Programme Area: Bioenergy

Project: Energy From Waste

Title: Technology Assessment Report

Abstract:

This deliverable is number 2 of 2 in Work Package 2 and presents the results of the technology testing programme carried out by the consortium. The report presents the results from the testing carried out within the project into the anaerobic digestion and thermal processing of selected waste feeds, and the results from preliminary combustion engine trials with simulated fuel gases, arising from these processes. This deliverable together with D1.3 from Work Package 1 provides a key input into the Energy from Waste system modelling work carried out in Work Package 3.

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

ETI Energy from Waste FRP Project

Deliverable 2.2
Technology Assessment Report

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Executive Summary

This report is one of a series of deliverables for the ETI Energy from Waste Project, following on from Deliverable 2.1 – 'Technology Data Report and Test Plan'. The current report, Deliverable 2.2 – 'Technology Assessment Report', presents the results from the testing carried out within the project into the anaerobic digestion and thermal processing or selected waste feeds, and the results from preliminary combustion engine trials with simulated fuel gases, arising from these processes. In addition to reporting the testing activities, the report is required to correlate the output data from testing with the feed compositions and identify technology development opportunities. In summary, it is intended as a data collation report, with a preliminary review of the impacts of the findings and options from dealing with the issues raised to inform the activities in later work packages. It does not form a stand-alone report, and so must be considered in the context of the preceding deliverables.

The overall project is aimed at improving the definition of the opportunity for significant levels of primarily electricity and heat generation (with other outputs such as by-products and chemicals where markets exist) from the waste available in the UK, today in coming decades. Waste is a highly variable material and processes for its use to date have been large scale and low efficiency, aimed at reducing the disposal volume rather than recovering energy. This project aims to explore the opportunity for the affordable and environmentally acceptable recovery of energy from a substantial portion of the bulk and segregated wastes available in the UK. As such, the focus of the work presented in this report was to explore the suitability of the likely distributed energy technology choices to handle a large fraction (e.g. 80%) of the waste arisings in any particular location. It was not aimed at niche opportunities for selected wastes or at identifying the wastes that would work best in any particular technology, but rather those technologies that stood the best chance of being able to handle widely variable waste feeds throughout an annual cycle, reliably and with flexibility in matching the electricity and heat demands of local communities.

To achieve this, it was important to explore the impact of widely varying waste feeds on the selected technologies and so combinations of well established, segregated waste streams were examined, reflecting the extremes of what might be available at any particular time in practice. This approach also allowed some limited analysis of the impact of changing feed compositions on the gas produced, thus allowing a preliminary view to be taken on the likely variability that would need to be handled by downstream components, gas cleaning, gas engines, etc. In addition, the practical experience gained would provide a view of the likely constraints and challenges to be overcome in operating such a scheme, e.g. feeding, process availability, residue properties, etc. As the primary purpose of the project was to seek clean, affordable and local solutions to waste disposal, which also provided a return in terms of electricity and heat, the test approach recognised that more detailed, optimised testing would be required for down-selected technologies from those examined here in support of the next phase of any development/demonstration programme.

For reliable system operation, it is essential to have an understanding of the properties of the fuel gases produced and their contaminants, as well as information other process products/residues and any operational problems which would need to be overcome.

AD of food waste and food waste/paper/card mixtures was successful, although those attempted with paper/card alone showed low gas production volumes. There is a clear operational limit to the amount of feeds used other than food waste due to viscosity constraints on stirring power requirements of around 20%, although this will vary with the type of added waste and the design of the digester. Therefore, in general, it is clear that where possible dry wastes are better processed by other means. The benefits from using non-food wastes in AD must also be considered in the context of whether the AD plants will be used alone or in combination with parallel pyrolysis/gasification units. In such circumstances, the optimisation of the overall combined system in terms of biogas amounts, H_2S an NH_3 levels is the priority. However, where there is a clear market and hence value for the AD residue, e.g. soil beneficiation, this is likely to prove the preferred option and so biogas cleanliness will be the main priority.

The thermal testing programme confirmed that it was possible to process mixed wastes of widely varying composition using thermal gasification/pyrolysis technologies. In addition, highly relevant waste feedstock and thermal process information were obtained to identify likely problem areas for future development and to inform the process modelling activities in the project. Feeding and operational difficulties experienced during these tests emphasised the need for affordable pre-processing to produce a more homogenised feedstock; methods of waste size reduction, selected segregation of wastes, controlled blending and improved feeding systems all require careful consideration in moving forward. The data gathered, in conjunction with the subsequent modelling work, provide a platform from which to estimate the compositions and properties of the gases and tars generated from different processes along with the requirements for gas cleaning (e.g. removal of NH_3, H_2S and HCl) to avoid excessive emissions (of NO_x, SO_x and HCl) and downstream engine problems. In addition, data on the distribution of hazardous species and trace metals in the various residues provide a basis from which to develop/select further treatment steps prior to safe disposal or use.

A summary of the main considerations for each of the technologies operating with mixed waste materials is presented below.

Technology	**General Considerations**		**Findings from Testing Programme**	
	For	**Against**	**For**	**Against**
AD	Wet biodegradable wastes; right scale	Limited fuel options.	Good with food waste; possible to include paper/card	H_2S levels
Updraft Gasification	Simple technology; right scale	High tar levels; operation dependent on fuel properties	Problems with some fuels	Low/medium CV gas; high tar levels
Downdraft Gasification	Simple technology	Small scale only; operation dependent on fuel properties	Few operational problems	Low CV gas;
FB Gasification	Flexible medium scale technology	More complex equipment & operation	Fuel flexible; moderate tar levels; few operational problems	Low CV gas; high NH_3; risk of agglomeration
Slow Pyrolysis	Simple technology;	Operation dependent on fuel properties	High gas CV – high CH_4 and H_2; some operational problems	High tar levels

These considerations identify fluidised bed gasification as the most suitable technology. Downdraft gasification also demonstrated merits for smaller scale plants with waste streams of defined properties, but is restricted in scale-up due to difficulties in maintaining steady/uniform gas flows as the fuel bed cross section increases. It should also be noted that the slow pyrolysis testing did not cover the range of technology options available for this process and so further consideration should be given to this option.

The operation of a reciprocating engine with clean gases of typical compositions as would be expected to be produced from of waste materials has been shown to be feasible. These tests show that a relatively high engine efficiency of 35% can be achieved without further optimisation, if the fuel system, engine hardware and operational parameters are appropriately designed.

The findings from the testing programme, in relation to the processing and gas utilisation technologies, reinforce the critical importance of i) reliable fuel feeding, ii) optimising processing conditions and iii) affordable cleaning of the gases produced in enabling successful high efficiency, energy-from-waste systems. Although not distinct areas of investigation within the current project, it is expected that the key development opportunities required to enable the efficient use of waste materials would be in the areas of feeding and gas cleaning. To explore the opportunities here, a follow-on piece of work is under consideration to identify where the best opportunities lie for the UK.

Report Compliance

This report forms Deliverable 2.2 in the ETI’s Energy from Waste FRP project. The agreed contents of this report, as defined in Schedule 1 of the project Technology Contract are:

- An executive summary
- Detailed description of test procedures and protocol for each technology tested
- Technology testing results in relation to input waste properties
- Description and discussion of chemical analysis of technology primary and by-products
- Description of and rationale for identified technology development opportunities
- Conclusions
- Referenced data reports as appendices and a full list of references

The overall report includes each of the above sections and every endeavour has been made to ensure compliance with this content. Specific reference has been made where content is included in the appendices to this report

Introduction

Waste materials are generally regarded as being life-cycle carbon neutral as their raw resources have already been extracted. Recovering their energy content in an 'Energy from Waste' (EfW) plant offsets both i) the methane that would be generated through their degradation in landfill (21x more active as a GHG than CO_2) and ii) the CO_2 emissions associated with fossil-fuel energy generation displaced by EfW plants. However, these carbon reductions can only be realised if the energy is recovered at a price that is competitive with other forms of generation to enable market deployment.

Currently, waste materials can be processed using mass burn incineration to reduce waste volumes, and hence subsequent landfill costs. Energy is mainly recovered from such systems with a low temperature steam cycle to avoid excessive superheater corrosion at an efficiency of around 20 – 30% (depending on technology), compared to ~45% for state-of-the-art coal power plants, leading to relatively high CO_2 emissions per KWh. The challenge is to find technology options which can exploit the synergy between growing needs to solve the problems of environmentally-friendly waste disposal (when re-use and recycling are not options) and the generation of clean affordable power and heat.

To achieve the carbon benefits from this synergy, technologies are needed which can recover the energy in waste materials at a higher efficiency, close to source, with comparable or lower generation costs than other competing energy technologies. The ETI Energy from Waste project seeks to identify these technology options and determine the CO_2 emissions reductions which could be achievable from using waste as a fuel resource. In addition, for the selected technologies, the development and demonstration needs for these savings to be realised will be determined, in the range of 1 to 10 MW_e.

Deliverable 2.1 assessed technologies which could be employed at each stage of an advanced energy from waste system. The current development state of each technology with respect to its use with typical mixed wastes was assessed and operational information collated where available. This information was collated to identify data gaps which needed further investigation to assist the development of spreadsheet-based models of the technologies in WP3. Specifically, only limited data were available on the operation of Anaerobic Digestion (AD) and Gasification technologies using the mixed wastes targeted in the present study in real-world situations. For reliable system operation, it is necessary to have an understanding of the properties of the fuel gases produced and the contaminants arising from the use of mixed wastes. From the available literature, it was impossible to make fair comparisons between the candidate technology options as each report/paper understandably focused on specific trials either with restricted feedstocks or only dealt with single technologies.

To enable sufficient data to be gathered to fill the identified gaps, to extend the evidence base for selecting preferred technologies for use with mixed waste streams, and provide an initial indication of the feasibility of applying these technologies in practice, a testing programme was proposed to test real-world wastes in various mixtures in laboratory- and pilot-scale rigs. In addition, where appropriate, it was important to assess the impact of widely varying waste mixtures on the performance of the systems as reliable product gas supplies of relatively stable compositions were required for the downstream operation of the gas engines or turbines which would drive generators. Further, to establish a firm basis for capital cost estimates of such integrated systems, it was necessary to have an appreciation of likely operational challenges and requirements for feedstock pre-treatment/blending and downstream gas cleaning to protect the gas engine/turbine and ensure that emissions would comply with the prevailing environmental regulations. Finally, any integrated systems as described would still leave some residues, and it was worthwhile to identify at an early stage any constraints for their subsequent disposal or use.

The proposed test programme comprised a series of tests in AD and thermal process options (gasification and pyrolysis) with appropriate different feedstock mixtures, carried out largely in parallel with studies of the inherent variability of the available wastes. In addition, studies of combustion engine performance were conducted using synthetic gases to simulate those expected from AD and thermal processes. The lack of appropriate data sets in the public domain illustrates the novel nature of these tests; the project objectives, budget and timeframe were such that a complete and authoritative assessment of each of the technologies performance over its possible operation parameter space with the full range of typical waste material mixtures was beyond the required scope. As such, the test programme was relatively high risk as limited opportunities existed for optimising the test conditions with the waste quantities collected within the timeframe of this WP. It was decided that it was more important to evaluate the diverse range of mixed feedstocks in as large a choice of technologies as possible rather than to optimise a particular technology for the range of feedstocks, as the latter would not assist technology selection and would not provide the types information required for the comparative modelling in WP3.

This report, which forms Deliverable 2.2 of the ETI Energy from Waste FRP project, presents the results from the test programme conducted and highlights their key implications for technology application and development.

Report Structure

The test programme conducted was based on i) AD and ii) Thermal (gasification and (slow) pyrolysis) process technologies and iii) internal combustion engine power generation. Each of these three elements of the test programme required its own experimental set-up, methodology and results analysis procedures and protocols. Full and detailed reports covering the test methodologies and results for these three areas are included as appendices to this summary report.

The summary below outlines the main results and conclusions for each element of the overall test programme. The implications for the development requirements for energy from waste systems are discussed in the subsequent section. The use of the experimental data in developing the technology component spreadsheet models is described in Deliverable 3.2 of the project.

Testing Programme Summaries

Anaerobic Digestion

Laboratory-scale AD assays were performed as batch experiments. The substrates of food waste and paper and card as well as an inoculum were added successively at the beginning of the experiments in the ratios listed in Table 1.

The digesters were subsequently sealed. The digesters were stirred during operation to ensure good mixing of the substrates. Biogas production, as well as methane concentrations from the digesters, was monitored over a period of 35 days.

Table 1 Ratios of substrates for AD Experiments

Variant No.	**Substrate 1**	**% of Substrate 1 (%VS)**	**Substrate 2**	**% of Substrate 2 (%VS)**
1	Food waste	100	Paper and card	0
2	Food waste	75	Paper and card	25
3	Food waste	50	Paper and card	50
4	Food waste	25	Paper and card	75
5	Food waste	0	Paper and card	100

The experimental designs used to carry out batch AD assays complied with the norms DIN 38414, part 8, as well as with the German norm VDI 4630. As a convention, gas volume is presented as Nm^3, i.e. m^3 of dry gas in normal conditions (temperature of 0°C, pressure of 1013.25 hPa). To enable cross correlation and checking of results, the batch digestion assays were performed using 3 different laboratory digestion processes: the HBT process (Hohenheim Biogas Yield Test), 2 litre-digesters and pressure bottles. The equipment used for performing batch AD trials are outlined in Table 2 and are discussed in detail in the full AD test report attached as Appendix B to this summary report.

Table 2 Characteristics of the laboratory equipments used for AD assays

Process	**Volume**	**Main characteristics**	**Monitored parameters**	**Determination method**
HBT process	30 mL	Syringes	Gas volume CH_4-content	Scale Infrared sensor
2L-digesters	2 L	Eudiometer-type	Gas volume CH_4-content H_2S-content	Scale Infrared sensor Electrochemical sensor
Pressure bottles	2 L	Pressure bottles	Gas volume CH_4-content H_2S-content	Gas counter Infrared sensor Gas chromatography

The aim of this analysis was to determine the order of magnitude of biogas production, and methane and contaminant concentrations of mixtures of waste substrates. In accordance with this aim, the batch assays carried out for this work were designed to evaluate the maximal methane yield of a substrate, provided that appropriate nutrient balance, process design and process control are implemented. The precise nature of the influence of substrate composition on the performance of semi-continuous digestion was beyond the scope of this work, as this can only be evaluated through semi-continuous experiments, which are usually more expensive, less precise, and more time-consuming (experimental period of several months) than the batch experiments conducted. Methane production in full-scale units would be expected to be about 20% lower than the maximal yields measured in the laboratory. However, in some particular cases of good operation, fine particle size and long retention time, maximal yields may also be attained in practice. In practice, methane production is also likely to be in similar proportions to the overall biogas yield and with a similar order of magnitude to the results obtained from the experiments conducted for this project.

For all three test techniques, food waste was found to have a high methane yield of about 460 Nm^3/t (VS), while paper and card had much lower specific methane yields of about 200 Nm^3/t (VS). The ultimate methane yields of finely shredded paper (powder-like) increased to 216 Nm^3/t (VS) (HBT Digesters) as compared to 172 Nm^3/t (VS) for coarsely shredded paper (2L Digesters), corresponding to a 20% difference. The mixtures of food waste together with paper and card showed intermediate behaviours in proportion to the substrate ratios. In terms of conversion efficiencies, these values represent approximately an energy conversion efficiency of 29% from the entire feedstock to the gas on a mass basis.

The production of H_2S through AD results from, and is correlated to, the sulphur content of the feedstock. The composition and contamination of the gas produced hence depends on which types of foods are digested, for example the meat/vegetable ratio. As food waste is, per definition, not homogeneous and reproducible, for real world operation the exact instantaneous H_2S production rate is not required to be known, but the important thing is to define the range of this fluctuation to dimension the gas cleaning system. The removal of H_2S from the biogas is technically feasible, and is carried out in practice using a range of technologies including activated carbon absorption, biological desulphurisation and lime scrubbing. However, the costs associated with each of these techniques are proportional to the H_2S concentration in the gas, and can thereby be can be decreased by lowering the original H_2S concentration of biogas.

The H_2S content of food waste was about 400 ppmv after complete digestion, with an initial absolute production rate of between 300 and 500 ppmv over the first 5 days, reducing to near 0 at 35 days. The concentration value measured is considered rather low since H_2S concentrations of several thousands ppmv might be expected from such substrates. Since H_2S usually originates from the degradation of proteins, it is likely that the food waste sampled was low in protein content. The digestion of paper and card alone resulted in a lower rate of H_2S production, reaching a peak of 100 ppmv around 7 days after the initiation of the experiment, and reaching a concentration of around 80 ppmv after complete digestion. Interestingly, mixing paper and card together with food waste in the 2L-digesters greatly reduced H_2S concentrations, and also removed peak H_2S concentrations, even at a low share of 25%. This suggests that adding paper and card might be a good strategy to reduce H_2S-related problems in biogas.

The lower production of ammonia makes mesophilic AD (temperature around 37°C) more suitable than thermophilic AD (temperature around 55°C) for the conversion of nitrogen-rich substrates, which usually contain a high share of proteins. Thus, for substrates having an excessive share of nitrogen, like food waste alone, mesophilic operation is recommended. In this regard, adding a share of paper and card into a biogas plant operated with food waste could have further benefits in increasing the stability of the digestion by reducing ammonia concentrations in the digester, increasing methane production rates and allowing the process to be shifted from mesophilic into more efficient thermophilic conditions

The experiments carried out for this work were preliminary in their nature and such interaction would have to be further examined with samples having higher rates of H_2S production as those measured in the experiments were rather lower than might be expected in full scale operations, which would have a greater range of feedstock properties by virtue of being larger vessels. In a commercial scale application, the inclusion of a high share of paper and card might also create stirring issues and floating layers due to the physical resistance and lower density of paper. Mixing paper and card together with food waste may improve the extent and stability of digestion but does not necessarily affect the residence time to be applied, and hence would not bring any benefits in terms of reduced reactor vessel size. Additionally the modelling work carried out by EIFER in parallel to the experimental tests shows that the inclusion of paper and car with food waste at proportions above approximately 20% has a severe impact on the dry matter content and hence a detrimental effect on the digestibility and biogas production rate of the feedstock.

For the experimental results the peak H_2S concentration occurred at the very beginning of the assay. This suggests that biogas plants with short retention times or high loading rates (and therefore having only a partial degradation of the substrates) may endure higher H_2S concentrations than biogas plants operated at longer retention times or lower loading rates. Moreover, ensuring a constant feeding rate of the substrate instead of batch feeding may limit H_2S peak concentrations. In practice, peak concentrations of H_2S mostly occur in the case of intermittent mixing, as a large amount of H_2S degasses suddenly from the digestion medium when the mixing starts. The use of continuous mixing may solve this problem, although examining the effect of mixing was beyond the scope of the current work.

The literature based technology landscaping identified that pre-treatments may be applied to increase the methane yield of lignin-rich substrates such as paper and card by removing some of the lignin and weakening cellulose-lignin associations. However, these methods are novel and are only just being tested in the field and therefore it is difficult to get access to their real costs and benefits to determine their value. The outcome of such a cost-benefit analysis will be highly dependant of the value and nature of the substrate considered but given the potential benefits of such pre-treatments in increasing the efficiency of digestion of otherwise difficult feedstocks, the further investigation of their costs and affects could be incorporated into a valuable subsequent project investigating high efficiency digestion systems.

Thermal Processes

Definition of the Testing Programme

The test programme for the advanced thermal waste processing technologies as defined in report 2.1 of this project was designed to provide the following information:

- The impact of changing waste mixtures on the major outputs streams – gas, tars and solid residues

- Preliminary mass balance data to inform element partitioning in the modelling work
- The chemistries of the major output streams to assist analysis of ancillary plant requirements (e.g. gas cleaning) and to identify high risk issues in the areas of engine reliability, environmental emissions and residue disposal, and
- Experience with processing real waste mixtures to identify process and operational problems

The technology assessment identified four main generic thermal process technologies based on pyrolysis and gasification which could be suitable for the processing of wastes. Of the possible variants of these technologies, it was agreed to carry out testing for the following four options:

- Fixed bed 'slow' pyrolysis
- Fixed bed, air blown up-draft gasification
- Fluidised bed, air blown gasification
- Fixed bed, air blown down-draft gasification

As indicated earlier, there were several priorities for the testing programme, which inevitably meant that compromises had to be made if a good spread of the areas requiring information were to be investigated.

The derived test plan is summarised in **Table 3**. Each waste material combination was proposed to be tested in each of the process configurations described above.

Table 3 Waste Mixtures used for Thermal Process Tests

Test Series	Sample Combination	Planned Ratio
0 (inc. Commissioning)	Demolition Wood	
1	Demolition Wood & High Density Plastics	50/50
2	Demolition Wood & Textiles	50/50
3	Textiles & Low Density Plastics	50/50
4	Paper and Card & Food	50/50
5	Paper and Card & High Density Plastics	50/50

To better describe their physical attributes and to aid differentiation, subsequent to Deliverable 2.1 high density plastics were re-labelled "dense plastics" and low density plastics re-labelled as "film plastics," although no changes were made to the material types which are covered by each of these classifications. The only alteration that was made when the test plan was executed was that the dense plastic element of Demolition Wood & Dense Plastics mix was substituted for film plastics to better represent a mixed construction and demolition waste stream, which would comprise mainly these energy bearing materials.

Whilst every endeavour was made to stick to this test plan, for reasons described in the appropriate section, it was at times found necessary to modify the ratio of the materials to enable a successful test to be carried out. However, for all tests a full laboratory analysis was made of the feedstock, and so comprehensive input and output data sets were compiled for all tests. Indeed, where the material ratios were required to be modified, important lessons were learned from the need for this change which could form the basis of engineering development opportunities.

Gasification/Pyrolysis Facilities

All of the thermal tests conducted at Cranfield University were based on two multi-configurable reactors. The updraft reactor comprised a vertical reactor of 150mm internal diameter which could be operated with gas injection through its base for fixed bed and fluidised bed tests. Rather than being refractory lined, this reactor was electrically trace heated to offset thermal losses through the walls. This feature also allowed the reactor to be operated in a slow pyrolysis mode without the need for the introduction of heat through the combustion of a fuel and recycled tars (as in industrial units). The same rig configuration was used for fixed bed gasification tests, but with air injection as the gasifying agent. For fluidised bed operation, the base of the rig could be changed to a conical one with central air injection and ash offtake.

The downdraft rig was operated solely as a downdraft (fixed bed) gasification rig for this project; this used a grate (as opposed to throat) to support the fuel bed. For all tests, the rig instrumentation and sampling locations were maintained for each of the rigs during all tests. Figure 1 and Figure 2 provide schematic diagrams showing locations for the updraft and downdraft rigs respectively.

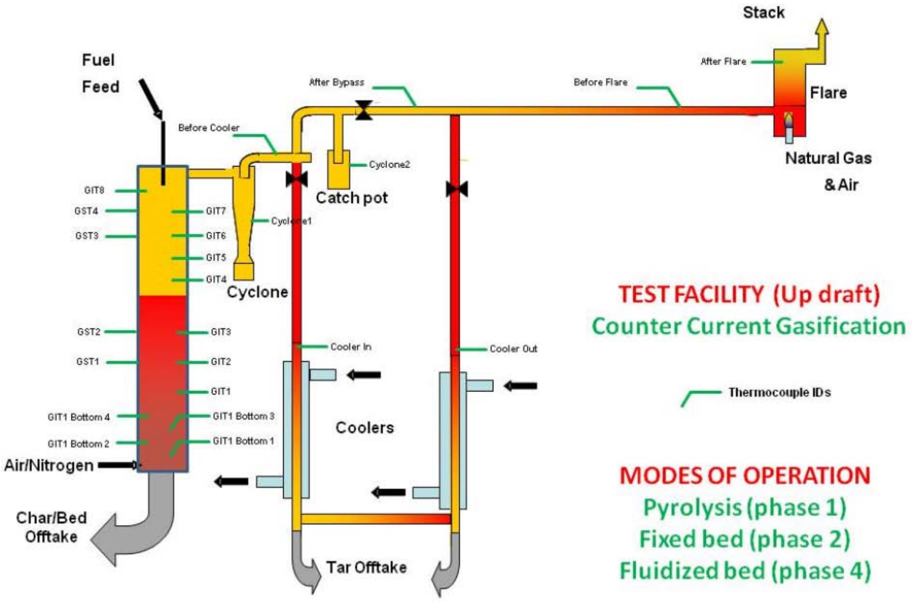

Figure 1 Schematic Diagram of Updraft Reactor for Fixed and Fluidised Bed Gasification and Fixed Bed Pyrolysis

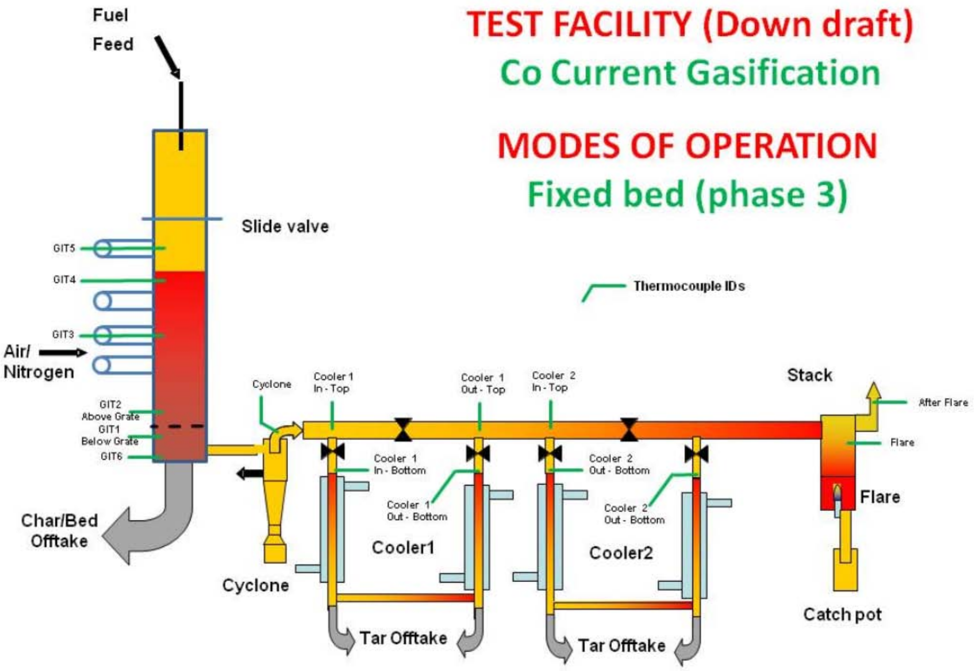

Figure 2 Schematic Diagram of Downdraft Gasifier

Analysis of Results

The experimental results for each waste feedstock mixture in each technology rig are collated in the detailed test report appended to this summary report. These test data include the proximate and ultimate chemical analysis of the feedstocks as well as the measured gas composition, gas contamination and chemical analysis of the bed residue and cyclone ash. These data were used to assess the implications of using these feedstocks in the technologies as discussed below, as well as to calculate mass balances and conversion efficiencies for each test as summarised in Table 4.

Table 4 Efficiency and calorific values for thermochemical tests.

		CV of gas produced [MJ/kg]	Gas efficiency* [%]	Carbon conversion** [%]	Mass Balance [%]	Tar contents [mg/Nm^3]
Pyrolysis	Wood	7.9	48.5	37.2	77.4	158450
	Wood & LDP	7.0	62.2	33.9	80.2	134590
	Wood & Textiles	4.4	19.2	16.4	74.5	281930
	Textiles & LDP	11.1	81.1	60.8	89.5	57610
	Paper & HDP	10.3	93.0	57.3	77.7	30930
	Paper & Food	10.3	91.3	47.9	73.8	4060
Updraft Gasification	Wood	4.6	22.0	49.1	71.5	21670
	Wood & LDP	7.6	91.1	90.8	75.0	22510
	Wood & Textiles	4.8	56.9	56.8	84.1	51910
	Textiles & LDP	3.6	8.3	88.6	95.4	49150
	Paper & HDP	2.9	18.1	91.0	84.5	52490
	Paper & Food	3.5	20.0	58.3	84.3	1510
Downdraft Gasification	Wood	4.9	51.8	89.0	97.6	22720
	Wood & LDP	3.7	27.8	91.6	89.3	5850
	Wood & Textiles	5.2	32.4	73.6	91.9	89120
	Textiles & LDP	4.4	13.2	48.2	82.5	12320
	Paper & HDP	3.6	14.8	60.3	89.9	20240
	Paper & Food	4.2	29.7	72.5	96.1	8700
Fluidised Bed Gasification	Wood	5.1	56.2	93.7	85.7	12350
	Wood & LDP	4.9	22.4	67.7	90.1	30880
	Wood & Textiles	4.6	51.1	94.7	88.7	29950
	Textiles & LDP	5.7	37.1	59.5	94.5	7340
	Paper & HDP	5.2	29.2	59.5	85.9	11440
	Paper & Food	4.4	33.4	70.2	87.6	7350

* Energy content of the gas produced as a percentage of the energy content of the feed

** The percentage of carbon in the feed converted into gas

Table 4 provides a summary of key process parameters for the thermal testing programme. Before discussing the data obtained, given the approach taken to the testing (which did not include any process optimisation or repeat testing unless basic criteria were not met), it is important to consider the quality of data available for further analysis. This quality review is illustrated in Table 4 using a "traffic light" system to compare the results obtained with what might have been expected from experience or available published data from similar tests with other fuels. In this, green indicates a "good" result (the results are comparable with the data found in literature), yellow represents some deviation from literature values, and red shows instances where the value obtained in testing was markedly different from a reasonable value for that parameter. Most of the red flags in Table 4 are related to the gas efficiency, in particular in the updraft and downdraft gasification tests. These results are questionable due to the presence of unburned fuel in the bed residues. Usually low values of the gas efficiency reflect low carbon conversion efficiency and a poor mass balance, as seen especially in the pyrolysis tests. The gas efficiency is an indirect measure of the tendency of the carbon to react with the oxygen and to form a syngas rich in CO, H_2 and CH_4. Low values of the gas efficiency will correspond to low syngas CVs.

The low values of gas efficiency in Table 4, especially in some updraft gasification tests (e.g. Textiles & LDP, Paper & Food, and Paper & HDP), reflect the low CO, H_2 (and CH_4) contents in the product gas. This could be due to two main factors: the process temperature and/or the equivalent ratio (ratio between the oxygen supplied in the process and the stoichiometric oxygen required for a complete combustion). In these cases, the gasification temperature was probably not sufficient to progress the gasification (i.e. the heat provided to the process was not enough to break all the chemical bonds in the waste materials and to promote and sustain all the gasification reactions). Also the equivalent ratio was probably too high or too low. In this situation, the oxygen supplied to the process promoted oxidation of the carbon in the fuel rather than the gasification reactions. Each waste fuel will have its own particular thermal conversion characteristics, and blends will have their own particular characteristics which are not necessarily a simple mixing of those of the feed materials. For example, we might expect that the mixtures of Wood & LDP and Wood & Textiles would show similar results, but we also have to consider that the results depend strongly on the parameters described above (temperature and equivalent ratio).

In summary, this review indicates that nearly all tests were acceptable in terms of gas CV and mass balance, but were further from optimum conditions with respect to gas efficiency and carbon conversion. This is not surprising as the tests were aimed primarily at obtaining preliminary gas composition data, with process optimisation limited to adjustment of the inputs of air and nitrogen to achieve stable gas compositions over a 20 minute period. As a result, in many tests (in particular the batch pyrolysis and updraft gasification tests), the bed residues would have comprised significant amounts of unburned feed material, inevitably leading to low gas efficiency and carbon conversion values.

As expected, and illustrated for each waste mix used in Appendix C, the gasification technologies produced large amounts of low CV gas and lower char/unconverted fuel residues compared to pyrolysis, which instead gave a higher CV gas and increased formation of tars due to the limited cracking reactions of the fuel components. Closely related to the gas CV values, are the corresponding gas efficiency values, which measure the percentage of the energy in the feedstock converted into fuel gas, and so are a measure of gas production. For the same extent of conversion, higher CV values will lead to higher gas efficiency values. Low gas efficiency values reflect either low conversion or dilution of the fuel gas produced, e.g. with nitrogen.

Carbon conversion is also linked to the CV values, and is an indicator of how much carbon in the fuel is converted into gas or tar. Traditionally, gasification technologies give better carbon conversion values than pyrolysis, because the more severe environment in gasification is aimed at converting fuel carbon by reaction with oxygen, steam or CO_2 to give CO and so these technologies have less carbon content into the ash, cyclones, and bed residue. Carbon conversion of 60% and above would be expected in the gasification of many fuels, and this has been achieved in most cases. Where this was not found, it is likely to be related to either specific characteristics of the waste mixes used or the premature completion of a test before the fuel bed had been consumed, making it difficult to estimate how much waste had actually reacted.

Analysing the data in detail, it can be seen that the high CV values found for the pyrolysis gases are due to their high H_2 and CH_4 contents. In addition to the inherent tendency of pyrolysis to produce high H_2 and CH_4 levels, this also reflects the use of indirect heating of the waste feedstock in the tests carried out (which used trace heating combined with a low flow of N_2 as a sweep gas), rather than by direct heating with hot flue gas from burning a supplementary fuel or recycled fuel gas or tars; both approaches are used in commercial systems. By comparison, the fuel gas CV values from the other technologies are derived from the combination of H_2 and the CO content of the gas. Gasification technologies mostly use air to oxidise the fuel and this leads to different chemical reactions than those producing the gases in pyrolysis. In general, low levels of CH_4 were generated for all the gasification technologies because the water-gas shift reaction was dominant over the slower methanation reaction. The water-gas shift reaction controls the equilibrium between H_2O/CO and H_2/CO_2 in the fuel gas. This equilibrium is driven towards high H_2/CO_2 levels by increasing the steam present in the reactor, from a combination of the fuel's moisture content, that from oxidation of H-bearing components in the feedstock or the controlled addition of process-derived steam. This latter approach is used commercially to adjust the chemistry of the fuel gas produced (and in utility-scale coal gasifiers to maximise CO_2 levels for pre-combustion CO_2 separation for subsequent storage). The fuel analysis (as presented in Appendix C) show typical values of 5-10% moisture present in the feedstocks, well within the range usually specified for gasifier operation.

Table 4 highlights that after detailed review, mass balance closures are mostly good, above 80%, with many above 90%, which represents a good overall result for the testing programme given the approach adopted. The mass balance calculation procedure is detailed in Appendix C to this report. The optimisation of test operating conditions (to achieve improved operation) and the re-evaluation of measurement methods (to improve the accuracy of results) through the repetition of tests was outside the scope for the thermal process testing in this project.

Although the tar concentration values listed in Table 4 are indicative of likely outputs from the feedstocks in each technology, it should be bourn in mind that these values are calculated from the volume of tars collected in the cooled chambers in the gas path of the rigs over the duration of each test. Due to the timeframe of the tests, it was not feasible to fully clean the rigs between tests, nor was this needed to achieve the required outcomes. As such, these measurements in the later tests may be affected by the operating history of the rig (e.g. tars condensed in the rig's upstream pipework in one test may be re-vaporised due to changed conditions and transported to the tar condenser in a subsequent test). Despite these limitations, a general impression of the level of tar production from each feedstock and technology can be obtained, with levels typically in the order of 10's of thousands of mg/Nm^3 of gas. These values are also widely reported from other sources, such as the Handbook of Biomass Gasification (Knoef [2005]). In determining acceptable levels of tar concentrations for downstream gas use, the condensation of tars is a cumulative process, and so any level of tars in the gas will cause degradation of the downstream equipment.

Although not included in Table 4, the waste mixes tested had mostly low (but variable) ash contents (less than 10wt%) and so are therefore suitable fuels for fixed bed gasifiers; high ash fuels can lead to problems in controlling the flow of the fuel through the reactor and disrupt steady gas production for which fuel-bed permeability is critical. Fluidised bed systems are more flexible in being able to handle fuels with higher ash contents, although agglomeration problems can occur if the ashes concerned have low melting points or can react with the bed material being used. However, with initial deformation ash fusion temperatures greater than 1140^{o}C in all cases, this is not likely to be a problem.

In terms of gas contaminants, the minor gas species were measured using Draeger tubes as this approach was most compatible with the timeframe for the testing. However, it should be noted that Draeger tubes have limited accuracy and their use proved difficult in some cases. While the emissions of these species are particularly important from an environmental perspective, they are also an indication of the gasification behaviour of the feedstocks, as their values are strictly related to the nitrogen, sulphur and chlorine content of the fuel; the higher the content of these elements in the fuel, the greater will be their emission in the gas produced.

Ammonia (NH_3) is the main product of fuel-derived nitrogen during the gasification process (along with lesser amounts of Hydrogen Cyanide (HCN) which could not measured). Similarly, Hydrogen Sulphide (H_2S) is the main product of fuel-derived sulphur during gasification process, with lower amounts of Carbonyl Sulphide (COS) (again not measured). Hydrogen Chloride (HCl) is the primary product of fuel-derived chlorine in the gasification process (although trace metals are often transported as chlorides in the product gas, depending on HCl levels), but in presence of free chlorine it can react to form other chlorine-bearing components such as dioxins.

NH_3, H_2S and HCl, if not cleaned from a fuel gas will result in engine emissions of NO_x, SO_x and HCl and so knowledge of the levels to be expected in service (and means of reducing these, if required) are critical for deployment. The test results indicate moderately high, though variable, levels of ammonia (up to 1000ppmv) for all fuels investigated in all tests. With some exceptions, the picture is similar for the H_2S values, although it was often not possible to measure the HCl concentration in the fuel gas due to the blockages in the Draeger tubes from the tars produced.

Finally, the trace metal species arising in the residues from the thermal processes were determined in the cyclone ash samples collected as these species can lead to process wastes which are difficult/expensive to dispose of to landfill, and can in some circumstances lead to engine corrosion problems, along with any alkali species which pass through the gas path (although these were present in low concentrations in the waste mixes). The post-test analysis of the cyclone ash collected in each test showed high levels of heavy metals such as lead, chromium, manganese, nickel, zinc, and copper in all the technologies and for all the fuels. These high values were derived mainly from the high concentrations of metals in the waste fuels, and to a much lesser extent from devolatilisation or erosion of metallic components within the system. By their nature, waste materials must be expected to have high concentration of trace metals, and so suitable control strategies will be needed to ensure safe and reliable operation while controlling operating costs. Where feedstock blends are such that high levels of trace metals would pass into the fuel gas, their removal to levels compliant with engine and emissions standards will be required.

Gas Engine

The efficient use of waste resources for energy generation requires the efficient and cost effective use of the produced gas to generate power (and heat). Internal combustion engines provide a low cost form of reliable power generation for a range of combustible gases, including biogas, which contains a high percentage of methane. However, the relatively high concentrations of H_2 and CO in gasification-derived gases present potential combustion challenges, and the use of these gases has not been well characterised in modern engines. To provide initial data on the operation of an engine on waste derived gases, tests were carried out with a single cylinder test engine using two gases with compositions representative of typical gasifier produced gases, but with very different combustion properties. The gas compositions tested are listed in Table 5 below:

Table 5 Gas Compositions of Gases Tested in Engine

Gas	Gas composition (%)					LHV[1] (MJ/kg)	LFS[2] (cm/s)	Stoichiometric A/F (mass)
	H_2	CO	CO_2	CH_4	N_2			
1	39	37	17	0	7	10.7	99.0	2.55
2	18	18	14	2	48	4.2	37.9	1.16

Gas 1 is based on a high Hydrogen and Carbon Monoxide gas with no Methane, and has a correspondingly high flame speed and flame temperature. As such this can be considered to be a "worst case" gas as regards engine operation. Gas 2 has lower proportions of Hydrogen and Carbon Monoxide, and includes a small amount of Methane. These gases were mixed by the gas supplier from pure component gases in the appropriate ratios, and hence were free from tars, particulates or other contaminants which are typically present in gasification gases and which could severely inhibit engine operation.

The tests, which are described in Appendix D to this Summary Report, showed that engine operation on gases comprised of varying proportions of H_2 and CO with adiabatic flame temperatures bounding that of CH_4 ("natural gas") is feasible. Using an engine configuration (compression ratio) designed for natural gas applications in conjunction with an optimised spark timing for the gas flame speed appears to indicate a thermal efficiency of 35% is achievable; it was beyond the scope of this work to examine whether the compression ratio could be optimised further, although this is likely to be highly fuel composition dependant, and hence difficult to define for "product gas" as a whole (due to wide range of compositions and properties this encompasses). The pictures and analysis of engine components post testing do show quite high levels of deposit formation, which appear to indicate increased service

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[1] LHV = Lower Heating Value

[2] LFS = Laminar Flame Speed

requirements when operating on these gases, although an accurate assessment of this impact would require longer term durability testing, which was beyond the scope of the present work. Similarly, the presence of tars, particulates, trace metals and other chemical contaminants (*e.g.* chlorine, sulphur etc.), as commonly found in product gases derived from waste material feedstocks, would be expected to have a highly detrimental effect on engine performance and longevity.

Implications of Outcomes from the Testing Programme

The studies reviewed in this summary report have highlighted a number of the expected issues with the use of waste materials (e.g. feeding problems, fuel bed sintering, etc) and identified the areas which will need further attention as part of a development programme for small-medium scale distributed energy systems using locally-available waste as a fuel source.

A review of the AD and thermochemical tests has shown that directing the ‘wet’ waste (food/agriculture-derived) to suitably-sized AD plants is a logical approach, although the addition of some bio-degradable paper and card may also be acceptable. On its own, paper and card provide only 40% of the biogas derived from food waste alone, and so any feedstock blending will reduce the overall output of biogas, which at best is around 29% of the energy content of the feed materials (i.e. >70% of the energy content of the waste is left in the AD residue). However, the use of a blend of paper & card with food waste is expected to be beneficial in terms of system stability and reduced H_2S production, if confirmed for continuously-fed systems and at larger scales. But, there is a limit to the amount of paper & card dilution of less than 20% before it affects the dry solids content of the mixture (i.e. the viscosity) and hence increases the power demand for stirring.

The benefits of adding components, other than food waste, into the AD blend is directly influenced by the choice between maximising the output of cleanest biogas and the overall gas output if the biogas production is in a combined system with syngas production from a parallel pyrolysis/gasificaion process, in which the AD residue is used as a feedstock. A detailed analysis of power and gas clean-up requirements is needed to identify the optimum way forward. A similar argument can be made with respect to NH_3 levels in the biogas from the alternative options of the mesophilic and thermophilic disgestion options. While the former provides the lower levels of NH_3 in the biogas, and hence leaves more N in the residue for soil beneficiation, if the residue is to be used as a pyrolyser/gasifier feed, then the combined system levels are more important. In these circumstances, where the AD plant is operated in combination with a pyrolysis/gasification plant, it will also be possible to consider the merits of using combined gas clean-up stages and so reduce capital costs.

It is also necessary to compare the capital costs of combined plants where there will be the option of directing the more digestible, non-food wastes to either an AD plant or to a pyrolysis/gasification plant which would be using the remainder of the waste fractions along with the AD residues. Further work is required to identify the optimum combination of plant components in terms of economics and environmental impact to handle the available mixed waste streams. In such an analysis, it will be necessary to assess the benefits of pre-treating the feeds to improve their conversion in the AD component as this will influence the overall outcome. The mixed food waste-paper & card thermochemical tests were also generally successful, after the food waste had been dried, so this provides an alternative option where an AD plant is inappropriate.

As indicated, the possible disposal routes or uses for the residual digestate need further study, including its use as a feed (dried or as a low proportion of a blend with other dry materials) for a parallel gasification plant. While the NH_3 levels in the AD trials were significant, as expected from protein-containing food waste, they were not problematic although were close to expected operational limits; this issue also needs further consideration.

As shown in the engine tests, gases with compositions/CVs similar to those produced in the AD and thermochemical testing (but following clean-up) are suitable for engine use. The range of gas compositions resulting from extremes of likely waste fuel feed blends suggests that all the gases will be combustible, but care will have to be taken to ensure that stable combustion in the engine can be maintained, e.g. as influenced by varying hydrogen levels. To avoid problems, and to assist in meeting varying load demands, any industrial scheme may consider the need for a suitable gas storage facility which will indirectly also assist in providing a mixed gas with a less variable composition. In addition, it may be considered worthwhile to blend the AD biogas with the fuel gas from gasification rather than use each gas separately, and so a gas storage facility will also aid this option.

The pyrolysis studies for the wide range of materials gave the expected high levels of H_2 and CH_4 in the gas produced, as well as significant tar levels as expected (noting the issue of accuracy of the tar measurements), although tar levels were high in the gasification tests as well. Tar recycling and further treatment/use (e.g. burning to provide process heat) remains a key issue moving forward.

The gasification tests proved that similar levels of gas could be produced for all waste feedstocks, and so variability of the waste blend with time should not be a major issue, provided the technology chosen and the associated ancillaries are sufficiently flexible to handle this variability. Gas compositions correspond well with waste fuel analyses and so an elemental approach to predicting gas compositions, and hence CV should be possible. Of the gasification technologies explored, both the fluidised bed and downdraft gave the best overall performance in terms of the practical issues associated with operation and the consistency of products produced and so are recommended for inclusion in future developments. The updraft testing did give useful results but these were more variable than those for fluidised bed gasification (partly due to the batch approach to the testing which may have shown the technology in a poor light). The industrially recognised versatility of the fluidised bed option, both in this testing and in the open literature, means that this is preferred for the medium-scale operation over the updraft option.

However, both of the selected gasification technologies are not without doubts over some of the data obtained and problems where the data does give a clear message. For future development, the following points should be recognised:

- Downdraft and FB gasification gave the lower tar levels compared to pyrolysis and updraft gasification, as expected. However, the tars remain a challenge which has to be confronted through their further processing (prior to disposal) or re-use/recycling (once dried) to provide heat for the gasification process. It will be necessary to separate the tars from water-based species and ensure that any recycled materials do not cause undesirable elements/species to build up in the recycle loop, e.g. trace metals. Combustion of tars (probably with recycled gas) to provide additional process heat is preferred over recycling directly to the gasifier which would be less effective in degrading the long chain hydrocarbons.

- Ammonia levels in the gas generated will lead to excessive NO_x emissions from the engine unless adequate gas cleaning is included. Reducing ammonia levels will involve a combination of optimising gasifier operation and the use of a suitable downstream clean-up step, e.g. wet or dry scrubbing. High ammonia levels are a common feature of fluidised bed gasification and considerable efforts have been devoted to finding solutions to the problem in the past. This effort needs to be continued if affordable and effective solutions are to be found.
- Hydrogen sulphide levels were generally low in the gas produced in the thermal tests. However, as the level of this gas will be directly related to the feedstock sulphur level, attention should be paid to what maximum levels might be experienced in future wastes, so that appropriate clean-up measures can be included. Also, the presence of H_2S in the gas will have implications for engine corrosion and possibly compliance with emissions levels. Several technologies exist for the reduction of sulphur species in fuel gases.
- Hydrogen Chloride levels were also low in the gases produced from gasification, largely due to low Cl levels in the waste feedstocks. As for hydrogen sulphide, care must be taken with respect to corrosion and emissions problems if the Cl levels in future waste feedstocks were to increase. The move to the recycling of PVC from segregated plastic wastes has had a significant impact on Cl levels; if this recycling were to become uneconomic for any reason, it would be essential to continue PVC separation to avoid the process problems indicated unless a suitably-sized clean-up stage is included.
- The issue of trace metals is difficult to resolve from the tests carried out. In the thermochemical tests, trace metals were measured in the cyclone ash and in the water and tars collected in the condensers; trace metals were not measured in the bed residues and attempt was made to collect any downstream of the condensers. As the cyclone in the thermochemical tests was trace heated, those collected there would have been in particulate form. However, many trace metals will form volatile species during gasification and so their appearance in the condensates collected downstream of the cyclone was expected. While no mass balances were attempted for the trace metals in the testing programme (this is notoriously difficult even in the best controlled pilot-scale tests), it is likely that most of what was present in the waste fuels and was volatile would have ended up in the water/tar mixture collected. In an industrial system, it is likely that condensation will be staged to separate water from tars and so the trace species may also be segregated. In addition, any passing this stage are likely to be mostly removed in any wet scrubbers used for cleaning other contaminants from the fuel gas. They would only pass through to the engine if a hot/warm gas cleaning strategy were to be attempted, and this is unlikely. So, care will need to be taken in identifying where potentially hazardous trace species may appear and what their impact would be on tar recycling or water/tar disposal.

In addition to the process data generated from the testing, one of the most valuable aspects of this project has been the lessons learned in using real waste materials in the tests. The waste materials tested were sourced from waste transfer sites and were pre-processed to a suitable physical form for the size of test rigs used. This pre-processing and the subsequent feeding into the reactors revealed important learnings which are also highly applicable to commercial energy from waste systems. These pre-processing problems and their solutions developed during this project may be viewed as provisional guidelines for future applications; these are summarised below:-

Fuel Preparation

- Most waste materials can be processed without major problems through standard shredding and milling (e.g. demolition wood and paper & card), but more intensive approaches (i.e. improved shredder design to give 25mm maximum dimension) can be needed to ensure that film plastics and textiles are reduced to suitable particle sizes to avoid equipment failure when they present as fibrous or stringy materials. Blending with the easier materials did not reduce the propensity for this to happen.
- Shredding power requirements differ between the components, with demolition wood being the highest due to the presence of nails, screws and hinges. Separate shredding of demolition wood and other waste components may be beneficial to reduce power requirements.
- No shredding was required for food waste, but may be necessary if contaminated with packaging materials. However, the water content of food waste means that drying may be required for pyrolysis/gasification applications where it is not blended with sufficient dry materials.
- Where food waste is to be used in AD plant, the separation of associated packaging materials is necessary.
- Pelletisation of some waste components (e.g. all except demolition wood) should be considered as it would assist blending, feeding and reactor performance. Further work is required to quantify the benefits and identify the optimum mixtures for pelletisation.

Fuel Blending

- Waste mixtures are generally stable and did not result in segregation in feed systems or in reactors
- Poor feeding behaviour can be resolved in part through careful blend formulation
- Of the available materials, it is likely that handling demolition wood and food waste as separate streams will be beneficial in controlling blends
- Blends also influence process problems such as reactor bridging, although care must be taken as individual components will react at different rates

Fuel Feeding

- Blockages can occur in screw feeders when oversize materials, in particular film plastics and textiles are fed (due to the presence of oversize strands of material wrapping round feeder components); in combination with improved shredding, redesigned feed screws (e.g. adjusted pitch) are needed.
- Blends with textiles can give variable performance in shredding due to their variable composition, with carpet residues proving the most difficult to feed due to their compressible nature which can lead to blockages and restrict the flow of blanket gas into screw feeders (to restrict syngas back-flow).
- Food wastes and similar materials can disintegrate and compress causing screw feed blockages; possible improvements include vibration devices to dislodge/break up blockages

at an early stage, non-stick coatings and improved screw design (e.g. optimised blade shapes).

Fuel Bridging

- Continuously-fed reactors with top feeders can suffer bridging due to adherence to reactor side walls; this is a widely reported problem for top-fed reactors at all scales. Bridging is influenced by the feedstock particle size, shape (interlocking forms) and moisture content (“stickiness”).

Considering the above issues, it is possible to rank the waste materials subjectively in terms of their generic ease of feeding, with 5 being the easiest and 1 the most difficult: Demolition wood – 5; Paper/card – 4; Dense plastics – 3; Film plastics – 2; Food waste - 2; Textiles – 1. Standards for ranking the feeding behaviour waste materials would be beneficial, leading to new monitoring and control approaches.

All of the above issues form a basis for further technology developments to enable more reliable and robust end-to-end systems to be developed, which should result in the ability to process a wider range of wastes and a lower final cost of generated energy.

The above technology implications of the thermal tests allied to the known challenges in fuel usage highlight the critical requirement for i) improved pre-treatment and feeding methods, ii) optimisation of processing conditions and iii) robust and cost-effective gas cleaning in developing advanced energy from waste systems based on gas-producing technologies. The following table provides a summary of the key findings and implications, and also provides preliminary options/recommendations for further consideration:-

Table 6 Key Issues from AD and Thermal Testing

Issue/Parameter	Findings	Technology Impacts	Technology Options/Recommendations
Waste Mixes	AD gave good performance as expected with food waste; the addition of paper/card may offer some process benefits. All pyrolysis/gasification technologies were able to process all feeds, but with varying performance – so all options are possible for waste mixes.	L - AD needs further technical development and should be focused on food waste, with or without paper/card as necessary to achieve the required products. M – selected gasification/pyrolysis technologies also need optimisation/ development – choice will depend on other parameters and required scale of operation. M – Variable performance could require gas buffer storage to even out output variability.	H – Optimisation of operation and definition of safe/reliable operating envelopes with selected technologies should be examined. H – Development of AD for waste feeds H – Further consideration of slow pyrolysis technologies needed as some variants should perform better than shown in test work. M – Consider the need/scale of gas storage required (also helps to de-couple gas production from electricity/heat demand).
Gas CV	Calculated gas CVs were broadly in line with expectations and reflected the C/H/O balance of the waste fuels. The CV of AD biogas depends on the mix of CH_4/CO_2.	H – Consistency of gas CV within a specified is essential for reliable system performance.	H – Need to define CV boundary conditions for different engine types. M - For the thermal processes, gas CVs can be improved through process changes if not suitable for current combustion engine use.
Gas Composition	Gas compositions varied between the thermal processes, with high CH_4/H_2 from pyrolysis and mixed H_2/CO from the gasification options. AD gave expected CH_4/CO_2 mix.	H – Variable gas compositions could lead to operational problems, e.g. high H_2 could cause flame speed problems/combustion instability.	H – Need to define safe envelope of gas compositions and compare with expected ranges from variable waste feeds. M - Gas compositions can be modified through process changes if needed to meet downstream process and engine requirements
Solid Residues	Gasification/pyrolysis residues likely to comprise unburned waste/unconverted carbon in all cases, the exact levels being process technology dependent. AD residues will be very wet.	M - Disposal issues will remain as they will probably be classified as hazardous – due to trace metals (should be low in sulphides). M – Carbon levels in residues may reflect significant energy loss M - Wet AD residues may lead to problems with use/disposal	M - Consider residue recycling to improve carbon utilisation. Char residues from mixed waste feeds unlikely to be suitable for soil improvement etc. M - If insufficient, consider post-processing/ combustion to extract lost energy and minimise disposal problems. M – Drying or blending of AD residues with the dry wastes for gasification/pyrolysis should be further explored.
Tars	High tar levels found in all pyrolysis/gasification cases, in particular for pyrolysis and updraft gasification as expected. FB and downdraft gasification gave the lower amounts.	H - Tars present a disposal problem as well as reflecting lost energy potential. FB and downdraft are the preferred technologies re tar levels.	H - Tar recycling or post-processing prior to disposal will need consideration. Could be used to provide process heat.
NH_3/HCN in gas	NH_3 measured/estimated in all pyrolysis/gasification tests. Levels were moderate in many tests, in particular FB gasification where higher than equilibrium values are common.	H - Resulting engine NO_x emissions if no reduction measures may be a problem.	H - Depending on standards, consider the impact on engine NO_x emissions. H - If needed, process changes should be explored to reduce NH_3/HCN levels. Alternatively, wet/dry scrubbing of the fuel gas will be needed. Low cost process improvements/gas cleaning essential for commercial viability.

H_2S/COS in gas	S levels were generally low in the separated wastes, with corresponding low levels of H_2S found in the pyrolysis/gasification gases. H_2S levels in AD biogas may be significant if using only food waste.	L - Generally not an emissions problem issue, but need to keep a watch on levels in separated waste, and may need to blend if required to reduce levels to comply with emissions standards. S-species retained in solid residues will mostly be present as sulphides leading to potential disposal problems.	H – Investigate solid residue sulphide contents H – If needed, consider post-processing to convert to sulphates to avoid high cost waste disposal.
Trace Metals	Trace metal levels in cyclone residues from pyrolysis/gasification reflect levels in waste mixes. Not measured in AD tests, but are expected to be retained in digestate.	H - The significant levels of trace metals in the separated wastes represent a significant challenge (as experienced in waste incineration).	H – Investigate waste types with high trace metals – consider their exclusion or develop suitable blending strategy to avoid exceeding limits.
Waste Fuel Feeding	Pre-dried/hand sorted waste mixtures were used in the testing work. Even so, feeding problems arose, particularly with the textiles which were variable in form. In all continuous processes, fuel feeding has to be done through a sealed system to avoid gas leakage. Screw feeders with agitation worked well for FB gasification. Gravity flow of the fuel bed in fixed bed (updraft/downdraft) systems caused occasional problems – which could lead to operational problems (e.g. varying permeability) with these highly variable waste mixes.	H - Careful control of waste mix 'quality' will be required along with sorting/screening in some cases.	H - An ability to blend referred mixes from available separated supplies will help to minimise this requirement. M - Further pre-processing (e.g. pelletising) may be needed with some waste components to ensure smooth feed blending and process operation.
Process Operability	AD, FB gasification and downdraft gasification gave the smoothest operation with waste fuel mixes, although some fuel flow problems were experienced in the downdraft tests. Agglomeration of waste components in the process reactors and deposition of tars/condensates are common problems with all gasification technologies and some instances of these occurred in the testing work.	H - In principle, the technologies giving smoothest operation across all waste mixes tried cover the required scales for commercial development, but other technologies may still be preferred in specific instances where the waste mix available is more suited to them.	L – consider alternative technologies for specific applications

Note: H = High, M = Medium and L = Low

Development Opportunities

Process Improvements

Improving the robustness and efficiency of the technologies investigated in this work will help to decrease the cost of energy generation, as well as improving their flexibility and reliability, thereby enabling their commercial application. From the experimental work, a number of specific technology development opportunities can be defined which would enable a more robust application of the technologies, as outlined below:

- Optimisation of AD feed combinations and reduction of biogas H_2S contamination, possibly through innovative waste feed material mixing to control the digestion rate
- Cost effective and reliable waste size reduction for segregated and combined waste components where necessary
- Thermal reactor feed system development for range of waste materials, possibly targeted to a certain reactor type
- The controlled use of feedstock blending to optimise performance and constrain emitted contaminants to within engine and environmental emissions limits
- Thermal process improvement to give increased conversion efficiency through improved reactor design and the use of alternative oxidants, e.g. steam, CO_2 and O_2-enriched air (although this would require the development of small scale, low cost air separation units which would be an enabling technology development in its own right)
- Optimisation of thermal process parameters to maximise carbon conversion/gas CV, while reducing/controlling tar and NH_3 production from mixed waste feeds
- The recycling of tars (e.g. to provide process heat) or their cracking to improve conversion efficiency
- The use of CO_2 separation (in-process or downstream solid sorbents could be a possible approach) from the fuel gases to improve syngas CV and provide CO_2 for process use
- Innovative, affordable/low energy integrated gas cleaning approaches to reduce residual contaminants in fuel gases such as NH_3, HCN, H_2S, COS, etc. Such schemes may involve smart use of particulate filtration with injected solids and the use of catalysts

These development opportunities complement those identified from the modelling work carried out for this project (Deliverable 3.3). The benefits from carrying out the most promising developments to enable the deployment of high efficiency energy from waste systems will be discussed in Deliverable 4.2 of this project.

System Development

As may be implied from the technology landscaping, the testing and the preliminary development opportunity identification carried out for this project, a great number of technologies have been developed, or are under development, aimed at improving system robustness. Whilst many of these technologies have been developed for biomass-based systems (both AD and thermal), they are mostly also applicable to energy from waste systems. A major barrier in the development of these systems is the multitude of configurations which may be realised through different combinations of pre-processing, processing and post-processing technologies, before the fuel gases or liquids are used for power and heat applications. This is especially the case for waste feedstock materials, the characteristics of which have been shown in the test work reported here to influence the gases and liquids produced, and hence their post-processing requirements. As such, the component technology development opportunities identified in this report are those which address the identified technical challenges, although their impact on commercial system performance, and hence their true value, is the subject of ongoing project work.

To investigate real world system performance, a key next step would be the development of a multi-configurable system test facility. The specification of such a facility would need to be defined in light of the modelling aspects of this project and the final benefits case, but the development of such a facility would enable technology demonstration and de-risking, facilitating the wider exploitation of waste materials for efficient and low carbon energy generation.

Conclusions

The testing programme reviewed in this summary report was originally intended fill in gaps in available data in the public domain relevant to the technologies which could be employed at each stage of an advanced energy from waste system. However, it was found that only very limited suitable data were available on the operation of AD and Gasification technologies using the mixed wastes, and so it was necessary to carry out a more fundamental study to determine the suitability of these technologies for use with highly variable mixed waste feedstocks.

For reliable system operation, it is essential to have an understanding of the properties of the fuel gases produced and their contaminants, as well as information other process products/residues and any operational problems which would need to be overcome. The novel test work conducted for the ETI Energy from Waste (FRP) project has provided valuable insight into the use of these technologies with mixed waste streams and empirical data to inform the development of computer-based models of advanced waste processing technologies.

AD of food waste and food waste/paper/card mixtures was successful although those attempted with paper/card alone showed low gas production volumes. There is a clear operational limit to the amount of feeds used other than food waste due to viscosity constraints on stirring power requirements of around 20%, although this will vary with the type of added waste. Therefore, in general, it is clear that where possible dry wastes are better processed by other means.

The benefits from using non-food wastes in AD must also be considered in the context of whether the AD plants will be used alone or in combination with parallel pyrolysis/gasification units. In such circumstances, the optimisation of the overall combined system in terms of biogas amounts, H_2S an NH_3 levels is the priority. However, where there is a clear market and hence value for the AD residue, e.g. soil beneficiation, this is likely to prove the preferred option and so biogas cleanliness will be the main priority. The benefit of the decreased biogas H_2S levels by the controlled inclusion of paper/card will also only be beneficial where the biogas is to be used in isolation and not combined with syngas form other parallel pyrolysis/gasification units.

Furthermore, the stabilisation effect of the inclusion of paper and card may allow the process to operate under more efficient thermophilic conditions. Although the nature of such interactions would require further investigation, the initial data suggest that plant capital and operational costs could potentially by reduced if input materials were mixed, by allowing savings elsewhere.

The thermal testing programme met its main objective in confirming that it was possible to process mixed wastes of widely varying composition using thermal gasification/pyrolysis technologies. In addition, highly relevant waste feedstock and thermal process information were obtained to identify likely problem areas for future development and to inform the process modelling activities in the project.

Feeding and operational difficulties experienced during these tests emphasised the need for affordable pre-processing to produce a more homogenised feedstock. This emphasises the need to design any selected process as a complete system, from waste reception through to electricity/heat generation and emissions/residue control. The careful design of waste pre-processing, handling and feeding is just as important in delivering a reliable plant as the design of the main reactors or gas cleaning systems. The data gathered, in conjunction with the subsequent modelling work, provide a platform from which to estimate the compositions and properties of the gases and tars generated from different processes along with the requirements for gas cleaning (e.g. removal of NH_3, H_2S and HCl) to avoid excessive emissions (of NO_x, SO_x and HCl) and downstream engine problems. In addition, data on the distribution of hazardous species and trace metals in the various residues provide a basis from which to develop/select further treatment steps prior to safe disposal or use.

Both the AD and thermal tests showed a direct correlation of gas contaminants to their pre-cursor levels in the waste feedstocks. The nature of the materials in the mixed waste streams from domestic, commercial, industrial, construction and agricultural activities is such that a wide range of low volatility (tarry) and potentially corrosive elements and compounds are liable to be present in any gases derived from waste materials. For other contaminants, e.g. trace metals, information was obtained on partitioning between the various product and residue streams.

A summary of the main considerations for each of the technologies operating with mixed waste materials is presented in Table 5.

Table 5 Summary of Process Technology Conclusions

Technology	**General Considerations**		**Findings from Testing Programme**	
	For	**Against**	**For**	**Against**
AD	Wet biodegradable wastes; right scale	Limited fuel options.	Good with food waste; possible to include paper/card	H_2S levels
Updraft Gasification	Simple technology; right scale	High tar levels; operation dependent on fuel properties	Problems with some fuels	Low/medium CV gas; high tar levels
Downdraft Gasification	Simple technology	Small scale only; operation dependent on fuel properties	Few operational problems	Low CV gas;
FB Gasification	Flexible medium scale technology	More complex equipment & operation	Fuel flexible; moderate tar levels; few operational problems	Low CV gas; high NH_3; risk of agglomeration
Slow Pyrolysis	Simple technology;	Operation dependent on fuel properties	High gas CV – high CH_4 and H_2; some operational problems	High tar levels

These considerations identify fluidised bed gasification as the most suitable technology. Downdraft gasification also demonstrated merits for smaller scale plants with waste streams of defined properties, but is restricted in scale-up due to difficulties in maintaining steady/uniform gas flows as the fuel bed cross section increases. It should also be noted that the slow pyrolysis testing did not cover the range of technology options available for this process and so further consideration should be given to this option.

The operation of a reciprocating engine with clean gases of typical compositions as would be expected to be produced from of waste materials has been shown to be feasible. These tests show that a relatively high engine efficiency of 35% can be achieved without further optimisation, if the fuel system, engine hardware and operational parameters are appropriately designed. However, tars and other contaminants present in the gas from gasification processes would be expected to adversely impact engine performance, increasing engine service intervals and durations. This would thereby increase the cost of energy produced, ultimately impacting the realisation of the CO_2 emissions reductions which could be enabled.

The findings from the testing programme, in relation to the processing and gas utilisation technologies, reinforce the critical importance of i) reliable fuel feeding and ii) affordable cleaning of the gases produced in enabling successful high efficiency, energy-from-waste systems. Although not distinct areas of investigation within the current project, it is expected that the key development opportunities required to enable the efficient use of waste materials would be in the areas of feeding and gas cleaning. To explore the opportunities here, a follow-on piece of work is under consideration to identify where the best opportunities lie for the UK.
The development of an integrated system whereby dried digestate from AD is used as a partial feedstock to a gasification process and where the AD biogenic methane-based gases are combined with the H_2/CO based gasification gases for efficient power generation is another opportunity for development. Such a system could provide a holistic waste treatment solution

whilst maximising the energy recovery from the variable and mixed wastes, although the integration of each of these technologies has not yet been carried out and would require considerable de-risking for market deployment.

References

Knoef H. A. M., “Handbook of Biomass Gasification”, Gasnet/Btg, 2005
Lettner F, Timmerer H, Haselbacher P “Biomass gasification – State of the Art Description”
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Appendix A - Project In and Out of Scope

Below is a list of agreed items and technologies that are not included within scope of this project:

- Waste testing (sampling) will only cover waste available at Shanks sites
- Hazardous waste, clinical waste, radioactive etc.
- Non energy bearing wastes
- Waste currently in Landfill – all waste will be collected pre-landfill
- Off-site waste preparation – sorting and separation
- Materials flow, energy use in sorting machinery
- Energy from landfill
- Current gas capture from landfill, uncaptured landfill, landfill gas, landfill gas processing technologies, waste already landfilled
- Recycling processes
- Sorting of recyclables, processing of recyclables, energy trade-off with recycling processes, recycling trade-off with raw material production, waste reduction, materials re-use
- Incineration/combustion
- Technologies, energy recovery using steam power generation as primary generator
- Technologies or systems with capacity for power generation <100 kWe, >10 MWe or equivalent materials throughput

Appendix B – Report on Anaerobic Digestion Testing

Appendix C – Report on Thermal Process Testing

Appendix D – Report on Gas Engine Testing