corporation 2001

Fichtner Report – Viability of ATT in UK 2004

IEA Bioenergy Agreement Task 33: Thermal Gasification of Biomass (2001-2003) subtask: Review of energy conversion devices, E. Scoditti, ENEA, N.Barker AEA

2.2 Scotgen

Process Category	Close coupled combustion	**Reactor Type**	Batch Oxidation
Primemover	Steam Turbine	**CapEx**	Unknown
Fuel/feedstock	Residual MSW	**Throughput**	60,000 tpa [*]
Development Stage	Early commercial operation	**Operating hours**	No data available
Design capacity	6 MW [*]	**Availability**	>90% [*]

[*]These figures are from the plant in Dumfries.

Scotgen uses a Canadian designed batch oxidation system, which, in 2003, had two plants operating:

- one had already operated for over eight years on a barge in the Vancouver B.C. harbour, burning international waste from ships, and
- another had been operating for five years at a scrap yard burning insulation from electrical wiring.[2]

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[2] Scotgen – Batch Oxidation of Waste

Experience from these two operations, in addition to extensive testing at the University of Wyoming, has led to the development of the system. The process typically consists of a pair of primary batch chambers that share one common afterburner. The primary chambers operate alternately, as one chamber is operating; the second is cooling and being cleaned of ash and recyclables and reloaded with waste. This process has the capability of accepting unprocessed MSW. The primary chambers are maintained at a low operating temperature (500˚C) and laminar gas flow rates in order to minimise particulates, heavy metals and noxious gas emissions. The syngas from the primary chambers passes to a secondary swirl combustion chamber where it is mixed with air and combusted. The resulting flue gases are passed through a heat recovery boiler where they generate super-heated steam that powers an open cycle steam turbine.

Scotgen's plant at Dumfries in Scotland was opened in August 2009. Our understanding of operations suggests that there have been some teething problems related to gas flowrates in the heat recovery boiler. We expect these difficulties to be overcome as this process has been applied in two other plants. The Dumfries plant has limited operating hours on two of its three 20ktpa lines, handling a mixture of hazardous waste, RDF (15ktpa from Shanks nearby MBT plant), C&I waste and MSW.

Figure 2: Scotgen process flow diagram (courtesy of www.scotgenltd.co.uk)

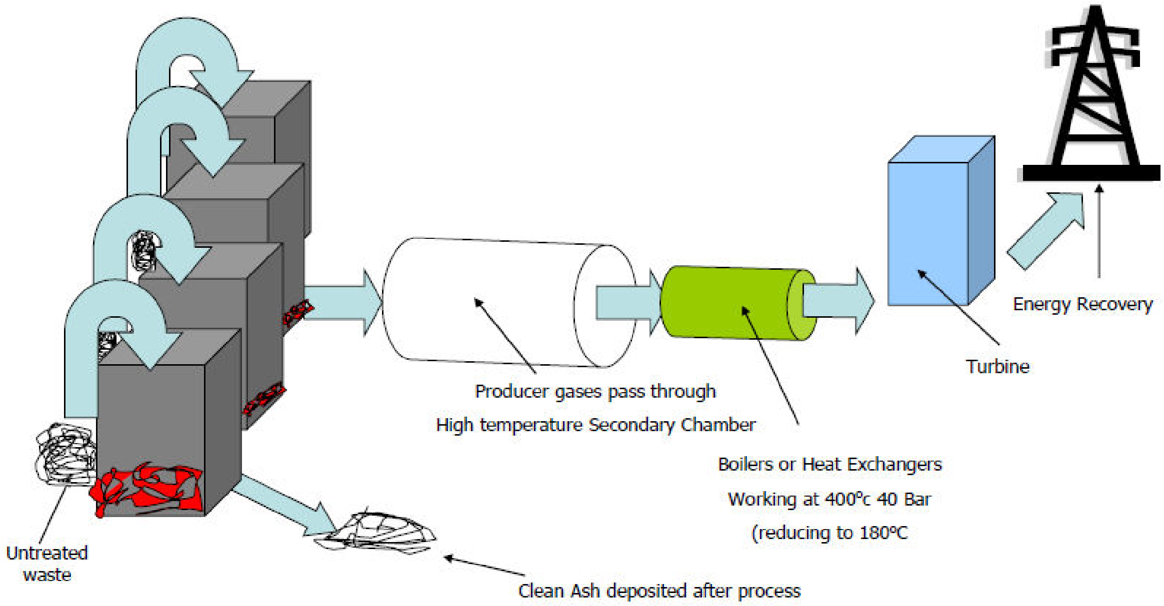


Figure 3: Scotgen Dumfries facility (courtesy of www.scotgenltd.co.uk)

Comments

AEA believes that Scotgen has demonstrated their batch oxidation system over a number of years. It is also noteworthy that this design uses well established technologies and has a relatively simple design, minimising the technical risk. This may explain why this system has not been confronted by the technical difficulties and delays related to syngas cleaning that more technologically advanced systems encountered.

Estimated operational output

Assumed black bag waste GCV	9	MJ/kg	GCV provided by in house database
Tonnage capacity	182.65	te/d	Scotgen stated capacity 3 x 20,000 tpa
Fuel input	19.03	MW	
Assumed condensing steam turbine efficiency	23%		
Operating electrical output (inc. generator losses 10% & parasitic loads 10%)	3.55	MWe	

Table 4: Scotgen – Dumfries Plant TRL

Unit Operation	TRL	Justification
Pre-treatment	9	No pre-treatment required. Simple insertion into reaction chamber before batch process begins.
Conversion process	9	2 Stage close coupled combustion, 1 proven plant, 1 operational for less than 1 year.
Post Treatment	9	Ash / aggregate removed manually once reactor has cooled. The flue gas is then cleaned up using the established approach of bag filters and absorption units.
Power generation	9	The syngas proceeds to high temperature combustion and heat recovery, raising steam for an open steam cycle (which is a well established approach to generating power in energy from waste plants).
Integration	9	The batch process is semi-continuous, so that the secondary combustion chamber receives a constant supply of syngas. Meanwhile, several batch reactors are managed through their cycles of loading, operation, cooling and cleaning periods, such that a reactor is always operating to deliver the syngas to the secondary reactor. This approach innovatively achieves continuous power generation while retaining the relative simplicity of a batch operation. It has been demonstrated in the 2 previous plants that use this design.
Overall TRL	8	The Dumfries plant had been operational for approximately 1 year 10 months at the time of writing and so we are unwilling to describe this process as fully developed at this site.

Data Sources

Confidential information relating to project from SEPA, Environment Agency & County Council Site visits.

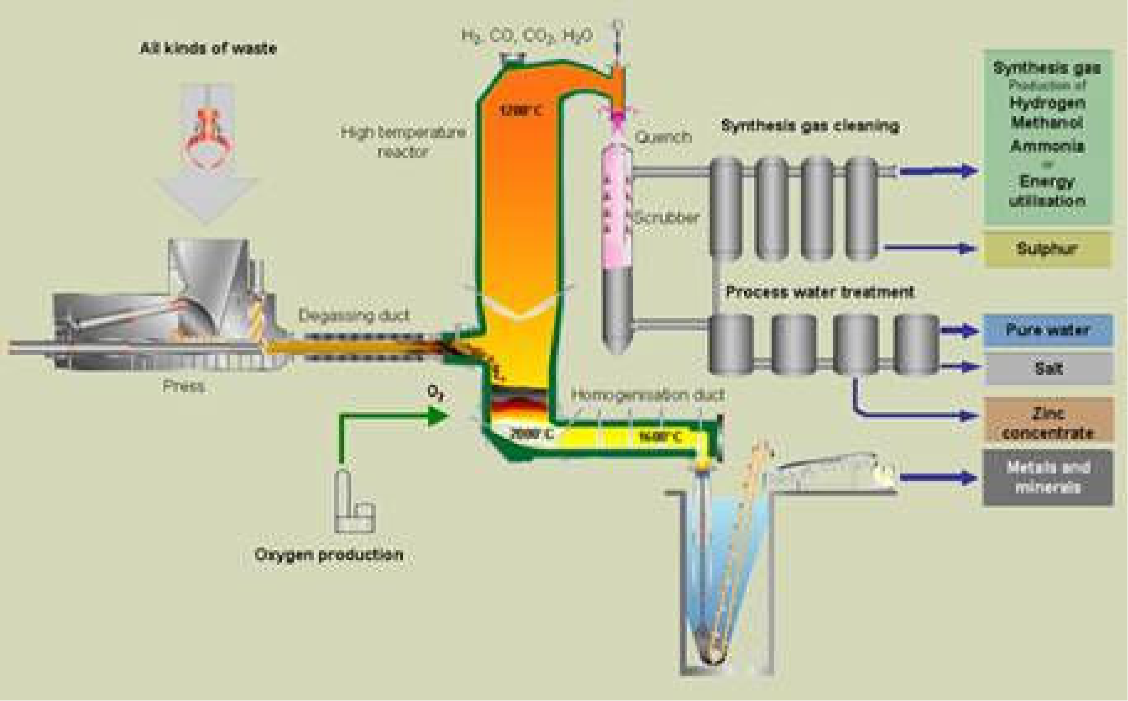
2.3 Thermoselect – Chiba

Process Category	Gasification	**Reactor Type**	Updraft (Oxygen injected)
Primemover	Gas Engine & Steam Turbine	**CapEx**	Unknown
Fuel/feedstock	Residual MSW	**Throughput**	75,500 tpa
Development Stage	Proven	**Operating hours**	8000 hrs
Design capacity	1.2 MW	**Availability**	90%

MSW EfW Plant – Thermoselect S.A. (Switzerland)

The Thermoselect process is a very high temperature waste destruction pyrolysis and gasification process that recovers a synthesis gas, a glass-like aggregate, a metallic fraction, water, salt and zinc concentrate from untreated MSW feedstock. The high furnace temperature (1600˚C) causes the fly and bottom ashes to melt, and these cool to a glass like aggregate in the slag.

Figure 4: Process Overview of Thermoselect Gasification Process



A Thermoselect plant has operated commercially in Chiba since 2002. The plant is equipped with two thermal treatment lines handling MSW. The plant has an integrated power production facility using reciprocating engines operating on syngas with some syngas supplied to an adjacent steel works. By using gas engines, it is possible to operate at higher power efficiencies (approx. 30% gross) than would be otherwise possible through burning the syngas in a boiler to supply a steam turbine.

Comments

AEA believes that Thermoselect has demonstrated their gasification process with several plants operating for several years in Japan. However, it should be noted that these plants operate in a regulatory regime that emphasises waste volume reduction and ash melting and not energy recovery. The process has a high operating temperature, reaching up to 1600˚C. Most gasification systems that operate at these elevated temperatures do not see the tar cleaning problems of cooler systems, because the tars are dissociated to simple gases at these temperatures. The consequence of this approach is normally a lower CV syngas with less useful chemical energy, because the energy has gone into achieving the operating temperature.

Analysis and in house modelling of the Thermoselect process suggests it has a cold syngas efficiency of 55-60%, much lower than the 70-80% that processes with a lower operating temperature can achieve. That said, it is a technical achievement that the process operates at such a high temperature and still produces a gas with a high enough GCV to permit the use of reciprocating engines.

Figure 5: External View of Chiba Thermoselect Facility (Courtesy of Thermoselect.com)

Table 5: Thermoselect – Chiba Plant TRL

Unit Operation	TRL	Justification
Pre-treatment	9	The Chiba plant accepts black bag waste which is pressurised and pyrolysed in an externally heated flow channel. The resultant char falls into the oxygen blown updraft gasifier and the pyrolysis gas enters the product gas stream directly. Radiation from the gasification reaction also contributes to the pyrolysis of the exposed feed channel discharge. This system is fully operational on several plants in Japan.
Conversion process	9	The updraft gasifier operates between 1200 and 1600°C, vitrifying ash into a molten glass granulate which is recovered by quenching in a water bath and sold as construction aggregate. Continuously operational in several plants in Japan.
Post Treatment	9	The high temperature gas from char gasification mixes with the pyrolysis gas in a high temperature reactor zone. The resulting product gas is then cooled through boiler passes and cleaned using the established approach of bag filters and absorption units. Continuously operational in several plants in Japan.
Power generation	9	The plant supplies syngas to a nearby steel works and fuels a 1.2 MWe Jenbacher Engine to generate power. They have also experimented with using the syngas to fuel a fuel cell, although the outcome of these trials is unknown. The Jenbacher engine is well known in industry as having the capability to generate power from low quality gases and also has a high electrical efficiency. Continuously operational in several plants in Japan

Unit Operation	TRL	Justification
Integration	9	The plant accepts black bag waste feedstock and generates aggregate for construction, and syngas for power generation and as a feedstock into adjacent steel works. AEA would consider this an excellent example of integration both within the plant and to neighbouring sites.
Overall TRL	9	A Thermoselect plant has operated commercially in Chiba since 2002, and would be considered fully developed on this basis.

2.4 TRL Assessment of ATT Successes

Table 6 below presents the TRLs for our sample of the successful plants reviewed. It should be noted that there are several plants that are operational which handle waste and so conclusions about reactor types should not be drawn from this list other than a number of reactor types can operate successfully. For example, the Mitsubishi R21 plant is currently operational in Japan; this design uses a rotating kiln reactor, Ebara uses the twin circulating fluidised bed, and Thermoselect uses an updraft reactor design with oxygen injection.

Table 6: Technology Readiness Level Assessment for ATT Successes

	Ebara	Scotgen	Thermoselect
Prime Mover (*)	ST	ST	RE
Pre-Treatment	9	9	9
Conversion Technology	9	9	9
Post-Treatment / Clean-Up	9	9	9
Power Generation	9	9	9
Integration	9	9	9
Overall	**9**	**8**	**9**

(*) ST = Steam Turbine; RE = Reciprocating Engine

3. Unsuccessful ATT Processes

The term “unsuccessful” is quite subjective, but AEA’s intention with this category was to select a number of projects that we consider have not met their original expectations, and from which lessons can be learnt concerning the difficulties that can affect ATT plants. We identified unsuccessful projects by applying the following criteria:

1. processes that, between them, provide an insight into the many problems that can occur when developing ATT processes; and
2. amongst those processes, those about which AEA has the most information.

Table 7 presents the processes / organisations we proposed to review.

Table 7: Selected Unsuccessful Projects

Process Name		Process Description	Process Type
Closed projects			
4	ARBRE	This was the first IGCCGT in the UK. Shut down after a short operating period due to syngas clean-up, financial and contractual problems.	Fluidised bed gasifier with gas turbine combined cycle
5	Brightstar	Scheme failed due to problems with gas clean up and by-product char management.	Close coupled combustion
6	TPS Greve	Circulating fluidised bed gasifier open steam cycle and direct firing of cement kiln. Failure due to organisational problems and retrofitting existing equipment.	Circulating fluidised bed gasifier, with remote combustion
Delayed and struggling projects			
7	Compact Power (Avonmouth)	Sequential pyrolysis, gasification of char and gas combustion. Successful at pilot scale. The process is still marketed but financial and contractual difficulties prevent scale up and commercialisation.	Close coupled combustion
8	Energos (Isle of Wight)	Close coupled gasification and combustion, plants currently operational delivering heat in Norway. Demonstration project in Isle of Wight currently experiencing difficulties caused mainly by retrofitting existing boiler.	Close coupled combustion
9	GEM (Yorwaste)	Fast pyrolysis of feedstock using rotating ablative heated surface. Technical progress stalled by financial constraints and difficulties managing by product char.	Ablative kiln fast pyrolysis
10	Hudol / Prestige	Entrained flow with multiple extraction points and temperature profile control. Continuous feed, designed for feedstock flexibility. Pilot plant in Wales; additional plants under construction in England. Huntingdon Pure Power plant experiencing technical problems, causes unclear.	Updraft
11	Refgas (UEA)	Refgas developed an advanced gasification CHP system to produce renewable energy. However, current plant installed at University of East Anglia still commissioning. Problems with ancillaries and tar production.	Downdraft
12	Stein	Rotating kiln pyrolysis/gasification with steam injection to reduce char production. Innovative energy recovery char & waste gas use. Technical progress stalled by financial constraints.	Rotating Kiln

3.1 ARBRE

Process Category	Gasification	**Reactor Type**	Fluidised Bed
Primemover	Combined Cycle Gas turbine	**CapEx**	Unknown
Fuel/feedstock	Residual MSW	**Throughput**	Unknown tpa
Development Stage	Shutdown	**Operating hours**	No data available
Design capacity	8 MW	**Availability**	0%

The ARBRE project was intended to be an integrated bio-energy demonstration plant that used gasified wood from short-rotation willow plantations to fuel a gas turbine combined cycle generator with an output of 8 MW_e. The project was a joint effort between Yorkshire Water plc, TPS of Sweden (a developer of biomass gasification technology) and Royal Schelde Group of The Netherlands, who constructed the plant.

The project was supported financially by the European Commission Thermie demonstration programme and was an important part of the EU strategy in this area. The motivation for support was that the route from biomass to electricity would never be economically attractive if it were confined to Rankin cycle steam cycles. Gasification would allow solid biomass to benefit from the advances being made in gas turbine and reciprocating engine technology. It was the second demonstration project of this concept following the successful Varnamo project in Sweden, which used the same model of gas turbine but operated at elevated gasifier pressures.

The UK and Swedish Government R & D programmes had supported feasibility trials on the technology at the TPS pilot plant in Sweden, which indicated that the technology would function as intended. Similar trial had been commissioned by Shell International with similar result.

The gasifier had an operating temperature of 850-900°C at near atmospheric pressure and generated low calorific value gas that was cleaned, cooled and pressurised to fuel a combined cycle gas turbine generator set.

The plant only reached the commissioning stage with very few hours of integrated operation before the project was shut down.

Comment

The ARBRE project attempted to be the first to develop a commercial Biomass fuelled Integrated Gasification Combined Cycle Gas Turbine (IGCCGT). This meant that it was attempting to develop and operate several technologies together. It was designed to process a consistent feedstock, avoiding concerns about feedstock consistency.

In retrospect, most of the technical failures could be traced to the root cause of the financial difficulties of the main contractor Schelde that led eventually to their liquidation. Schelde was removed from the contract for non performance but not before serious mistakes had been made. Throughout, the plant was built in a manner that minimised cost at the expense of quality and fitness for purpose. For example;

- The main process vessel flanges were too thin and distorted to the extent that it was impossible to achieve a gas seal on the vessels. These had to be seal welded which made dismantling and modification extremely difficult.
- The plant did not have an integrated control system. Rather, each subcontracted plant item was supplied with its own control systems. This lack of an overall control system made operation and commissioning difficult, verging on impossible, because of conflicts between the respective safety protocols.
- It was known that the product gas cooler would operate with a high dust loading but was designed with no facility for cleaning. This caused most of the commissioning problems and would have required a further £1 million for its resolution.

There were also process related problems connected with the performance of the gas cleaning systems. These were most likely related to the selection of local limestone as catalyst as opposed to the Swedish material used in testing and the design of the reactor base. Both were soluble but compounded the difficulties experienced by the product gas cooler.

An organisation with stronger financial and technical resources would not have built in so many handicaps at the design stage and would have had the resources to overcome the inevitable challenges and develop a successful project.

Data Sources

Discussion with AEA expert (Nick Barker) who was involved in the project development and sat on IEA task 33 committee.

Project ARBRE: Lessons for bio-energy developers and policy-makers (Athena Piterou a,, Simon Shackley b,1, Paul Uphamb)

Lessons

- Integrated gasification combined cycle power plants have not been successfully developed on any feedstock, including the clean short rotation crops expected to fuel ARBRE. The failure of the catalytic convertor to live up to expectations may have been overcome for clean homogenous biomass fuels. However, we do not believe this technology could be applied to waste, due to the more variable feedstock and the much higher probability of significant concentrations of chemicals, which would poison any catalytic process. It would be extremely challenging to use waste derived fuels for such a new process, as has been the experience of other developers who have attempted to apply catalytic techniques to cleaning syngas from heterogeneous waste derived fuels.
- Where consortia are developing ATT plant, agreeing and maintaining the objectives is crucial to the success of the plant, particularly because such developments carry significant technical risk.

Table 8: ARBRE – Eggborough Plant TRL

Unit Operation	TRL	Justification
Pre-treatment	9	ARBRE was designed to use chipped homogenous short rotation crops as a feedstock. The technology for chipping, drying, storage and feeding was conventional, with several similar systems and suppliers available.
Conversion process	9	The ARBRE gasification technology supplier was TPS who specialise in bubbling and circulating fluidised bed, and twin fluidised bed designs. They successfully delivered several systems in Sweden and Europe.
Post Treatment	5	The dolomite catalytic tar cracker failed to deliver the tar reduction rates anticipated. However, AEA's expert, Nick Barker, believes that the difficulties could have been overcome. If waste derived fuels are used, there are still significant concerns about the effectiveness of the dolomite catalyst and its susceptibility to the physical blocking of the active surface due to fused low melting point ash from chloride. The rest of the gas cleaning and ash handling units are unremarkable within the power generation / waste disposal markets.
Power generation	8	The gas turbine had purpose-designed low CV gas burners and fuel gas manifold developed by Alstom (now Siemens) in a previous demonstration project. The heat recovery boiler and steam turbine were conventional. Gas turbines are a mature technology that can use several fuels. However, the use of low CV gas to fuel the gas turbines is a relatively major departure from the natural gas standard. Experience elsewhere has shown this particular configuration has been relatively trouble free if the strict fuel specifications (particularly with regard to particulates/aerosols) are respected. Siemens has continued development of the burner and compressor configurations necessary for biomass and waste use, and is now able to offer improved variants.
Integration	7	The ARBRE plant suffered from poor overall integration. This was extremely costly in lost time during commissioning.
Overall TRL	6	The ARBRE subsystems were all sufficiently developed through testing and prototyping to operate as expected. However, they did not achieve commissioning & testing as a complete process.

3.2 Brightstar

Process Category	Fast Pyrolysis	**Reactor Type**	Vibrating Fluidised Bed
Primemover	Gas Engine	**CapEx**	£70 Million
Fuel/feedstock	Residual MSW	**Throughput**	150,000 tpa
Development Stage	Shutdown	**Operating hours**	nda
Design capacity	5.6 MW	**Availability**	0%

Brightstar Environmental commissioned a demonstration "waste-to-energy" plant during 2001 in Wollongong, New South Wales, using the “SWERF” process. This process (see Figure 6) was based on drying waste and then using it as feedstock in a flash pyrolysis process with steam gasification of the char generated. The syngas was then cleaned and used to fuel gas engines. $150 million (equivalent to £70 million) capital was invested in developing the technology, and the project had a design capacity of 100,000 tonnes per annum.

The scheme closed in 2003 due to technical and financial failure. During intermittent operations, the project suffered delays, shutdowns and technical glitches, particularly with the char gasifier, which resulted in the Wollongong facility running at least two years behind schedule, and operating at 25,000 tonnes per annum, a fraction of its licensed capacity. Modifications were made to the char removal design, which originally incorporated hot char removal from the primary gasifier, because operation of the char removal system at 400 - 500°C proved challenging. This system was replaced with a wet char removal system which improved plant operations, but the resulting char and pyrolysis oils were highly reactive with air, and char handling and transfer was difficult due to the viscous and adherent qualities of the char and pyrolysis oils. This is because the reactions stopped for kinetic rather than thermodynamic reasons (an experience that is consistent with other fast pyrolysis processes). As a result, disposal of char to landfill was not viable.

Changes were made to the primary gasifier / pyrolyser, resulting in a vibrating gasifier which required the feedstock to be supplied as “char balls” to operate successfully. Specialist feedstock handling facilities were designed and successfully developed on purchased charcoal, but it was found that the char balls from waste derived feedstock powdered in the gasifier because of vibration, rendering the modifications ineffective. It is also known that the plant was cited for exceeding its licence limits for arsenic and sulphur trioxide emissions.[3]

Comment

Technically, there were challenges associated with the following critical steps: feedstock preparation; the reactor’s operating parameters; and managing the syngas clean-up to a quality that allowed sustained operation of the reciprocating engines and meeting regulatory requirements on emissions.

Lessons

- + The sorting autoclaving and pulping operations appeared to work adequately and to produce a consistent feedstock.
- + Optimising the pyrolysis of the MSW derived fuel proved far harder than expected despite its consistent form.
- + Insufficient component proving at prototype scale was undertaken before building a full-scale waste management installation. It is difficult to understand the risk management strategy underlying the investment.
- + The energy lost in the high char, pyrolysis oil production levels and the excessive cost of their disposal would make this process uncompetitive against gasification or combustion – even if other problems were resolved.
- + Development of ATT plant requires significant financial and technical resources.

Data Sources Lessons

SWERF Technical Presentation by Whytes Gully, 15th February, 2002

Fichtner report - viability of ATT in UK (2004)

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[3] The viability of Advanced Thermal Treatment of MSW in the UK 2004, Fichtner Consulting Engineers, 2004. Internal AEA expert.

Figure 6: SWERF Process diagram (The viability of Advanced Thermal Treatment of MSW in the UK Fichtner Consulting Engineers)

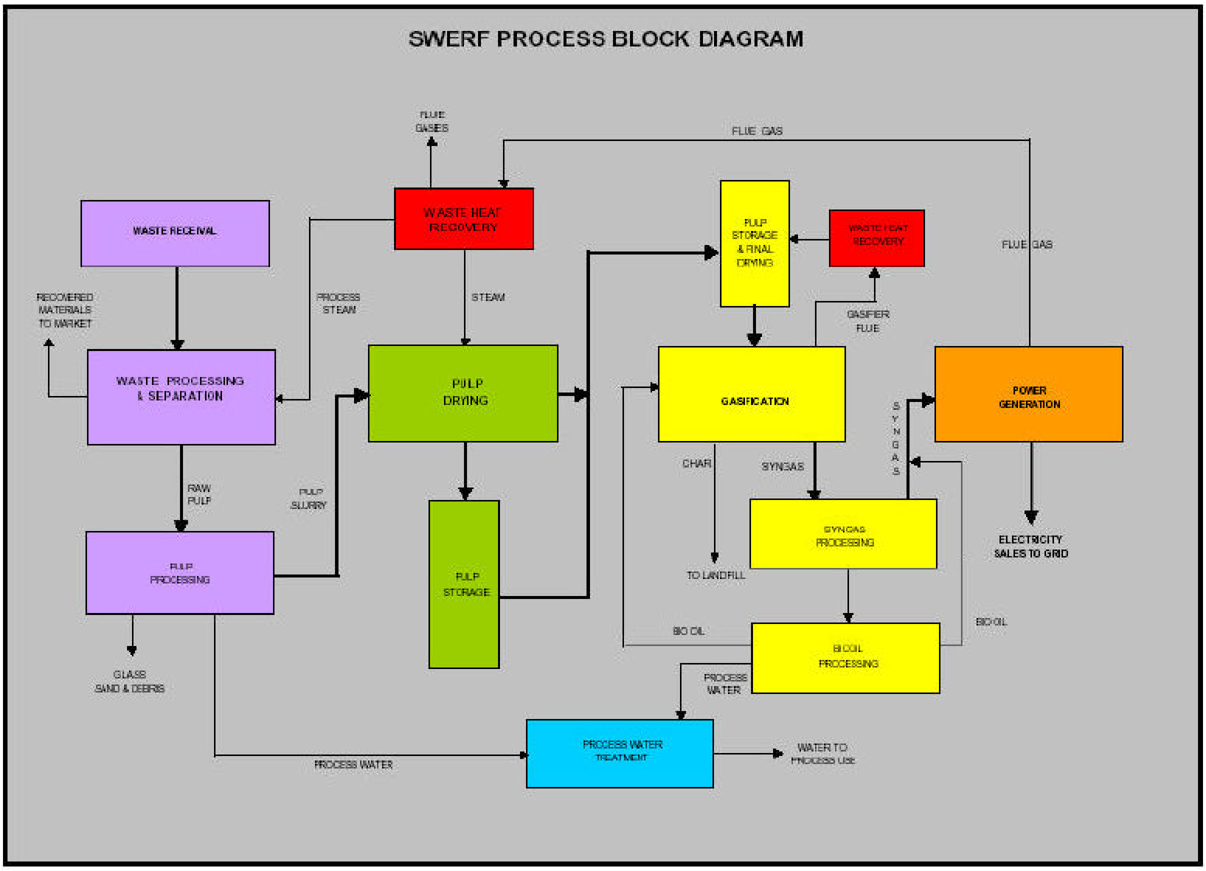

Table 9 Brightstar – Wollongong Plant TRL

Unit Operation	TRL	Justification
Pre-treatment	7	Pre-treatment required the development of the material handling system capable of producing a consistent fuel by extracting recyclables and pulping and drying the residues. It is our understanding that this system successfully operated as specified. A similar configuration, The Orchid Process, is on sale in the UK and is technically successful but with limited deployment.
Conversion process	6	The vibrating fluidised bed reactor was developed, installed and commissioned but operations showed that the feedstock residence time was too short to be optimal. As a result, there was excessive char production and low gas yields.
Post Treatment	6	The char removal systems underwent several iterative developments resulting in a wet system that worked but produced a material that was difficult to dispose of. Technically, the system worked; its implications for the whole process resulted in a hazardous material that could not be disposed of and imposed an additional cost on the process.
Power generation	7	The Brightstar facility used reciprocating engines, although the precise specification is unknown. There are engines in the market from Jenbacher, Caterpillar and Deutz that are known to be capable of using low quality gases as fuel, provided the gases meets strict specifications, particularly concerning contaminants.

Unit Operation	TRL	Justification
Integration	6	In principle, this facility was reasonably integrated, with a design that was intended to maximise the gas yield from the waste stream. However, the sub-systems were not validated on the feedstock until they were installed, and, as a result, significant modifications were required, with knock on effects on other sub-systems.
Overall TRL	7	The Brightstar facility suffered several technical problems, particularly related to taking experience in the lab to full-scale operation. This is a recurring occurrence with processes that attempt to fuel reciprocating engines or gas turbines with syngas generated from fast pyrolysis.

3.3 Greve

Process Category	Close coupled combustion	**Reactor Type**	Indirect circulating fluidised bed
Primemover	Steam Turbine	**CapEx**	$20 Million
Fuel/feedstock	Residual MSW	**Throughput**	60,000 tpa
Development Stage	Shut down	**Operating hours**	No data available
Design capacity	6.7 MW	**Availability**	0%

The Greve power station was developed during the early 1990s, and designed to use pelletised refuse derived fuel generated from surrounding areas as feedstock for two low pressure, air blown, circulating fluidised bed gasifiers at an operating temperature of 850-900°C.

The resulting syngas was fed to a purpose-designed combustor and steam raising energy recovery unit, powering an open cycle steam turbine with a capacity of 6.7 MW_e. The plant was designed to have a capacity of 200 tonnes per day (70,000 tpa). The plant was also designed to produce more syngas than the combustion unit could accept, with the excess piped to a nearby cement kiln, providing some flexibility in terms of customers for the syngas generated. It should be noted that the design of the energy recovery unit was undertaken prior to the involvement of the gasification technology provider (TPS, who provided similar technology to the ARBRE project).

The plant was commissioned in 1993 and, between 1993 and 2003, operated for 4500 hours, generating power and delivering gas to the nearby cement kiln. During this time, the plant experienced significant problems with tars in the syngas fouling the energy recovery boiler. To overcome these problems, the plant required a complete re-design and retrofit of a new energy recovery boiler, to cope with the increased tar fraction present in the syngas. After the retrofit, the plant operated below design capacity, which had a negative impact on economics of the project.

Comments

The Greve plant is an example of the need to ensure that syngas cleaning and energy recovery systems are designed to process the syngas produced by the ATT system. In the case of Greve, the energy recovery system was designed prior to the involvement of the gasification technology provider. As a result, it was unable to operate continuously with the syngas it was fed by the gasifiers. In this particular case, the gasification system appears to have performed as expected.

In AEA's opinion, the project was compromised by poor integration of the downstream equipment, which was located too far away, allowing tar to accumulate in the connecting pipework. Similar applications of circulating fluidised bed gasifiers have functioned with exceptional reliability in lime kilns and co-firing applications.

Data Sources

Case Study on Waste-Fuelled Gasification Project, Greve in Chianti for IEA Bioenergy Agreement Task 36 – June 2003

Lessons

- ATT plants tend to perform when the complete process is designed from the outset to meet specific objectives.
- Retrofitting existing plant is challenging.
- Development of ATT plant tends to be more difficult than developers expect. [4]

Table 10: Greve Plant TRL

Unit Operation	TRL	Justification
Pre-treatment	9	At the time of writing, there was no specific information regarding pre-treatment of feedstock, although it is known that it was not a limiting factor on this facility. There are also several suppliers in the market capable of delivering this sub system.
Conversion process	9	The Greve facility conversion technology supplier was TPS, who specialise in bubbling and circulating fluidised bed, and twin fluidised bed designs. They have successfully delivered several systems in Sweden and Europe. All information indicates that the TPS supplied technology operated as specified.
Post Treatment	9	The flue gas is then cleaned up using the established approach of bag filters and absorption units.
Power generation	9	The heat recovery boiler was designed by a contractor who had little experience of boiler design for dirty syngas; in addition, the design was finalised prior to discussions with the gasification supplier. As a result, there was significant deposition of tar on the boiler tubes due to low syngas velocities. Even after modification, the capacity of the heat recovery boiler remained the limiting step in the process. However, the open cycle steam turbine system for power generation is a conventional design.
Integration	5	This facility was designed to be well integrated into the industrial area, and was designed to deliver syngas to a nearby cement facility. However, the decision to procure / design the heat recovery boiler prior to specifying or entering discussions with the gasification supplier meant that the final facility was internally poorly integrated, with result that the boiler could not operate at full load.
Overall TRL	9	It seems the failure of this facility to operate as expected was avoidable and can be attributed to the unconventional design process and an inexperienced design contractor.

3.4 Compact Power / Ethos Renewables

Process Category	Close coupled combustion	**Reactor Type**	Twin screw pyrolysis / updraft gasification
Primemover	Steam turbine or process steam	**CapEx**	Unknown
Fuel/feedstock	Residual MSW	**Throughput**	8,000 tpa
Development Stage	Demonstration plant	**Operating hours**	nda
Design capacity	0 MW	**Availability**	0%

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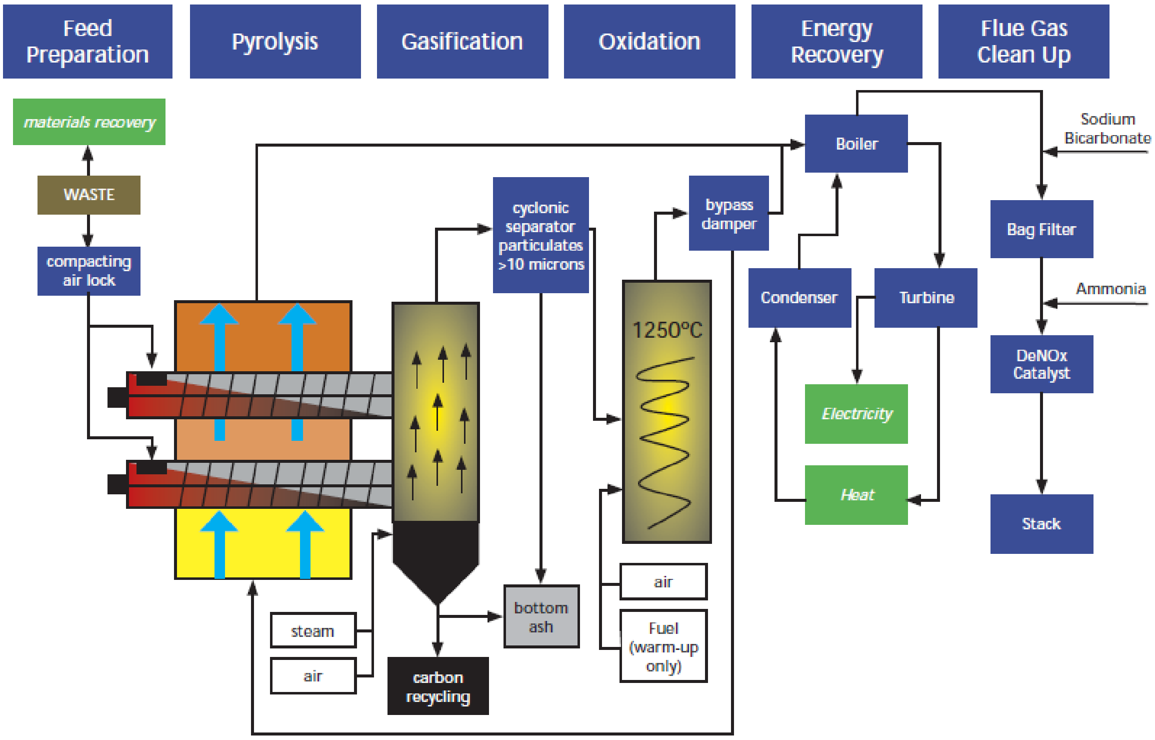
[4] Case Study on waste – fuelled gasification project Greve in Chianti, Italy for IEEA Bioenergy Agreement – task 36. D.L. Granatstein Natural Resources Canada / CANMET Energy Technology Centre. June 2003

The Compact Power process treats waste thermally in two stages; pyrolysis in two screw reactors externally heated by product gas combustion, followed by updraft steam/air gasification. The product gas is then burned in a high temperature cyclonic chamber, with the resulting flue gases being routed around the pyrolysis screws before entering a waste heat boiler to raise steam. The steam is used either for power generation or for steam sterilisation of clinical waste.

Figure 7: Compact Power process diagram (courtesy of the Defra NTDP)



In 2001, after several years of development, Compact Power built an 8,000 tpa demonstration plant at Avonmouth on a site that processes clinical waste and was leased from Bristol County Council. After several process-proving trials, the process was deemed too small to prove the technical and economic viability of the process. In order to develop further the scale of the process, Compact Power applied for and won support under Defra's New Technology Development Programme (NTDP), to develop a 32,000 tpa version of the process.

In 2008, Ethos Renewables Ltd acquired the business and assets of Compact Power, with the intention of developing the larger scale version of the process. However, this plant has not been built due to a dispute between Ethos Renewables and Bristol County Council about the Avonmouth site. The resulting delays meant that Ethos Renewables could not meet their milestones and they have had their support from Defra withdrawn.[5]

Compact Power/ Ethos have also developed a smaller version of the technology for the MOD, which is used for waste disposal on board warships.

Note – the withdrawal of funds was not entirely Compact Power's fault. There were interminable delays in the programme management of the Defra scheme that gave extreme cash flow problems for such a small project.

Comments

The Compact Power process was originally developed as a proof of concept and it succeeded in its objective. However, it was known that its operating costs were high; in particular, the need to replace the pyrolysis reactor screws twice annually made maintenance costs prohibitive. It was hoped that economies of scale could be applied to a commercial-scale version of the Compact Power process, and this was viewed as having potential. In particular, it was chosen for support by the Defra in the NTDP's competitive bidding process.

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[5] Ethos Renewables (Avonmouth) Limited Defra New technologies Demonstrator Programme Final Report, February 2010.

Despite the problems, the basic concept is strong of pyrolysis followed by char gasification with the product gases burned in a turbulent combustion chamber. Emissions of all controlled species were extremely low and the installation was cited in the Environment Agency annual report as an example of what can be achieved. Operation of the proof of concept plant was, we understand, reliable with several thousands of hours achieved.

Progress with developing a commercial-scale version of the process was undermined when a dispute arose between various parties involved in the development. This dispute caused sufficient delay to stop progress and Defra support was withdrawn. This experience emphasises the importance of the relationships between organisations involved in a development, because the Compact Power process showed potential but failed for commercial, organisational or contractual reasons.[6]

Lessons

- Where consortia are developing ATT plant, agreeing and maintaining the objectives is crucial to the success of plant, particularly because such developments carry significant technical risk.
- As with the Brightstar project, there was urgency to move to commercial operation to generate cash flow to safeguard the continuation of the company. The delays in the award of Defra funding to support scale up created great difficulties for the original owners, who were eventually forced to sell. In short, the development was underfunded for the scale of the challenge, and relied on repeated and protracted cash calls on the private market, which disrupted progress.

Table 11: Compact Power – Avonmouth Plant TRL

Unit Operation	TRL	Justification
Pre-treatment	7	The facility successfully treated incoming feedstock, although there were high operating costs associated with the need to replace the pyrolysis screws twice annually. AEA would expect that the maintenance cost could be managed by material selection, given normal product development.
Conversion process	9	The facility successfully generated syngas from feedstock, combusted the syngas and used the heat to raise steam.
Post Treatment	9	The facility handled medical waste and successfully operated flue gas and ash handling equipment meeting the requirements for handling medical waste. The ash handling and flue gas abatement technologies are well developed and deployed in medical incinerators and crematoria across the world.
Power generation	9	Initial operation generated 200kW power under the Renewables Obligation using a small industrial steam turbine and dry saturated steam. Some problems were experienced with ash deposition in the fire tube boiler used, but these would be soluble given adequate product development.
Integration	9	This plant operated as intended, with any heat generated being used to pre-treat the incoming feedstock in an MHT facility.
Overall TRL	7	The Compact Power plant was intended as a demonstration facility and succeeded in that objective. When the objective was changed to the commercialisation of the facility, attempts to increase the plant capacity and make it commercially viable fell foul of organisation problems between the parties involved in the project.

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[6] MRMC site visits – Compact Power Thermal Treatment Plant Report

3.5 Energos – Isle of Wight

Process Category	Close coupled combustion	**Reactor Type**	Moving Grate
Primemover	Steam Turbine	**CapEx**	£11 Million
Fuel/feedstock	Residual MSW	**Throughput**	25,000 tpa
Development Stage	Process proving	**Operating hours**	nda
Design capacity	2 MW	**Availability**	0%

The retrofitting of the Energos gasification thermal treatment technology to the existing Energy from Waste plant at Newport, Isle of Wight, was one of a number of Defra-supported projects under its New Technologies Demonstrator Programme.[7] The gasifier/oxidiser process equipment installed in the demonstrator plant was developed from existing designs, which had been fabricated for a project in Norway that had been aborted. It should be noted that the original designs were to provide heat to district heating systems; the Isle of Wight plant was the first project to use this technology to generate power.

The Energos technology comprises the two-stage thermal treatment of refuse-derived fuel (RDF), with partial oxidation to produce a syngas. This syngas is then passed into a second chamber where it is fully combusted. The flue gases pass through the energy recovery plant, where a boiler generates steam to drive an open cycle steam turbine generating power.

Following delays in the plant's commissioning, the agreed operational phase ran from 1 December 2008 to 14 October 2009, a period of 10½ months. During this period, the plant processed a CV-enhanced RDF, which is not expected to be representative of RDF derived from UK waste arisings. It is known that the physical characteristics of the RDF feedstock at this plant have caused difficulties with the original feed screw, and significant modifications were underway at the end of 2009. In addition, and perhaps unsurprisingly, the plant appeared to be having difficulties meeting the required emissions thresholds, given the gasifier/oxidiser system was nominally rated to process 40,000 tonnes per year of RDF, while the existing boiler/steam plant, turbine and abatement plant were sized for circa 30,000 tonnes per year of RDF.

Estimation of Energos electrical efficiency

Energos stated CV enhanced RDF NCV	11	MJ /Kg	Energ literature
RDF input	5	Tonne / hr	Energ literature
Fuel input	15.28	MW	
Energos stated thermal output	13.5	MW	Energ literature
Boiler efficiency	88%		
Energos stated electrical output	3.4	MW	Energ literature
Condensing steam turbine efficiency	22%		

Comment

The Energos process may well develop into a viable and mature technology for generating electricity. Many aspects of the plant are similar to other successful systems, such as the use of steam turbine cycles. The plant has been developed by an organisation with significant financial and technical resources, and the gasification technology is proven for other applications. However, at the time of writing, the plant uses a CV-enhanced feedstock that raises questions about how it would perform on other fuels.

The plant has been repeatedly closed by the EA and operations suspended for lengthy periods, due to exceeding permitted emissions of dioxin. The plant owners are confident that this can be resolved and, in our opinion, this is true, as it is probably a result of retrofitting new technology to an old boiler. This is backed up by emissions data from the Norwegian operations, which are extremely good.

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[7] Research, monitoring and evaluation of the Waste Gas Technology (UK) Limited (previously Energos) gasification thermal treatment technology on the Isle of Wight. Produced for Defra by M Pugh, D Mitchell and D Grigsby, AEA Energy and Environment May 2010

It also demonstrates the technical difficulty of attempting to combine existing plant infrastructure designed to meet other objectives. This appears to be the root of the difficulties getting the plant operational and meeting its emissions requirements.

Figure 8: Simplified cross-section of the Energos process

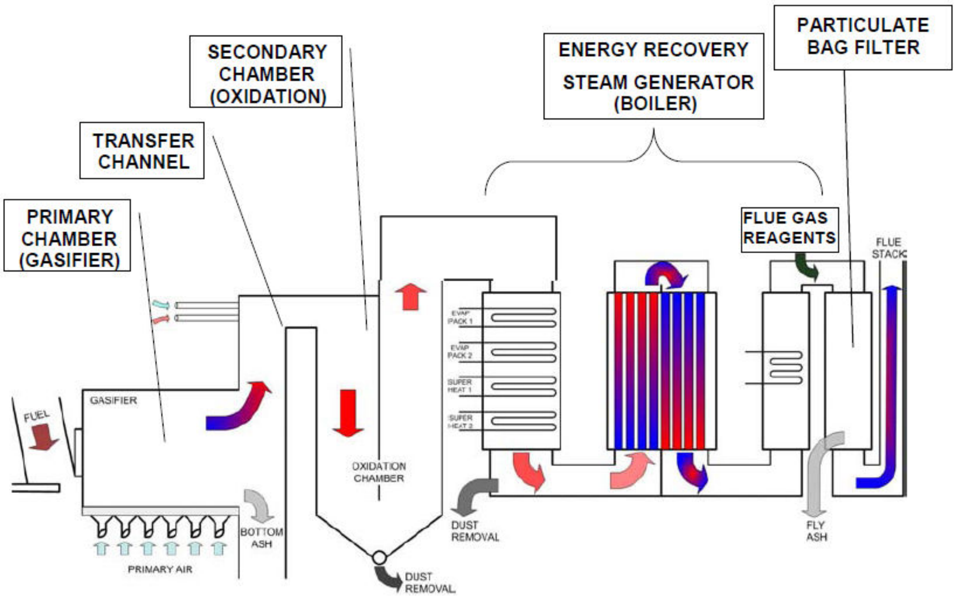

Figure 9: Energos EfW Plant

Data Sources

Energy Management February 2008

Fichtner report - viability of ATT in UK (2004)

Letsrecycle, 1 October 2010 "Energos Isle of Wight plant fails further emissions tests" http://www.letsrecycle.com/news/latest-news/waste-management/energos-isle-of-wight-plant-fails-further-emissions-tests

DEFRA NTDP – Research, Monitoring and Evaluation Project Report (AEA)

Lessons:

- Retrofitting existing plant is challenging and the problems generated may outweigh the value of the cost savings. This decision seems to underlie most of the problems that have occurred. It is difficult to predict emissions and other performance parameters in an existing piece of equipment when the combustion system has been so radically changed.

Table 12: Energos – Isle of Wight Plant TRL

Unit Operation	TRL	Justification
Pre-treatment	9	The facility successfully treated incoming feedstock using technology readily available in the market. RDF is supplied as a floc.
Conversion process	9	The facility successfully generated syngas from feedstock, combusted the syngas and used the heat to raise steam and demonstrated it could generate electricity
Post Treatment	9	The flue ash abatement facility was undersized and it was found during commissioning that the plant exceeded it emission limits. However, other plants based on the same process operate successfully in Northern Europe.
Power generation	9	The plant uses a heat recovery boiler to raise pressurised steam, which drives an open steam cycle. The capacity of the turbine on the Isle of Wight facility is relatively small for such processes, but this a well understood and mature technology.
Integration	7	This facility is attempting to integrate a new gasification technology into a previously existing heat recovery system in order to meet pre existing permitting requirements. While the integration of the technologies has had some challenges during commissioning this plant, given sufficient resources we believe these difficulties will be overcome.
Overall TRL	9	The Energos power plant is based on a process design that has resulted in several operational facilities in Norway, such as the Ranheim plant.

3.6 Scarborough Power / GEM

Process Category	Fast Pyrolysis	**Reactor Type**	Ablative reactor
Primemover	Gas Engine	**CapEx**	£13 Million
Fuel/feedstock	Residual MSW	**Throughput**	25,000 tpa
Development Stage	Process proving	**Operating hours**	No data available
Design capacity	2.4 MWe and 2.2MWth	**Availability**	0%

The Scarborough Power scheme is based in Seamer Carr, Scarborough, and is intended to provide electricity and heat. The project is a development on Yorwaste's integrated waste management facility, which already includes a materials recycling facility to process all kerbside collected materials from the area, a mixed residual waste sorting plant, open windrow composting operations, and an adjacent engineered landfill site for residual waste disposal with associated landfill gas fuelled energy generation.

The ATT development is a GEM pyrolysis unit, including fuel store, dryer and thermal oxidiser. This project was supported by the Defra New Technology Development Programme (NTDP). The site was due to commence operation in September 2008. Recent news on the GEM website indicates they are still in the process-proving stage, having suffered from higher than expected levels of char production; they have also increased the reactor residence time to 50 seconds from 2 seconds. In addition, it is known that the scheme partners have encountered financial difficulties, although at this time they appear to have sufficient resources to continue commissioning. It is understood that the plant has yet to go into commercial operation.

The pyrolysis scheme has been designed to be eligible for Renewable Obligation Certificates, but the scheme's classification as Advanced/Standard pyrolysis is not clear.[8]

Comment

The GEM process set out to achieve the commercialisation on MSW derived feedstock of a process that is yet to be successfully implemented on any fuel. The project is known to have had a precarious financial footing, and technically there are challenges associated with the following critical steps: feedstock preparation; the reactor's operating parameters; and managing the syngas clean-up to a quality that allows sustainable operation of the reciprocating engines.

A sense of the difficulties that have been experienced can be gleaned from the report extract presented in Box 1.

Box 1: Extract from Executive Summary of Scarborough Power RME report

It is evident that the plant overall did not perform to full design expectations during the RME contract period and, until such time as continuous operations are established, the process must be considered, as yet, unproven overall.[9]

The University of Leeds was awarded a contract to undertake Research, Monitoring and Evaluation (RME) of the Scarborough Power Ltd., plant and commenced in January 2008. The Research Monitoring and Evaluation specification prepared by the University of Leeds set out a programme based on the expectation that full commissioning of the Scarborough Power Ltd plant would be completed by late summer/ early autumn of 2008. However, since summer 2008 through to the end of the extended 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 on which a meaningful study could be undertaken during the RME period.

The University of Leeds have therefore undertaken only very limited work on the monitoring and evaluation of the plant and none of this work relates to operation at design specification. Scarborough Power Ltd. have reported (December 2009) that due to the lack of monitoring instrumentation and data logging, the gathering of data on the plant throughout the Research Monitoring and Evaluation contract period was very poor and that insufficient data was gathered to enable a meaningful evaluation of the plant.

Scarborough Power Ltd report that the quality of data recorded, although sufficient for their internal purposes, would not withstand the quality assurance level required for evaluation by Leeds University. During short run commissioning trials the steady and consistent operational periods needed to gather data for reliably assessing performance do not exist.

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, even with the extension of this contract until 31st December 2009. However, it is understood that Scarborough Power Ltd. remain committed to completing the modifications needed to permit the plant to be fully commissioned.

Data Sources

Advanced Thermal Treatment of Municipal Solid Waste - 2005

Research, monitoring and evaluation of the Scarborough Power/GEM pyrolysis facility in Seamer Carr, Scarborough, Yorkshire (University of Leeds)

Lessons

+ Pyrolysis of MSW has not been successfully developed, despite several attempts.
+ Pyrolysis inevitably produces large volumes of char which must be managed.
+ Development of ATT plant requires significant financial and technical resources.

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[8] http://www.GEM-ltd.co.uk

[9] Research, Monitoring and Evaluation of the Scarborough Power/GEM Pyrolysis Facility, Seamer Carr, Scarborough, Yorkshire. Final Report, Prepared by: Paul T. Williams & John Barton (University of Leeds), 5th March 2010

Figure 10: Overview of Scarborough Power / GEM process (Image Courtesy of Defra NTDP)

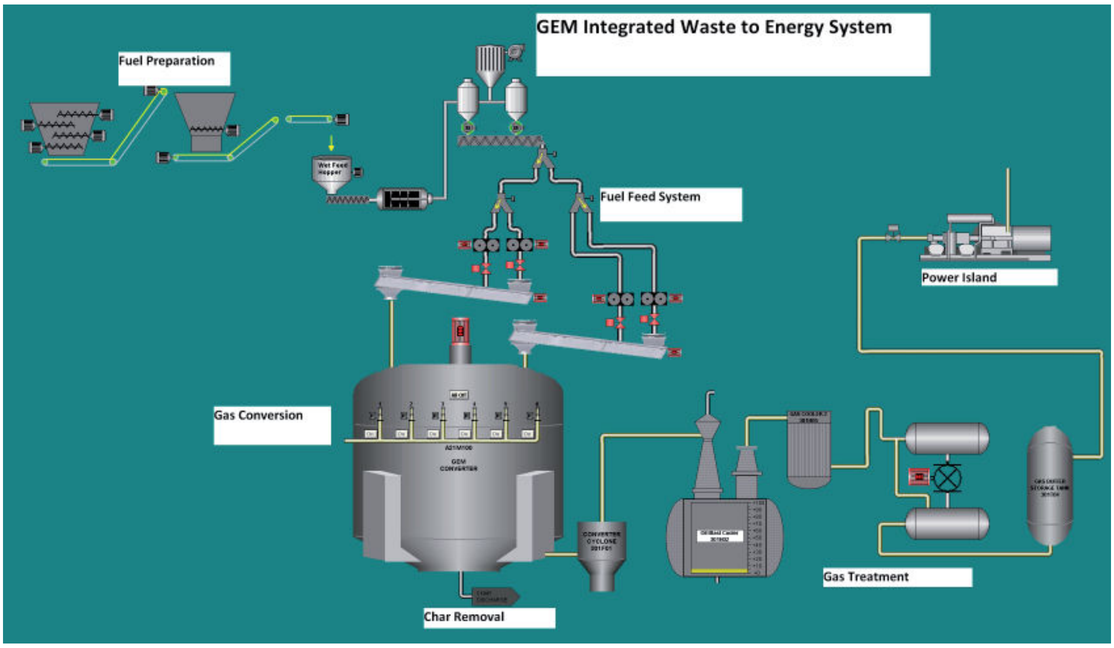


Table 13: Gem – Yorwaste Plant TRL

Unit Operation	TRL	Justification
Pre-treatment	8	Ablative fast pyrolysis is particularly sensitive to the physical size and shape of feedstock material and to its moisture content. At the time of writing, the plant has not operated enough to comment on the operability of the feedstock handling system. However, such systems are known to operate in an acceptable manner, for example the Dynamotive facility in Canada, which generates fast pyrolysis oils from biomass.
Conversion process	4	The facility uses a spinning hot ablative plate reactor design, which, to our knowledge, has only been developed successfully in a lab / pilot plant environment. This technology poses several technical and process challenges because of the complexity of the design and the significant number of high temperature moving parts.
Post Treatment	6	At the time of writing, the plant has not operated enough to comment on the operability of the post treatment technology, although the design, which makes use of cyclones for hot gas cleaning and coalescers, is reasonably conventional. There is insufficient information to state whether this design is capable of removing the elevated levels of char, tars, aerosols and pyrolysis oils generated in pyrolysis processes.
Power generation	7	The GEM facility uses reciprocating engines, although the precise specification is unknown. However, there are engines in the market from Jenbacher, Caterpillar and Deutz that are known to be capable of using low quality gases as fuel, provided the gases meets strict specifications, particularly concerning contaminants.
Integration	6	In principle, this facility was reasonably integrated, with a design that was intended to maximise the gas yield from the waste stream. Integrated operation has not been realised in practice.
Overall TRL	7	The GEM facility suffered several technical problems particularly related to taking experience in the lab to full scale operation. This is a recurring occurrence with pyrolysis processes that do not take adequate steps to manage the inevitable char production.

3.7 Hudol gasification / slow pyrolysis (Pure Power Huntingdon plant)

Process Category	Steam / air gasification	**Reactor Type**	Custom counter flow design
Primemover	Gas Engine	**CapEx**	£10 Million
Fuel/feedstock	Waste wood	**Throughput**	10,000 tpa
Development Stage	Process proving	**Operating hours**	nda
Design capacity	2.4 MW	**Availability**	>90%

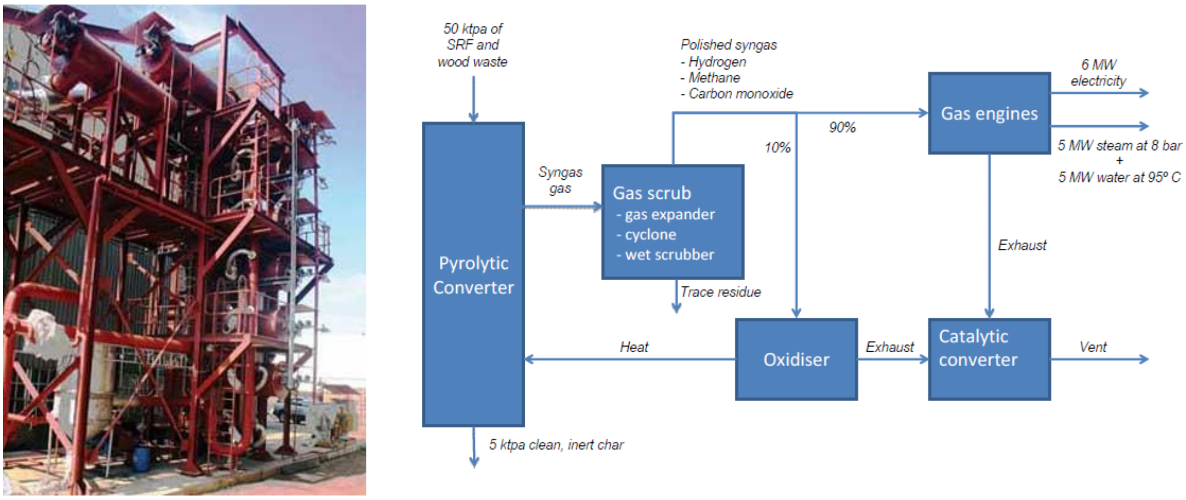
The Prestige Thermal / Hudol Gasification Technology was developed to destroy waste from contaminated land; as such, the plant was designed with feedstock flexibility in mind. A demonstration plant at Hudol Ltd in Wales has been successfully used to process a number of feedstocks.

The Pure power plant in Huntingdon was the first instance of the technology being used to generate power, having been designed to process 10,000 tpa of waste wood. The process consists of wood chipping, a pre-pyrolysis step, and then counter-current indirect steam gasification / pyrolysis. This is heated by the combustion of 10% of the syngas generated, which heats the outer wall of the main reaction chamber. The syngas generated was extracted, cleaned and used to fuel a Jenbacher reciprocating engine. It is known that the Huntingdon plant has experienced technical difficulties with achieving continuous operation, and has decided to dispose of its reciprocating engine. This may suggest redevelopment of the project using a steam cycle.

Comment

The Hudol process was originally designed to dispose of waste and therefore syngas quality was not a concern during the design phase. The process has several innovations that allow it to minimise char ash production and to optimise the temperature profile and the feedstock residence time, according to the particular feedstock. The developer Prestige Thermal Equipment appears to have some pedigree in developing thermal processes. However, in its current configuration, this plant appears to have had difficulties with removing tar in the syngas. The process is known to generate syngas with particularly high GCVs (17-18 kJ/Nm^3) and has a relatively low operating temperature. These parameters are also seen regularly in fast and slow pyrolysis plants, where this is a common problem. As a result, the process has been unable to provide syngas that is sufficiently clean for the reciprocating engine.

Figure 11: Hudol Gasification Process



Data Sources

Discussions with private clients – May 2009

Personal knowledge of facility (George Mkushi)

Lessons

+ Pyrolysis of MSW has not been successfully developed, despite several attempts.

Table 14: Hudol – Pure Power Huntingdon Plant TRL

Unit Operation	TRL	Justification
Pre-treatment	9	Conventional waste wood chipping facility.
Conversion process	7	The conversion reactor was originally designed as a contaminated land waste destruction facility. It has since been attempted to adapt this technology to generate power. The conversion technology is validated at the development facility in Wales and by the design and build contractor in South Africa to operate with several feedstocks.
Post Treatment	7	The flue gas is cleaned up using the established approach of bag filters and absorption units. There are clearly problems with the Huntingdon project, however.
Power generation	9	The Hudol facility uses a Jenbacher reciprocating engine, which is known to be capable of using low quality gases as fuel provided the gases meets strict specifications, particularly concerning contaminants.
Integration	6	This site seems to be experiencing difficulties due to the inability of the gas cleaning facilities to provide a syngas that is sufficiently clean to allow the engine to operate on a sustained basis.
Overall TRL	7	At the time of writing, there is insufficient data to state that the Huntingdon plant is operational, although it is known that at least 2 prototypes were built in Wales and by Prestige Thermal.

3.8 Refgas University of East Anglia

Process Category	Gasification	**Reactor Type**	Downdraft
Primemover	Gas Engine CHP	**CapEx**	Confidential
Fuel/feedstock	Biomass	**Throughput**	16,000 tpa
Development Stage	Process proving	**Operating hours**	nda
Design capacity	1.42 MW	**Availability**	Not operational

Refgas Ltd was formed in 2007 specifically to design, manufacture and supply gasification technology to process biomass / waste. Staff at Refgas comprised a team with “over thirty years’ experience in design and manufacturing of recycling equipment and five years research into biomass gasification”. The Refgas gasifier system is designed to produce 4MW of combined heat and power using a various different fuels, such as woodchip (100-150mm) and RDF. The process configuration consists of a biomass storage feed system, a downdraft gasifier, hot gas cleaning cyclone, ash removal, cold gas cleaning and syngas. The syngas is used as fuel in a reciprocating CHP engine.

Comment

On initial review, the Refgas design is relatively simple and traditional. However, the Refgas UEA project has suffered from a lack of design, development and operational experience with gasification, and the team only had 5 years’ research experience. As a result, they specified a downdraft design which, while a mature design, is particularly sensitive to feedstock quality in terms of chemical composition, physical properties and moisture content. The throughput is also well in excess of those in any accepted design guidelines.

The lack of design, development or operational experience resulted in technical difficulties with the feed system that could have been avoided with a more experienced developer. It is known that the design of the gasifier plant makes maintenance of the gasifier internals difficult. Despite significant investment, the original budget has been significantly exceeded, and, to date, the gasifier has not operated for any extended period of time.

Data Sources

Discussions with developer – 2010

Lessons

- + Development of ATT projects requires significant technical resources [10]

Table 15: Refgas – UEA Plant TRL

Unit Operation	TRL	Justification
Pre-treatment	7	Badly designed fuel elevator meant it was not possible to supply gasifier at a sufficient rate. However appropriate technology is readily available.
Conversion process	4	First full scale downdraft gasifier designed by team with relatively little experience. Throughput is outside accepted limits.
Post Treatment	5	The established approach of cyclones and electrostatic filters would probably function if the concentration of tars in the product gas could be reduced. Currently, it would appear the system is being overloaded.
Power generation	9	The UEA facility used a Caterpillar reciprocating engine, which is known to be capable of using low quality gases as fuel, provided the gases meets strict specifications, particularly concerning contaminants.
Integration	5	This facility is designed to be a CHP that is externally integrated into the site heat delivery facilities, as well as generating power. However, delays are known to have been caused by poorly or individually specified subsystems that are unproven together.
Overall TRL	5	At the time of writing, the plant is yet to undergo a full process start up, and is delayed by more than a year. The main contractor has been removed and the University is managing the activities.

3.9 Stein Slow Pyrolysis Case Review

Process Category	Slow Pyrolysis	**Reactor Type**	Rotating Kiln
Primemover	Gas Engine	**CapEx**	Unknown
Fuel/feedstock	Residual MSW	**Throughput**	Unknown
Development Stage	Demonstration plant	**Operating hours**	No data available
Design capacity	Unknown	**Availability**	Unknown

The Stein slow pyrolysis technology was developed several years ago to process RDF, with a demonstration plant commissioned in Rotherham, UK. The process consisted of: a feedstock preparation step; a rotating kiln slow pyrolysis chamber with some steam injection to minimise char production; syngas cleaning; and a syngas-fuelled reciprocating engine. Flue gases from the engine and char were used to fuel a swirl combustion chamber that, in turn, heated the rotating refractory before venting to atmosphere. The main innovation was the highly integrated process approach, with heat being recovered as much as possible, while ensuring that all flue gases meet regulatory requirements.

It is known that the developer suffered continuing financial difficulties, and activities were eventually wound up. The system is now being marketed by an organisation called First Power.

Comment

The Stein process was developed by an engineer with significant experience in the sector and this shows in the technical design of the process and individual units. In particular, there were specific innovations associated with the rotating kiln, the char swirl combustion chamber and the process integration. However, developing the process clearly cost more than anticipated, making progress

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[10] Confidential discussions with AEA staff close to the Refgas project

difficult and potentially meaning the process had to be adapted to changing objectives as partners invested in or divested from the project.

Similar technologies were developed by Novera in the UK and Pyropleq in Germany, but have not been commercialised. In our view, this was probably due to the targeting of the technology at the highly conservative MSW market, and the proposed use of steam cycle generation, which would have offered little if any commercial benefit over a conventional combustion solution, to compensate for the higher risk. The char management was not as advanced as the Stein solution.

AEA feels that there is much that is positive in this technology. It acknowledges that char production is inevitable and uses it in a beneficial manner to supply internal process heat. Ash flue gas from the process and the engine set are combined and emissions eliminated by high temperature oxidation. WID compliance can also be assured by the residence time in the flue gas oxidation step.

Indirectly heated kilns are used in the activated charcoal market and commercial solutions are available. Similar kilns are also used in mineral processing and in the Mitsui-Babcock R21 waste treatment

Figure 12: Stein demonstration plant in Rotherham (courtesy of First Power ltd)

Data Sources

Personal knowledge of facility (Nick Barker)

First Power web site. http://firstpowerlimited.eu/

Lessons

\+ Development of ATT plant requires significant financial and technical resources.

Table 16: Stein – Rotherham Plant TRL

Unit Operation	TRL	Justification
Pre-treatment	7	Bespoke pre-pyrolysis sub system, operated successfully on prototype.
Conversion process	7	Integrated rotating kiln subsystem, operated successfully on prototype.
Post Treatment	9	The process uses an established approach of cyclones, bag filters and absorption units. Ash is said to be removed as slag, but this may be optimistic and may operate in dry mode.
Power generation	9	The Stein process used an unspecified reciprocating engine, which should work provided that the gases meets strict specifications, particularly concerning contaminants.
Integration	7	Innovative integrated use of char to maximise overall energy efficiency, operated successfully on prototype.
Overall	7	A process prototype was developed by the developer, who had financial difficulties before the plant could be commercialised.

3.10 Summary of TRL Assessment of ATT "Failures"

Table 17: Technology Readiness Level Assessment for ATT "Failures"

	ARBRE	Brightstar	Compact Power	Greve	Energos (Isle of Wight)	GEM Yorwaste	Hudol / Pure Power Huntingdon	Refgas (UEA)	Stein
Process type	G	G	G	G	G	FP	G	G	SP
	IGCCGT	RE	None	ST	ST	RE	RE	RE	RE
Pre-Treatment	9	7	7	9	9	8	9	7	7
Conversion Technology	9	6	9	9	9	4	7	4	7
Post-Treatment / Clean-Up	5	6	9	9	9	6	7	5	9
Energy	8	7	9	9	9	7	9	9	9
Integration	7	6	9	5	7	6	6	5	7
Overall	**6**	**7**	**7**	**9**	**9**	**7**	**7**	**5**	**7**

IGCCGT = Integrated Gasification Combined Cycle Gas Turbine
ST = Steam Turbine; RE = Reciprocating Engine
FP = Fast Pyrolysis; SP = Slow Pyrolysis; G = Gasification

4. ATT Future Developments

AEA's research into the unsuccessful processes highlights that projects experienced difficulties in two areas;

- handling and cleaning dirty syngas once it was generated, and;
- processing char.

Developing technologies that could overcome these barriers would lead to a significant improvement the success of waste gasification and pyrolysis processes. The options for overcoming the difficulties in syngas cleaning are:

- the development of a conversion step that produces a syngas with lower tar and pyrolysis oils content than can be achieved currently;
- improved unit processes / performance for removing syngas tars and oils to levels that enable sustained and long term operation of advanced prime movers such as engines or gas turbines; and
- the development of prime movers that operate above the tar dew point (in excess of 300°C) avoiding the problems caused by the condensation of syngas tars and pyrolysis oils.

Char management is best dealt with by understanding the function of the conversion reactor and making provision for the steam and/or oxygen injection necessary for its conversion to fuel gas. In AEA's view, it is unwise to rely on a landfill or sales route for char disposal. Experience at Brightstar has illustrated that it can be a fire risk. No one that we are aware of has managed to sell by-product char into the established and highly specialised active carbon or thermal charcoal markets.

There are also obvious benefits in the development of prime movers, which are more efficient than the mature reciprocating engine, gas turbine and steam cycle systems (in either CHP or power only configurations). Thus, AEA has identified organisations who are working in the particular areas concerning syngas handling and prime mover development.

Table 18: Selected Future Developments

	Process Name	Process Description
13	Bloom energy	SOFC manufacturer, Auto reforming fixed bed, modular design, flexible fuel use deployed to several sites in California
14	ECN	Developing Olga tar scrubbing technology. Pilot scale plant behind Bivkin reactor. Scrubber based on contact of gas with organic liquid. After separation contaminants recycled to gasifier. Successfully employed on biomass gasifiers.
15	Lurgi AG	Supplier of syngas cleaning processes for many decades using chilled methanol and amines.
16	KBR	Currently Coal to Synthetic Natural Gas
17	Molten salt gasification	University of Maryland
18	Sasol	Fischer Tropsch liquids market leader has operating plants using coal and gas as feedstocks
19	Sumitomo Metal Industries (PreCon)	Molten Iron bath gasification - a new type of waste gasification and smelting system, using iron-making and steel-making technologies based on high-temperature metallurgy, has been developed for feedstock flexibility
20	Ze-Gen	Innovative liquid metal heat transfer medium in reactor

Note: due to the early development stage of many of these processes, their available data may be incomplete or unverifiable.

4.1 Bloom Energy

Technology	Unit operation
Auto reforming solid oxide fuel cell (SOFC)	High efficiency and high temperature prime movers

Bloom Energy has developed and is in the process of commercialising solid oxide fuel cells. They have received significant financial investment and operate in a regulatory environment that is keen on the development of fuels.

Currently, the fuel cell operates on clean fuels, so there are technical risks associated with using biomass and waste derived fuels, although Bloom energy are known to be developing the fuel flexibility of their designs. In addition, these fuel cells have limitations on the physical nature of the feedstock they can accept, and the inlets to these units may be susceptible to fouling. The key potential advantages of this technology are the high operating temperature at 900-1000°C, greater-than-Carnot electrical efficiency, and no moving parts, therefore lower maintenance costs.

4.2 ECN

Technology	Unit operation
Organic liquid gas cleaning	Developments in syngas cleaning and tar removal technologies

ECN is a well-respected company that has contributed to many European gasification projects. They are currently developing tar cleaning technologies based on the use of non-polar hydrocarbon based solvents rather than water. Pilot trials with these technologies suggest they may outperform current tar cleaning technologies.

4.3 Lurgi

Technology	Unit operation
Rectisol, Purisol & Amine gas cleaning processes	Syngas cleaning technology based on chilled methanol to remove carbon dioxide, tars and oils. Capable of improving the quality of syngas to the standard needed for chemical processes.

Lurgi has a history of working in the gasification area, specialising in the design and development of fixed bed downdraft, updraft and entrained flow gasifiers for coal. It has developed processes for cleaning syngas and analogous gases using chilled methanol to physically absorb carbon dioxide, tars and oils, or amines to chemically bind these components. Lurgi has a long history of successfully developing processes which generate, condition and utilise syngas from coal.

4.4 KBR

Technology	Unit operation
Methanation	Opportunities for using waste derived syngas for fuel production

KBR is known to be developing a process for converting biomass into biosynthetic natural gas (BioSNG). The process could be up to 80% efficient with waste heat recovery and export, and would take advantage of the current gas grid infrastructure, in effect making all natural gas dependant technologies sustainable at a stroke. Technically, there are risks associated with the use of waste as a feedstock, due to the challenges of contaminants in the waste.

4.5 University of Maryland

Technology	Unit operation
Molten salt gasification	Technology with low tar production

This academic department has significant experience in molten salt oxidation, though little is known about the current level of development of such processes. The molten salt acts as a solvent, improving reaction rates, and the high operating temperatures and the homogenous nature of the process result in very low tar production. There is some risk that the process may not be suitable for feedstock such as biomass or waste, as the contaminants may reach high concentrations within the molten salt. Molten salt is also known to cause significant corrosion problems in high temperature plant.

4.6 Sasol

Technology	Unit operation
Fischer Tropsch Liquids	Opportunities for using waste derived syngas for fuel production

Sasol is a market leader in the commercialisation of Fischer Tropsch liquids technologies, with several decades' experience using coal and natural gas as feedstocks. However, they have not developed a process using biomass or waste as a feedstock. Potentially, the process could be up to 65% efficient, and would take advantage of the current oil distribution infrastructure,. Technically, there are risks associated with the use of waste as a feedstock, due to the challenges of contaminants in the waste.

4.7 Sumitomo Metal Industries

Technology	Unit operation
Molten metal gasification	Technology with low tar production

During the early 1980s, Sumitomo Metals developed several pilot plants using molten metal baths for the gasification of different qualities of coal. In the process, the molten metal acts a solvent, improving reaction rates, and the high operating temperatures and the homogenous nature of the process result in very low tar production. There is some risk that the process may not be suitable for feedstock such as biomass or waste, as the contaminants may reach high concentrations within the molten metal. The scale of the process is limited by the configuration of the molten bath and the saturation concentration of carbon in the molten metal. Sumitomo was successful in proving the concept but the technology was not commercialised. AEA considers that there must be a financial barrier to commercialisation (possibly due to poor economics when compared with alternatives), given the technology was reasonably developed some time ago.

4.8 Zed-Gen

Technology	Unit operation
Molten metal gasification	Technology with low tar production

Little is known about Zed-Gen as an organisation, and the same technical concerns apply to Zed-Gen as to Sumitomo Metals Corporation.

5. ATT Conclusions

This landscape review of advanced thermal treatment technologies shows that the successful development of a process (or processes) that can make use of biomass or waste derived material is relatively rare and difficult to achieve.

Those projects that have been successful have tended to develop schemes based around a close-coupled open steam cycle process and have focussed on designing processes which are tolerant of variation in feedstock parameters, which has often been the most significant issue facing the processes.

In contrast, many factors have caused the failure of projects, and some are seen to be repeated on a number of occasions. AEA draws the following general conclusions from the study:

+ Project development costs tend to be far more than expected. This places pressure on technical objectives and drives companies toward premature commercialisation to attract private equity. Adequate financial resources and clear technical objectives are required for success but very few, if any, UK developments have benefitted from these.
+ Gas turbines and reciprocating engines are very sensitive to the presence of contaminants in the syngas. The seemingly simple process engineering task of removing these has proved intractable and as a result there are very few examples of successful implementation, and many of failure. Successful projects have sidestepped this issue by using direct combustion in a boiler and steam cycle electricity generation.
+ The use of steam cycle generation means that there is a limited prospect for significant increases in thermal efficiency over incineration, and this comes with increased technical risk. It is debatable whether the increased performance is worth the risk premium in a conservative industry such as waste management.
+ The conclusion from the two points above is that understanding gas cleaning and developing commercially successful solutions are by far the most important research challenges in this area.
+ There are some technical themes that reoccur in successful projects:
  - Gasification only succeeds when the feedstock is consistent. This can be achieved in waste installations by:
    - a preliminary pyrolysis step that presents char to a gasification step; or
    - extensive fuel preparation;
  - The pyrolysis route has worked at small and large scales; extensive fuel preparation is probably more appropriate to larger installations only.
  - Large fluidised bed gasifiers (several MW) have proved successful and reliable if the feedstock is controlled.
  - Char from pyrolysis should be converted to gas within the process and not removed. A pyrolysis process is only half the solution.
  - Ceramic filters remove dust from product gas effectively.
  - Organic scrubbing, particularly by esters, is effective at tar removal.

In summary, there are currently very few operational ATT processes, despite a wealth of investment and R&D input. There are far more examples of problems and failures than fully operational facilities. This is a reflection of the problems explained above and concerns about feedstock quality, consistency and the resources required to make these processes success when using waste as a feedstock.

More progress is now being made in the gasification of clean biomass with several installations now operating successfully, but these processes were outside the scope of this review. It would be valuable to extend this review to analyse the lessons from this field. Biomass gasifiers have now achieved many tens of thousands of hours of operational experience, most notably in Austria and Denmark.

Five or so years ago, one of the authors of this report asked Professor David Wilson MBE about his thoughts on gasification, which seemed to be the up and coming technology for waste management. Prof Wilson replied that, when he started his career 40 years earlier, gasification was the up and coming technology for waste management then, too! We might conclude that the fact that so much effort is still being put into ATT technologies must mean that a lot of people can see its potential, but that that is possibly a triumph of hope over experience.

AEA Technology

July 2011

Annex I: Full List of ATT Processes and Organisations

Process Name	Process Description	Technology provider	Reactor type
Advanced Plasma Power		Tetronics	Fluidised bed
Aesi	Close coupled gasification and combustion, no operating plant, undergoing pilot plant testing	n/a	Close coupled combustion
AHT Pyrogas	Fixed bed downdraft gasification	n/a	Downdraft
Alfagy	Biomass gasified in a downdraft gasifier. Limited data available, mainly CHP provider	n/a	Downdraft
Alter NRG	Downdraft plasma gasifier	Westinghouse plasma	Downdraft
Amer	-	Lurgi	Circulating Fluidised Bed
Anellot	n/a	n/a	
Anhui	High temperature updraft pulverised coal feedstock for fertiliser production ammonia production, Sinopec - Yueyang, Hunan. Generates high pressure steam @ 120 bar & process efficiency 80 - 83%. Several examples of Shell China coal gasification licences	Shell Coal Gasification	Updraft
Ankur	Biomass gasified in a downdraft gasifier. Limited information, several plants operating on Indian sub continent	n/a	Downdraft
Aqua Critox (Super Critical Fluids International - SCFI)	Specialised water oxidation technology to convert organic wet waste into clean water. Aqua Critox is a supercritical water oxidation process that leads to complete sludge destruction, the production of renewable energy and the recovery of resources such as phosphorus from sewage sludge.	Aqua Critox	New Technology
Arbre (IGCCGT)	Eggborough plant shutdown (the first IGCCGT had problems with gas clean up of corrosive tars) shut down after 8 days operation (commercial problems may have contributed to problems)	Thermiska Processir of Sweden (TPS)	Circulating Fluidised Bed
Associated Engineering Works (AEW)	Fixed bed downdraft gasification	n/a	Downdraft
Aston University	Specialists in Pyrolysis		Academic

Process Name	Process Description	Technology provider	Reactor type
Austrian Energy & Verbund	Fluidised bed gasification	n/a	Fluidised bed
Babcock Hitachi		n/a	Close coupled combustion
Bedzed	CHP	n/a	Downdraft
Biomass engineering	Batch gasification, with hot gas filter, bag filter	n/a	Downdraft
Biomass Technology Group (BTG)	Conical Vortex Gasifier		Academic
Biossence	Under construction	Enerkem	Bubbling fluidised bed
Biosynergi Process Aps	Fixed bed		Unknown
Bloom energy	SOFC manufacturer, Auto reforming fixed bed modular units, flexible fuel use deployed to several sites in silicon valley	SOFC	Primemover
Brightstar	Scheme failed due to problems with gas clean up	n/a	Close coupled combustion
Burgau	Slow pyrolysis	n/a	Rotating kiln
Carbona (Oy)	CFB gasifier mated to steam tar reformer gas cleaned and fuels Jenbacher engines and gas boilers	Carbona	Circulating fluidised bed
Condens Oy	Fixed fluidised bed	Carbona	Circulating fluidised bed
CHO power	Plant under construction	Europlasma	
Choren Industries Gmbh	3-stages gasification, pyrolysis and fluidised bed		Fluidised bed
Clean Fuel	Downdraft bed gasification, then fluidised bed reformer		Downdraft
CLEW - Thermal Technologies Inc	Downdraft bed with air		Downdraft

Process Name	Process Description	Technology provider	Reactor type
Conoco Philips	E-Gas. Two stage oxygen blown entrained flow slagging gasification		Entrained flow
Cosmo Powertech	Fixed bed updraft gasification		Updraft
Costich	Downdraft bed gasification		Downdraft
Cranfield University	High temperature process research		Academic
Cratech	Pressurised fluidised bed		Fluidised bed
CRIEPI	Unknown		Academic
Dalhousie University Canada	Super critical water oxidation - research to examine if the heat transfer in SCW reactor can be further enhanced by adding solids to it. Propose to develop fluidised bed based SCW heat exchanger. It is a new concept pioneered by Dalhousie CFB lab	Super Critical Waster Gasification System	Academic
Danieli Ambiente SRL	Downdraft bed gasification		Downdraft
Danish Technical Institute (Viking)	2 stage gasifier		Academic
Dasag Renewable Energy	Fixed bed		Downdraft
Desser Rand	Reciprocating engine		Primemover
Drebe	Moving bed		Unknown
DTU Biomass Gasification Group	Pyrolysis + downdraft bed in 2 stages		Downdraft
Dynamotive	Fast Pyrolysis reactor fuelled by char from sawdust feedstock		Bubbling fluidised bed
Eagle	Oxygen blown two-stage gasification.	Eagle	Academic
Ebara	Innovative twin internally circulating fluidised bed. Less pre-treatment required.	Ebara	Close coupled combustion
ECN	Developed Olga tar scrubbing technology. Pilot scale plant behind Bivkin reactor. Scrubber based on contact of gas with organic liquid. After separation liquid recycled to gasifier		Academic

Process Name	Process Description	Technology provider	Reactor type
Ecologia Informatica	TWR. Rotary hearth and stationary gasification		Rotating kiln
Energia Natural de Mora	Fluidised bed gasification		Fluidised bed
Energie Ressourcen Institut	Pyrolysis + downdraft fixed bed		Downdraft
Energos	Close coupled gasification and combustion, plants currently operational delivery heat in Norway		Close coupled combustion
Enerkem / Biossence	Innovative catalytic gas cleaning, 1 operating plant in N America 2 more under construction, 1 plant under construction in UK. Produces methanol and other chemicals. Uses treated wood. New plant will handle MSW.	Enerkem	Bubbling fluidised bed
Ensyn	Rapid Thermal Processing (RTP) technology that converts second generation biomass like forest and agricultural wastes to bio-oil or pyrolysis oil for use in power and heating applications.	Fast pyrolysis	Circulating fluidised bed
Entech	Pyrolytic gasification + combustion. Stepped Hearth design		Close coupled combustion
Entimos Oy	Combined updraft & downdraft, large turndown rate	Entimos Oy	Downdraft & Updraft
Enviroarc Technologies	Pyro-arc. Fixed bed updraft gasification + plasma polishing		Updraft
Envirotherm	Developer of following types of gasifier: 1. Pressurised fixed bed, (British Gas/Lurgi "BGL") 2. Atmospheric circulating fluidised bed and 3. Pressurised circulating fluidised bed based on the high temperature Winkler Process	1. Lurgi 2. Winkler process	Circulating fluidised bed & fixed bed
EPI (Energy Products of Idaho)	Fluidised bed and steam boiler, incorporating new high-volume trap removal system. In 1987, replaced with a bubbling fluid bed unit complete with in-bed heat transfer unit. Plant 2 (50MW utility power plant) - boilers converted to external fluid bed combustion - firing of wood, coal and RDF	Gasification	Close coupled combustion
EPi (Environmental Power International)	Slow pyrolysis	Pyrolysis	Close coupled combustion

Process Name	Process Description	Technology provider	Reactor type
EPRL Thetford	Not gasification		n/a
Eskom Enterprise	Downdraft fixed bed		Downdraft
Ethos (previously Compact Power)	Passes waste through a heated pyrolysis tube and a deep bed gasifier.		Close coupled combustion
Europlasma group	Use a combination of partial combustion and plasma-assisted gasification – two plasma torches for cracking the gasification products and vitrifying the ash, respectively		Plasma gasification
Exus Energy B9 Energy	Fixed bed downdraft gasification		Downdraft
Ferco	Bubbling fluidised bed indirect vapour		Bubbling fluidised bed
Fluidyne	Downdraft fixed bed		Downdraft
Foster Wheeler	Large scale FEED process consultancy		Academic
G&A Industrieanlage	"drehrohr"		Rotating kiln
GEM (Yorwaste)	Fast Pyrolysis of feedstock using rotating ablative heated surface	GEM	Ablative kiln
General Atomics (US)	Super critical water oxidation - good for the destruction of many hazardous and toxic agents such as those used in military equipment		Supercritical water oxidation
General Electric	Entrained flow gasification		Entrained flow
Greve - demonstration plant in Italy (two 15 MWt TPS CFB gasifiers)	Starved-air gasification process in a combined bubbling and circulating fluidised bed reactor (850C), slightly above atmospheric pressure. Uses RDF – Dolomite tar cracker for cleaning the gas which is nigh in tar components	Termiska Processer (TPS)	Circulating fluidised bed
Grubl	Downdraft fixed bed		Downdraft
Güssing (Austria)	biomass fuelled CHP plant, based on a steam blown gasifier, producing heat and power with a gas engine, with the capacity to cover the total electricity demand in Güssing – utilising steam instead of air as gasifying agent (inputs: wood)	Reprotec	Fluidised bed

Process Name	Process Description	Technology provider	Reactor type
Haldor Topsoe (FT) (Topsoe Fuel Cell is a fully-owned subsidiary of Haldor Topsøe)	First Solid Oxide Fuel Cell (SOFC) unit running on landfill gas has been in operation for more than 1,500 hours in Vaasa, Finland. 24 SOFC fuel cell stacks are incorporated into the WFC20 unit. WFC20 is developed and operated by Wärtsilä. The WFC20 is based on planar SOFC technology	Wärtsilä SOFC	Primemover
Harvest Power	Anaerobic digestion		n/a
Hitachi Metals		Westinghouse plasma	updraft
Hitachi Zosen	Fluidised bed gasification fusion furnace. First installation in Japan at the end of 2002. As of March 2009 had constructed 8 facilities and had plans to construct a facility in South Korea (May 2010) Horizontal Internal Circulation Bed (HICB)		Close coupled combustion
HoST	-	ECN	Circulating Fluidised Bed
Hudol	Entrained flow with multiple extraction points and temperature profile control. Continuous feed, Design for feedstock flexibility, Pilot plant in Wales. Additional plants under construction and commission in England. Further project underway in India, US, Greece, Bulgaria. Huntingdon UK plant experiencing technical problems.		Updraft
IGT - Institute of Gas Technologies	The gasification campus is available for use by organisations and companies conducting research and validation of enabling technologies that have shown promise after laboratory and bench testing and need demonstration at the next scale. Two facilities for testing gasification technologies.		Academic
IHI (Ishikawajima-Harima Heavy Industries - Japan)	Pressurised fluidised-bed combustion (PFBC) boilers and Circulating fluidised-bed combustion boiler (CFB)		Close coupled combustion
Imperial University	High temperature process research		Academic
Indian Institute of Science (IISc)	Downdraft gasifier development		Downdraft
InEnTec	PEM. Plasma Gasification		Plasma gasification

Process Name	Process Description	Technology provider	Reactor type
Intervate	Commissioned a gasification plant in Esholt - inputs clean and waste wood - incorporates several novel innovations to the traditional Imbert downdraft gasification process - appears to have developed a more efficient gas clean up system. Have received planning permission for another plan in the West Midland (Oct 2010)	Imbert downdraft gasifier	Downdraft
ITI Energy	With the University of Newcastle, ITI Energy has developed a patented gasification system that incorporates elements of up-, down- and cross-draft technology to produce syngas that is low in tars and oils. ITI has applied a modular approach to its energy from waste gasification plants. 2 projects operational (Teesside and Nottingham) - 2 under development (Derbyshire and South West England) will process in the region of 12,000 tonnes of fuel per year. Densified combustible solid material (biomass, RDF, chicken litter, autoclave floc)		Updraft, downdraft and cross-draft
Jenbacher	Known to produce engines capable of tolerating low quality gases	Reciprocating engine	Primemover
JFE Engineering	Thermoselect process is a gasification and melting technology that uses a gas reforming process to recover purified synthesis gas from municipal waste and industrial waste. Also utilising the Babcock & Wilcox Vølund ApS updraft gasification technology of waste wood (Babcock & Wilcox Company)	Thermoselect, Babcock & Wilcox Vølund A/S	Updraft
Kara Energy System BTG	Updraft fixed bed		Updraft
Kawasaki Giken	Shaft Furnace		Updraft
Kedco	The gasifier technology is based on a two-zone stratified fixed-bed downdraft design, operating at above 850 °C. Modular system (2MW), skid mounted - 1 plant operation in Cork processing wood producing 100kW of electricity - Received planning permission for a second plant in Enfield, London	Zeropoint	Downdraft
KHI (Kawasaki Heavy Industries)	Kawasaki produces three types of fluidised bed boilers--the Bubbling Fluidised Bed Boiler (7 boilers delivered), the Outer Circulating Fluidised Bed Boiler (2 boilers delivered) and the Inner Circulating Fluidised Bed Boiler (2 boilers delivered). The latest, \`the Inner Circulating Fluidised Bed Boiler', has been developed as a highly efficient and clean system to generate power by utilising various waste and sludge as a \`fuel' as well as waste containing corrosive substances and environmental pollutants and solid fuels derived from plastic waste. Second type - Woody biomass gasification system using CCA-treated wood - produced 600 tonnes per year of pellets and waste heat recovery boiler (small scale system) - 1 woody biomass gasification CHP system started operations in 1 Feb 2011		Fluidised bed and fixed bed down draft gasifier

Process Name	Process Description	Technology provider	Reactor type
Kobelco	Fluidised bed gasification		Fluidised bed
Kobelco Eco-Solutions Ltd	Cylindrical fluid bed, Compact, easy material recycling of unoxidised steel and aluminium, swirl flow melting furnace. The system employs auto-thermal melting, using the energy of the waste itself, so no electricity or fuel is needed for the melting. In March 2010, Kobelco Eco-Solutions completed the Minami Refuse Incineration Plant in Sagamihara, Kanagawa Prefecture, and the heat recovery facility at the Shigenka (Recycling) Center in Kawagoe, Saitama Prefecture.		Fluidised bed
Kbr	Coal to SNG		New Technology
Krupp Uhde	Entrained flow slagging gasification. Precon		Entrained flow
KRW Energy Systems	Agglomerating fluidised bed gasification		Fluidised bed
KSTU	unknown		Unknown
Kvaerner	A 130MW biofuel-fired boiler plant using bubbling fluidised bed (BFB) combustion was built in Sweden, close to the town of Örnsköldsvik in 2008. Kvaerner produces two types of fluidised bed boilers, the HYBEX, which produces 20–300MWth from biomass and recycled fuel, and the CYMIC, which produces 50–600MW$_{th}$ from biomass, recycled fuel and coal. Hydro beam floor can burn various fuels. The company focuses on the 5–60MW$_{e}$ range and above. It has recently secured contracts for power boiler modernisations in Sweden, Lithuania and Slovakia.	HYBEX and CYMIC	Bubbling fluidised bed and circulating fluidised bed
Lurgi	Several commercial processes with varied feedstocks, very experienced in gasification processes (supplied Sasol), innovative retisol gas cleaning system based on methanol.	Lurgi	Downdraft & updraft
Marcegaglia CCT	Fixed fluidised bed		Fluidised bed
Martezo Renewable Energy	Fixed downdraft gasification		Downdraft
MHI - Mitsubishi Heavy Industries (gasification)	Developed the "Mitsubishi MSW Gasification & Ash Melting System" in 1998. Current focus is the enriched airflow integrated coal gasification combined cycle (ICGCC). Inputs = coal, dry feed system. •Air-blown-dry coal feed entrained flow gasifier •Gas clean-up MDEA*(Methyldiethanolamine) chemical absorption		Entrained Flow

Process Name	Process Description	Technology provider	Reactor type
Mitsui (Mitsui Engineering and Shipbuilding – MES)	Kiln type gasification and melting process - MES has already completed 6 kiln-type gasification and melting waste treatment facilities in Japan and put them under satisfactory operation. The 7th facility is now under construction. In March 2006, MES completed and delivered a treatment facility for Automobile Shredder Residue by means of pyrolysis carbonization recycle technology.	R21	Rotating Kiln
Mitsui / R21	Pyrolysis + Combustion + Melting	R21	Rotating kiln
Molten salt gasification	University of Maryland		Academic
Mothermik GmbH	Fixed bed		Unknown
NEDO	Coal Gasification Technology. Project aims to develop the most advanced oxygen-blown, single-chamber, dual-stage, spiral-flow gasifier that can efficiently produce synthetic gas (CO+H2) - EAGLE project. Also carrying out research into Solid Oxide Fuels for coal	Eagle	Spiral flow gasification
Nexterra Energy	Fixed bed updraft gasification		Updraft
NGK Insulators (Rotating Kiln)	Carrying out research into improving Solid Oxide Fuel Cells (lowered the temp and enhance the performance of the fuel cell)		Rotating Kiln
Niigata Electrical Power	Niigata has been developing the diesel and gas engine technologies by the Customers' requirement. In 1989, Niigata developed and manufactured first low - NOx gas engine, and has been brushing up these technologies and experience.		Primemover
Nippon Steel	According to manufacturer, this system has been highly praised for its reliable operation for nearly 30 years since its introduction in 1979, and thus, we have received 36 orders in Japan and overseas. This system is capable of treating a wide range of waste, such as burnable garbage, non-burnable garbage, sludge, and incineration ash all together, and steel slag and metals are all recycled into resources		Shaft furnace type gasification
Nippon Steel	Slagging updraft gasifier. DMS (Direct Melting System).		Updraft
Novera	Sold Defra new technologies gasification site to Biossence in 2009; company is focusing on wind power		n/a
NREL (National Renewable Energy Laboratory)	NREL has developed a pilot-scale process and design model for the indirect and direct gasification of lignocellulosic biomass to ethanol		Academic

Process Name	Process Description	Technology provider	Reactor type
Organics	Organics has developed and proven its own in-house technology for the efficient gasification of varied biomass streams. Of particular interest is MSW. Limited info on website		Unknown
Primenergy	Fixed bed updraft gasification		Updraft
PRM Energy Systems	Fixed bed updraft gasification		Updraft
ProCone	Downdraft fixed bed		Downdraft
Puhdas/Absolute Energy	Fixed bed updraft gasification		Updraft
Pyroforce	Spiez Switzerland		Downdraft
Pyrogenesis	Plasma Resource Recovery System - combining gasification with vitrification. Air Torch – these high power torches use compressed air as the plasma forming gas and range in power from 50 kW to 500 kW. Reverse Polarity Torch and Compact Coaxial Plasma Spray Torch (Minigun)		Plasma gasification
Rainbow (Rainbow Xuzhou Plasma Environmental Tech Co Ltd)	Specialises in processing methods for hazardous waste matters and producing dedicated devices. Mainly work at the application and development of green environment protection. DC plasma arc technique. Have produced a set of RAINBOWTECH series with rich feature and independent IPR in the field of the international leading technique - hazardous waste matters plasma arc fluxing cracking technique.		Plasma gasification
Refgas (UEA)	Refgas has been established for some years, and develops and produces moderate-scale renewable energy facilities. Refgas has developed an advanced gasification CHP system to ensure the efficient production of renewable energy. Wood, timber and wood waste, RDF, compost residues, animal manures, sewage cake, etc feedstock		Downdraft
Reprotec	In 2001, Reprotec made a breakthrough in biomass gasification with the CHP plant Güssing. Since then, the plant, based on a steam fluidised-bed gasification (prototype plant of the FICFB-process), reliably delivers electricity and heat for the municipality of Güssing. Furthermore, the system provides a platform for numerous research projects.	Reprotec	Twin fluidised bed
Reprotec / TUV	Fluidised bed gasification	Reprotec	Fluidised bed
Rhade	Downdraft/updraft/fluidised bed		Unknown

Process Name	Process Description	Technology provider	Reactor type
Rural Generationi Ltd	Fixed bed		Unknown
Sasol	Fischer-Tropsch liquids market leader	Lurgi	Updraft
SCA Energy	Slagging gasification		Unknown
Schmack	Anaerobic digestion		n/a
Schmitt Enertech	Small capacity (250kW$_e$), uses wood sawdust and waste wood residue		Downdraft
Scotgen	Batch slow pyrolysis with low level air injection	Planet	Close coupled combustion
Shanghai Huanuan Boiler Vessel Co. Limited (SHBV)	Oil and gas fired packaged burners - recently did a deal with W2E Engineering in Scotland - Difficult to find information		Unknown
Shell Global Solutions	Oxygen-blown slagging entrained flow gasification.	Shell Coal Gasification	Entrained flow
Siemens	Supplier of gas turbines for low quality fuels (blast furnace gases)	High temperature gas turbines	Primemover
Skive	Demonstration plant operating since 2008. The gasification plant is designed to utilise wood pellets and/or wood chips. The gasification plant was supplied by Carbona, a subsidiary of pulp and paper technology firm Andritz Oy, which also possessed circulating fluidised bed gasification technology (CFB).	Carbona	Bubbling fluidised bed
Solena	Fischer-Tropsch liquids market leader	Westinghouse plasma	Circulating fluidised bed
Stein	Rotating Kiln pyrolysis / gasification with steam injection to reduce char production. Innovative energy recovery char & waste gas use.		Rotating Kiln
Sumitomo Metal Industries (PreCon)	Molten Iron bath gasification. To promote heat and material recovery, a new type of waste gasification and smelting system, using iron-making and steel-making technologies based on high-temperature metallurgy, has been developed for many kinds of waste.	Sumitomo molten iron	New Technology
Turbosystems Engineering	Super critical gasification - transpiring-wall SCWO reactors		New Technology

Process Name	Process Description	Technology provider	Reactor type
Takuma	The design, construction and management of a wide variety of boilers, plant machinery, pollution prevention plants, environmental equipment plants, and heating and cooling equipment and feedwater / drainage sanitation equipment and facilities		Fluidised bed
Takuma	Rotary kiln pyrolysis + melting		Rotating kiln
Techtrade	Techtrade GmbH, founded in 1999, is in the tradition of PLEQ Plant & Equipment Engineering. Rotary Pyrolysis Kiln, Hamm Germany, similarly in Burgau in Germany		Rotating Kiln
Techtrade / Pyropleq	Rotary kiln / pyrolysis		Rotating kiln
Tetronics (Advanced Plasma Power)	Tetronics Ltd is a global leader in the supply of Direct Current (DC) Plasma Arc systems for a wide range of applications including Waste Recovery, Hazardous Waste Treatment, Metal Recovery, Production Processes and Nano Materials.	Tetronics	Plasma gasification
Thermochem Recovery International	Indirect gasification		Twin fluidised bed
Thermogenics Inc	Downdraft fixed bed		Downdraft
Thermoselect	Updraft gasifier, wet scrubbing, wet ESP, 2 Jenbacher engines, development of cleaning scrubbing water. European demonstration plant had catastrophic failure in 2009	Thermoselect	Updraft
Thide	The heating temperature ranges from 450 to 700°C. The temperature used is chosen to favour the production of synthesis gas or of Carbor®. The process also separates and purifies the metals and inerts contained in the input materials. Slow pyrolysis.	ARTHELYSE	Rotating kiln / Close coupled combustion
TKE	Staged fixed bed, circulating fluid bed		Circulating fluidised bed
Toshiba	Pyrolysis + gasification + Melting. PKA. IGCC (Integrated Gasification Combined Cycle) Power Plant		Unknown
TPS (Termiska Processer Sweden)	Fluidised bed gasification		Fluidised bed
Vista International / Nathaniel Energy	Gasification + close-coupled combustion		Close coupled combustion

Process Name	Process Description	Technology provider	Reactor type
Volund	Updraft gasifier, wet scrubbing, wet ESP, 2 Jenbacher engines, development of cleaning scrubbing water.		Updraft
VTT	Updraft in-situ catalytic tar cracking in upper part of reactor (known by Condens Oy)	Carbona	Updraft
Westinghouse Plasma		Westinghouse plasma	Updraft
Wuxi Hujing	Biomass (agriculture - rice husks, straw etc) gasification		Downdraft
Xergi	AD process developer		n/a
Xylowatt	Built on-site at Despond SA Bulle. Dry ash removal	IISc / GAZEL gasification developed at UCL	Downdraft
Ze-Gen	Innovative liquid metal heat transfer medium in reactor		New Technology

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