Programme Area: Bioenergy

Project: Energy From Waste

Title: Energy from Waste Appendices

Abstract:

This document includes Appendices A and D-H of the Energy from Waste UK Benefits Case (Deliverable 2 of 2 in Work Package 4).

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

Energy from Waste

UK Benefit Case

Appendices Deliverable 4.2

Prepared for the Energy Technologies Institute

Distributed Energy Programme

July 2011

Appendix A: Summary of Work Packages

Appendix B: AEA Energy from Waste Technology Landscape Review

Appendix C: CARE Energy from Waste Technology Landscape Review

Appendix D: Modelling user manual for WP4

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Appendix A: Summary of Work Packages

Work Package	**Waste Assessment (WP1)**
Project lead organisation	Cranfield University
Project team members	Cranfield: Phil Longhurst, Stuart Wagland; Shanks: Stephen Wise; CAT: Zane van Romunde, Bryan Silletti; EDF/EIFER: David Eyler; CPI: Graham Hillier; AEA: Adam Read;
Aims	The purpose of WP1 is to define the overall market potential for energy from waste. The overall EFW project benefits are based on the foundation of recommendations determined from the availability of material waste streams and the opportunity for the UK to make use of these for energy. Therefore WP1 sets out to define the current knowledge for UK data on wastes that have the potential to produce energy, either thermo-chemically or biologically. To then specify the need for and produce; a new, extensive and robust analysis of data from waste samples, to inform the evaluation and design of EfW technologies.
Methodology	The WP set out a programme of work to collate the most up-to-date information available on waste arisings in the UK that have a fuel value. The work drew together two main sources of information; existing data sets and waste sampling with the main stages being as follows: 1. To collate and assess existing data 2. To specify the additional data that needed collecting 3. Develop a sampling method and experimental design to maximise the opportunity for new data for the most relevant areas 4. Sample waste from differing sources 5. Prepare a defined sample of waste for chemical analysis 6. Undertake waste chemical analysis 7. Report on initial waste compositions 8. Report on total waste data and compositions Seasonal sampling of wastes was undertaken throughout the study. The results from WP1 are recognised as being the foundation to the analysis and assumptions used for the further work packages. For this reason; an ongoing review of reports of waste analysis from other organisations was maintained, close links with the Defra waste and evidence team were established, and most importantly, information on the wider supply and market for UK waste was exchanged with Shanks, the industrial project partner.
Main findings	The first stage of the work considered all waste sources; municipal solid wastes [MSW], commercial and industrial [C&I], construction and demolition [C&D], agricultural and all other forms of dredgings, sludges and silts. The first results showed that the highest priority should be paid to the C&I waste streams which had the highest volume, highest calorific value and least information available about composition. MSW and C&D also had relevant fuel values, as did agricultural wastes though these were comparatively low in volume and considered to be more problematic to recover from farms. WP1 findings show that up to 70% of C&D wastes by weight is inert, i.e. material that is not biodegradable and of no energy value. C&I wastes were observed to contain higher quantities of paper and card than MSW thus increasing its calorific value. Recycling targets related to MSW and policies relating to the MSW and C&I waste streams cause these differences. These two waste categories contain large quantities of film plastic, which yields the highest CV of all components analysed [39,000 kJ/kg]. Potentially recyclable materials present in the residual wastes, in particular

	those in the C&I sources are important. Plastic materials contribute significantly to the CV of the overall material. As the proportion of these materials are policy and economically driven understanding future recycling trends is important. The economics of recycling plastics or recovering energy from materials has been compared. It was concluded that where both heat and electricity is recovered and exported it is economically favourable due to the increase in overall efficiency to recover the energy. However, where only electricity is recovered in a typical incinerator, e.g. moving grate it is more economically favourable to recycle the plastic. Many recyclable materials, such as plastics and paper, cannot be continuously recycled due to the degradation and/or contamination of the materials as they are reprocessed. As a result, there will always be 'recyclable' materials within the residual stream. To achieve higher recycling rates of up to 70% for C&I wastes, approximately 90% of the paper, card, dense plastics, glass and metals will need to be removed from the residual C&I stream. Recycling is a first option which will remain for as long as it is practically and economically viable to do so. The environmental impacts of recycling and/or energy from waste is recognised as important, and further work is required to enhance the current understanding, alongside a review of existing data. Within WP1 an innovative image analysis tool was developed as part of this project. This has shown potential as an alternative method of monitoring waste composition. Additionally analytical methods developed at Cranfield University could be utilised in understanding the biogenic carbon content of heterogeneous waste materials, which is useful for the allocation of renewable obligation certificates [ROCs].
Deliverables (reports)	Reports 1.1; 1.2, and1.3
Contact details	Phil Longhurst, p.j.longhurst@cranfield.ac.uk, 01234 754953; Stuart Wagland, s.t.wagland@cranfield.ac.uk, 01234 750111 ext.2404.

Work Package	Technology Assessment (WP2)
Project lead organisation	Caterpillar, with testing conducted by Cranfield University, EIFER and Caterpillar
Project team members	Caterpillar: Zane van Romunde, Stephen Neeson, Arnold Kim Cranfield: John Oakey, Kumar Patchigolla, Giacomo Peligrinisusini, Stuart Wagland EIFER: David Eyler CPI: Graham Hillier; Steve Donegan
Aims	The purpose of work package 2 was to identify the component technologies which may be combined to produce and end-to-end energy from waste (heat and power generation) system capable of higher total conversion efficiencies than the incumbent solution, thereby enabling reductions in the CO2 (and CO2e from methane) produced by wastes. The actual operational performance of key component technologies was to be established using waste mixtures representative of UK waste compositions identified in WP1. This was to be achieved through rig scale testing of the technologies using collected waste samples, including their inherent variability. The performance of the technologies using wastes (and waste derived products) was to inform the modelling work conducted in WP3 and benefits case in WP4.
Methodology	An initial literature review was conducted alongside utilisation of consortium member and project stakeholder knowledge to identify suitable technologies for further investigation. At a system level, these were grouped into pre-processing, processing, post-processing and power generation. Emphasis was placed in technologies applicable to mixed wastes, to maximise total efficiency including waste sorting and separation (outside of project scope). The technology assessment and subsequent proposed test plan are presented in Deliverable 2.1. Following technology identification, waste material mixtures were tested in small scale rigs for: downdraft, updraft and fluidised bed gasification, updraft (slow) pyrolysis and Anaerobic Digestion. Engine tests were also carried out on two clean gases with compositions representative of the boundaries of flame speed (engine limits) of gases which may be expected from the gasification of waste materials. Gasification tests were carried out by Cranfield University, AD tests by EIFER and engine test by Caterpillar. The Anaerobic Digestion tests were carried out using three different techniques to investigate the biogas yield and the H_2S (contamination) concentration, as well as a set of validation tests. The results from the tests and ensuing conclusions are presented in Deliverable 2.2.
Main findings	The technology assessment conducted for this WP indicated that increases in efficiency of energy recovery from waste are theoretically possible. Current energy recovery from waste (beyond landfill gas capture) is largely based on waste combustion to raise steam for steam turbine power generation. Whilst this is recognised as a robust energy recovery technique, limitations in the theoretical efficiency of the Rankine (steam) cycle limit the maximum electrical energy that may be recovered using this technology. Higher system efficiencies may be achieved through the conversion of the raw feedstock to an alternative fuel source, and then utilising this fuel in an efficient combustion engine, such as a reciprocating engine or turbine. Conversion processes applicable to wastes include gasification and pyrolysis (thermal processes) of low moisture content materials and anaerobic digestion of high moisture content materials. Whilst these

	process technologies are well developed for characterised, segregated materials, their performance and application to variable mixed materials has been less well characterised. In addition, the utilisation of gasification derived gas fuels in gas engines has been reported to pose potential issues associated with the hydrogen and carbon-monoxide based composition, which alter the combustion properties from that of usual methane based gases. The test work found significant issues associated with the pre-processing and feeding of the materials into the reactors, although some of these were a function of the scale of the rigs and their "standard" feeding equipment not necessarily optimised for feeding mixed wastes. In terms of the processing, all the thermal technologies were eventually tuned to process the low moisture content wastes, although the range of thermal degradation properties from material mixtures was found to cause some process issues, especially regarding pyrolysis. Overall, the fluidised bed reactor was found to be the most stable and controllable on a variety of waste mixtures. As expected, downdraft gasification was generally measured to produce the lowest levels of gas tar contamination, and hence was suggested for further consideration in WP3 for smaller scales. The anaerobic digestion of food and paper and card was found to be successful in a range of mixture proportions, with the food waste having a considerably faster degradation (and hence biogas production) rate. The inclusion of a small amount of paper and card was found to reduce the food's initial degradation rate, thereby reducing the level of H2S produced in the gas, although the commercial implication of this would require further validation testing. Gas engine tests were successful with both high and low flame speed gas compositions (H_2 and CO based gases), achieving an engine thermal efficiency of up to 35%.
Deliverables (reports)	Reports 2.1 and 2.2
Contact details	Zane van Romunde, 01733 583987, van_romunde_zane@cat.com John Oakey, 01234 754253, j.e.oakey@cranfield.ac.uk

Work Package	**Technology Performance and Assessment (WP3)**
Project lead organisation	Centre for Process Innovation (CPI)
Project team members	CPI: Graham Hillier, Steve Donegan, Gustavo Valente, Callum Wilson, Jonathan Kearney Azhar Juna, Cranfield: John Oakey, Stuart Wagland; CAT: Zane van Romunde, Bryan Silletti, Jalaja Repalle
Aims	Technology Performance Modeling and Assessment – The technology performance data collected in WP2 in relation to the wastes assessed in WP1 was modeled at an end to end system level. These models were used to assess systems for overall performance potential. The models were optimised to incorporate the identified technology improvements to determine their impact on system performance. Four sub-packages were undertaken: 3.1 Model Selection and Validation 3.2 Initial System Modelling 3.3 Modelling of Optimised Systems 3.4 Patent Search
Methodology	This Work Package identified the identified technology improvement opportunities for Energy from Waste technologies through a systematic approach of empirical modelling of the waste and technology data collected from Work Packages 1 and 2 combined with actual operating data. The aim was to model systems built up from component models integrated into systems. Over 18 component models were developed in Lotus and Matlab and initial integrated systems models were run. However it was found that there was a lack of definitive data from published sources, practical results and the WP2 trials that would allow the integrated model to function effectively. As a result the model element data was used to create the set of Energy from Waste technology systems for further study. These systems were built to assess EfW at the scale of typical communities and were used to model and assess technology systems so that structured recommendations for significant, measurable improvement on the current technologies and Energy from Waste systems could be made. Throughout the process, a systematic protocol (including independent validation) was used to ensure that the models were as reliable and robust as possible. The component models were produced and handed over, the integrated community based system models were also completed and handed over. The systems model has formed the core of the WP4 benefits package models. Reports were produced on the component models, on model development and on Technology System Opportunities and this was the main deliverable of the Work Package. 3.4 was modified to be an independent technology assessment report that looks at operating gasification and anaerobic digestion facilities and their level of commercial operability.
Main findings	The system model was produced and was used to assess the economics of different technology configurations relative to the waste disposal and CO_2 emissions reductions relative to a baseline of mass burn incineration. This assessment indicated the technological developments that could decrease the cost EfW and deliver emissions reductions as well as define system performance by process scale and hence population centre size. Over 18 engineering component models were developed and integrated into a system level model that represented different configurations of end-to-end energy from waste systems. The system model functions appropriately, although with a number of discrepancies. The discrepancies appeared to come from the test and industry data and further generic data are required for an automated integrated system model. The integrated model based on

	community scenarios were developed using input from the component models and practical operating experience. These simple robust models were used to develop integrated systems models at the scale of a city, town, village and rural community. The outputs from these models were used, in collaboration with those from the industry and the technology development community. Technology development opportunities were identified with operating, financial and emissions parameters identified. This work has identified targets for technology improvement. The areas selected for development were low cost gas clean-up gasification, incineration and anaerobic digestion at scales that are appropriate for the towns and smaller communities. These proposals are reflected in WP4 and the WP4 models have been built on the findings of WP3. Additional findings indicate that gasification with chemical production can add considerable value and there are opportunities for technology development on all scales,
Deliverables (reports)	Over 18 excel and matlab component models. Community scenario models for cities, towns, villages and rural communities that can be reconfigured and rerun with different forecast or measured data sets. Reports 3.2; 3.3 and two technology review publication.
Contact details	Graham Hillier, grahamhhillier@uk-cpi.com, 01642 447293; Steve Donegan, steve.donegan@uk-cpi.com, 01642 443641.

Work Package	UK Benefits Case (WP4)
Project lead organisation	EDF Energy
Project team members	Laurent Mineau, Gary Bond, Paul Howell, Tom MacDonald, Damien Zachlod, Freya Phillips, William Hetherington, Kemal Ahson
Aims	To determine the benefits to the UK with the commercial deployment of the identified TDOs from the previous WPs. The WP provided recommendations to inform the ETI strategy and identified future projects. The two primary objectives of WP4 included: • Propose to the ETI, in the form of a memorandum [Deliverable 4.1], the framework for the project delivery and the technology evolution criteria that the technologies will be assessed against, • Enable the ETI to determine and quantify the cost, impact and opportunity for identified technology development opportunity on UK CO_2 emissions, affordability and security of energy supply, waste landfill reduction, current and potential TRL score and acceleration potential, as well as any potential subsidiary benefits.
Methodology	Led by EDF Energy the work examines the benefits to the UK with the commercial deployment of the identified TDOs and compared these against technological, environmental and economic factors of the current EfW opportunity. The first stage of the approach to deliver WP4 sought to agree the framework for the delivery of the project and the UK Benefits Case. Deliverable 4.1 – Framework for Project - was developed in the form of a MEMO established the criteria to evaluate the 'Benefits and costs of system improvements' – deliverable 4.2.1 – and the Analysis of the Benefits of Energy from waste opportunity in the UK – deliverable 4.2.2. The agreed framework was disseminated to the ETI and the project consortium on the 09th November 2009 and is presented in appendix X. The second stage of the approach to deliver WP4 integrated the findings of WP1, WP2 and WP3 in order to assess the benefits and costs associated with the individual development of the identified TDOs against the agreed evaluation criteria: affordability, CO2 reduction, energy security, and robustness. EDF Energy, after validation by the ETI, elicited from the published WP1, WP2 and WP3 deliverables through review and their contributory authors through interview both qualitative and quantitative data to develop a credible benefits case, providing recommendations to inform ETI strategy moving forward and identify future projects. The qualitative data allowed the development and presentation of several TDO against the specification outlined in 4.1 and evaluation against robustness and energy security. The quantitative data allowed the assessed technologies – incineration, gasification and pyrolysis – to be evaluated against the CO^2 reduction and affordability criteria. The final version of the UK Benefits Case was agreed by the consortium after the development of several drafts. The drafts of the report were

	critically reviewed by the ETI and the consortium and through several iterations and a final review at a specially convened workshop on the 24th March 2011 consensus was achieved amongst all of the project actors and stakeholders. The final consortium approved UK Benefits Case was forwarded to the ETI on the 31st Match 2011.
Main findings	The project has identified several TDO for further development detailed in the Benefits Case report. These TDO lend themselves to the appraisal and development of several demonstration projects.
Deliverables (reports)	4.1 - MEMO 4.2 – UK Benefits Case
Contact details	laurent.mineau@edfenergy.com M: +44 (0) 78 7511 0052

Appendix B: AEA Energy from Waste Technology Landscape Review

See attached report

Appendix C: CARE Energy from Waste Technology Landscape Review

See attached report

Appendix D: Modelling user manual for WP4

This guide has been produced to support third party access and modifications to the UK benefits case model and should be read in accordance with this.

Where a worksheet tab is referenced it will be 'within apostrophes'

Assumptions

'Assumptions Master'

This tab includes all of the core assumptions for the emissions and financial assumptions. For each assumption there is a source, description and value (one for each community scale).

The assumptions are linked through to the rest of the workbook; changes made here will affect the scenario scales and summary output.

Emissions

'City', 'Town', 'Village' and 'Rural'

The above tabs are the first building blocks for the emissions modelling output where the assumptions are used to generate scenario scale outputs. The only differences between these tabs are the assumptions used in the calculations which are identified by the appropriate column in 'Assumptions Master'.

Each scenario scale tab processes the assumptions and identified waste data, in accordance with the following steps for each waste treatment process.

1. Transport to site
2. Pre-processing
3. Processing
4. Product conversion
5. Transport of by-products to landfill

Transport – emissions for transport are related to the number of miles a vehicle would need to drive, which is then converted into equivalent carbon dioxide emissions

Pre-processing – collates emissions from power consumption (converted to carbon dioxide equivalent) and any direct emissions from any waste transformation that is necessary.

Processing – Uses assumptions to derive direct emissions from processes, in the case of closed systems (gasification) the emissions from this stage are carried forward into product conversion.

Product conversion - Uses assumptions to derive direct emissions from the conversion of waste treatment product into saleable end product.

Landfill –The steps governing the landfill emissions are as follows

1. Transport to landfill
2. Decomposition into landfill gas
3. Calculate captured and lost landfill gas
4. Calculate emissions from the combustion of captured landfill gas

The resulting values for each process and each scenario scale provide the total emissions relating to the treatment option, these values are then carried forward into 'Summary Output'

Financial

The financial modelling uses the assumptions on 'Assumptions Master' to create scenario scale lifetime cash flows. These cash flows are then discounted to a net present value for the purposes of investment appraisal. The cash flows considered are;

1. Initial capital cost to setup the facility
2. Ongoing operating costs
3. Revenue from feedstock acceptance (net of transport cost)
4. Revenue from the sale of valuable products and by products

The resultant NPV values are carried forward to 'Summary Output'

'Summary Output'

Here the scenario scale values described above are pulled together. Various metrics are calculated from these core values in the lines beneath.

From Line 56 down in 'Summary Output' the scenario scale values are scaled up to a UK case. This is achieved by working out the number of plants that would be required to fulfil the total UK waste for each scale. The previous scenario scale values are then factored up by this number of operational units to give a view of a total UK case.

'2030 Scenarios'

This tab allows for a degree of dynamic modelling by allowing the user to generate data sets with varying assumptions. The changeable assumptions are highlighted in grey and comprise;

- Carbon dioxide emissions intensity's can be altered in cells G9:H9
- Conversion, electrical and heat efficiency (cells D120:O125) N.b these inputs relate to gasification, incineration and anaerobic digestion separately but must all give the same overall efficiency in each row, otherwise the output will be out of step with the emissions.
- Modelled Scenarios (cells E141:H148) the scenarios can be selected by altering the descriptions / values of these cells.

Appendix E: Task 4.1 project framework deliverable

Introduction

Purpose

This memorandum is the Task 4.1 Project Framework Deliverable. It outlines the agreed approach to determine:

- Benefits and costs of system improvements (Task 4.2.1) - the benefits and costs associated with the development of the identified technology improvement opportunities; and
- UK Benefits Case (Task 4.2.2) - the benefits to the UK from the commercial deployment of the identified technology improvement opportunities and compare these against technological, environmental and economic factors of the current energy from waste opportunity.

The outcomes of these tasks will inform the ETI strategy and identify future demonstration projects.

Background

The aim of Task 4.1 is to confirm the project framework and ensure the project scope; project objectives and deliverables are aligned with the ETI objectives and meet their requirements. In addition, to ensure that the dependencies between work packages are understood and the information will be transferred between these work packages.

The Energy from Waste project will focus on power and heat conversion up to 10MWe. The production of transport fuels from energy from waste is excluded however information on the volume and specification of the liquids and gases produced from the waste processing technologies can be used by the ETI transport team.

Appendix B outlines the agreed technologies and areas that are excluded from the Energy from waste project.

Workshop

On the 22 September 2009, Caterpillar and EDF Energy held a workshop with the ETI to agree:

- The Technology Evaluation Criteria to allow the technologies to be compared;
- The financial modelling approach and key assumptions for the calculation of the benefits; and
- The definition of the existing market and baseline technologies to compare against the proposed optimisation and improvements.

Appendix C outlines the agree outcomes from the ETI and consortium workshop.

Technology Evaluations

The evaluation criteria for the benefits and costs of the system improvements and the UK Benefits case have been broadly developed around the ETI Objectives, i.e.:

- Affordability - Does a technology have the potential to be commercially viable?
- CO2 Reduction - What scale of CO2 abatement is likely to be achieved through mass deployment of a particular technology?

- Energy Security - What is the likely impact on UK energy security?
- Robustness - How resilient are technologies under different scenarios?
- ETI Leverage – Can the skills and capabilities of the ETI contribute to a step-change in technology improvement?

The ETI does not expect ETI leverage to be assessed as part of the UK benefits case deliverable however it is anticipated a discussion will be held with the consortium.
Task 4.2.1 Benefits and Costs of Technology System Improvements

The benefits and costs associated with the development and implementation of the system improvements will be either at the individual component technology or at the end-to-end system level. Individual component technologies will fall into different categories (i.e. Pre-processing, waste processing, post-processing and power & heat conversion). The system level comprises of all these four categories.

The modelling of technology systems will occur in Work Package 3 (WP3). Component technologies will be modelled in their current state, and then in their developed, improved state, where improvements are identified. System optimisation will determine the best combination(s) of current and optimised technology components to maximise end to end performance (i.e. range of wastes convertible, total efficiency of conversion). This process will identify the component technology and system developments with the greatest impact as measured against the ETI objectives.

The information from WP3 will form the basis of the cost benefit analysis of the development and improvement of the individual component technologies and/or systems and be described on the basis of the following:

1) Scope of the development - Detailed description of technology development including, where appropriate, schematic and or other diagrams. The costs, timeframe and key risks for the development and implementation of the technology developments will be assessed to assist in understanding the benefits of the ETI investing to accelerate the technology improvements.

2) Material impact of the developments - Description of the likely operational impact of development on technology and system performance in terms of the technology evaluation criteria outlined in Table 1.

3) Technology Acceleration – Assessment of current state of technology or system in relation to the NASA Technology Readiness Level (TRL) scale based on commercial deployment and where possible an assessment of the current rate of development of the technology. An assessment will also be made of how the proposed development(s) will accelerate the development rate and increase the technology TRL score through overcoming technical barriers to market deployment.

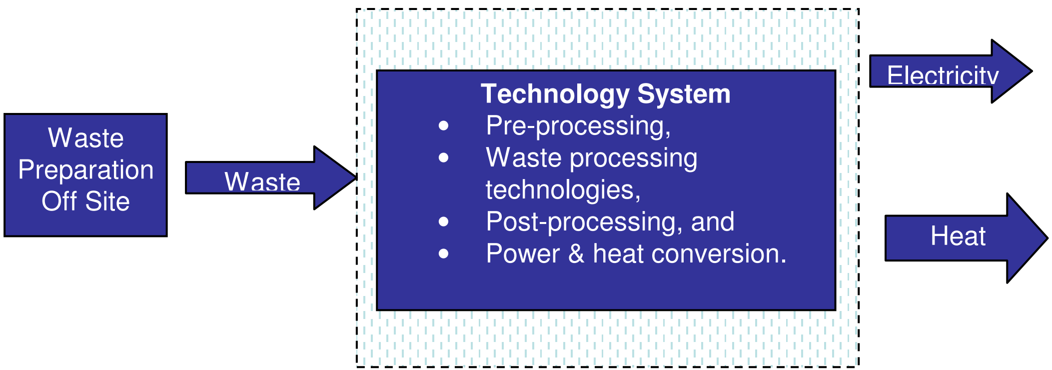


Figure 1 – Technology System Improvement Modelling boundaries

Task 4.2.2 UK Benefits case

The UK Benefits Case is essentially targeted at the board and is a holistic assessment of the program area (EFW), in terms of its overall potential to impact on the ETI core focus areas i.e. 80% greenhouse gas reduction, energy security, affordability, robustness and additionally as outlined in Section 2.3, Table 1

The UK benefits case will integrate the findings of the project from Waste Assessment (WP 1), the Technology Assessment (WP 2) and the Technology Performance Modelling and Assessment (WP 3) in order to assess the benefits to the UK of the commercial deployment of the identified technology improvement opportunities. It will compare the 3-5 selected technology system improvements based on commercial assessment for energy from waste plants. A comparison between the improved technology systems and an existing baseline will not be undertaken, unless it becomes clear later in the project that a simple baseline needs to be set in terms of clarifying the opportunity space to the ETI Board for setting the context not for detailed comparison.

The development of the UK benefits case and the assessment of the commercial deployment will be undertaken using a 3 stage approach:

- Preparation of a sorted waste stream that is transported to site i.e. “Ideal Waste Stream” for each selected technology system;
- Assessment of a generic energy from waste plant for each of the selected technology system improvements;
- Aggregation into the UK benefits case.

The outcomes of the UK benefits case will inform the ETI strategy and identify future demonstration projects.

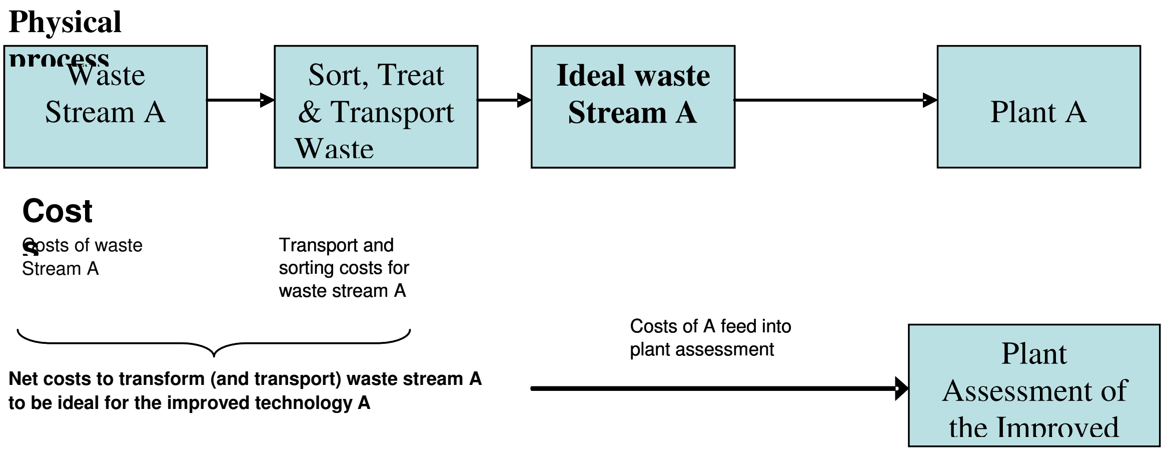
Ideal Waste Stream

To ensure a consistent assessment at the plant assessment level it will be assumed that each plant i.e. any of the 3 to 5 technology improvements, requires a waste stream that is ‘ideal’ for that plant. The creation of each ideal waste stream and its physical delivery to the plant requires the original waste stream to undergo sorting, treatment and then transportation to the site.

The ideal waste stream assessment for the plants will incorporate an estimate of the differences in cost of acquiring the waste and the landfill fee foregone, and the costs, estimated energy consumption and GHG emissions associated with the sorting and treatment of the waste plus the transportation of the waste to the plant. A simple sensitivity analysis (i.e. +/-10 or 20%) will be undertaken to test the variability and overall impact.

As each plant receives its own ideal waste stream no technology is favoured over another on the basis of the waste stream input to that plant. Other fuels and wastes that can be processed by the technology system will be identified however they will not undergo a full costs, estimated energy consumption and GHG emissions assessment.

The costs and greenhouse gas (GHG) emissions associated with the transport of waste will be based on per mile rate using a standard 44 tonne gross weight truck.



Generic Plant Assessment Methodology

The improved technology systems will be assessed at a plant level. These systems will be treated as a stand-alone fully operational plant set up as a company in its own right. The plant will be assessed against the evaluation criteria outlined in Section 2.3, Table 1 i.e. affordability, GHG reduction, energy security and robustness.

The assessment will include the costs, energy consumption and GHG emissions throughout the process required at an operational plant, including:

- The sorting, treatment and transport of the waste on an appropriate generalised basis;
- The capital, operational and lifecycle expenditure, energy consumption and GHG emissions associated with running the physical plant including balance of plant requirements;
- The overall plant management costs, stand-alone workforce and administration / compliance.

The financial modelling will result in a pre tax and finance cash flow model (and associated profit and loss and balance sheet) that will allow for any of the desired outputs/metrics. The outputs will include, for example:

- Lifetime cost of electricity (£/MWh) and cost of heat (£/MWh);
- Internal rate of return; and
- Net present value.

The cost of electricity and heat generated by the optimised system(s) is intended to enable the ETI to determine the value of subsequent projects to carry out the identified technology developments and demonstrate these on a commercial basis. Therefore it will be assumed that:

- Heat will be modelled to the gate of the plant thus the volume and quality will be outlined. District heating network cost, both capital and operational will be excluded;
- Electricity sold back into the national grid at wholesale market prices.

The greenhouse gas emissions and energy consumption assessment will include the sorting, treatment and transport of waste and the physical plant including balance of plant. The broader environmental assessment as outlined in Table 1 will focus at the plant level.

UK Benefits Case

The UK benefits case will be developed based on evaluating benefits for a generic plant for the selected improved technology. The number of potential sites will be identified using the information generation in work package 1 on the types of “Ideal Waste Stream” used by each improved technology system that is available, specifically the volume and energy content of this ideal waste, and the number of locations there is sufficient waste across the UK.

The overall UK Benefits case will be an aggregation of generic plant by the number of potential sites multiplied by the generic plant.

Evaluation Criteria

The below table outlines the Evaluation Criteria for the Technology System Improvements and the UK Benefits Case that have been broadly developed around the ETI Objectives.

Table 1 – Overview of the Evaluation Criteria for the Technology System Improvements and the UK Benefits Case

	Task 4.2.1 Technology System	**Task 4.2.2 UK Benefits Case**
General Description	Scope of potential technology developments • Sub-system to which identified development applies • Description of physical incarnation of development • Key risks of the development • Initial cost of the development Improved System Performance • Improved system conversion performance • Improved system waste handling capability	
Affordability	1) Technology System or Individual Technology Component Costs • Capital Expenditure • Replacement Expenditure • Operational Expenditure (not fuel)	1) Plant Costs (system including balance of plant etc) • Capital Expenditure • Replacement Expenditure • Operational Expenditure

	2) Comparison of costs to the existing state of that technology system	2) Financial modelling of costs and revenues of technology opportunities • Operational Performance • Plant Cost • Revenues
CO2e Reduction & Environmental	UK GHG emissions reductions from system development • GHG emissions from technology system output • GHG avoided from power generated by other sources (Grid (UK Gov long term projections for 2015, heat at 80% efficient gas boiler) • GHG avoided from landfill (GHG potential of wastes accessible by system)	1) GHG Emissions Levels • Total GHG emissions of the technology opportunities • GHG emissions from plant including technology system • GHG reduction from waste (landfill reduction) • GHG from the transport of the waste (generalised). 2) Reduction in waste arising and to Landfill • Reduction in waste compared to BAU 3) Strategic Environmental Assessment • Comparison against existing and future environmental limits - Strategic Environmental Assessment Planning and other key legislative assessment 3) Environmental Performance • Emissions to Air, Water, etc • Residues • Waste 4) Energy balance and energy efficiency across the technology system as a whole
Energy Security	1) Preliminary analysis of the UK waste could be accessed 2) Assessment of potential energy generated by technology systems	1) Generation capacity levels • Generation capacity range • Opportunity in UK for roll - out of technology • Comparison to existing UK electricity generation mix 2) Fuel supply (future trends of waste arising) • Security of fuel

		supply and supply chain assessment 3) Technology Supply chain • Development of Technology Supply chain – qualitative
Robustness	1) Technology System Diversity • Other end uses and systems in which the improved component technology could be deployed • Other feedstocks which could be processed by the system • Capacity scales and ranges over which component technologies and systems could be operated	1) Operational Performance • Diversity - Number of fuels the plant can operate on waste and biomass • Plant operational flexibility to meet demand profiles • Length of time taken by plant to adapt to another fuel source • Plant Efficiency - Level of performance per waste type • Plant life - Technical life of plant & equipment 2) Potential for technology scalability • Scalability - Technology ranges

Financial Assumptions

The key financial modelling assumptions for the commercial assessment are:

- Electricity volumes are modelled to the plant 'gate' and sold to 'the grid' based on a single variable tariff.
- Heat volumes are modelled to the plant 'gate' and assumed valued at a single variable tariff. Heat demand modelling will not be assessed and the associated district heat network cost will not be modelled.
- Renewable subsidies will be modelled but will be assumed as zero in the first instance, as directed by the ETI. A sensitivity analysis will be conducted on the cost of carbon using 3 prices in-line with the treatment of the plant under the EU ETS rules.
- Tariffs for electricity and heat and indexation rates across revenues and costs are to be agreed with the ETI.

Refer to Appendix A attachment for the agreed detailed financial assumptions.

Financial Assumptions (Appendix A)

Initial financial model assumption list to promote discussion - Waste to Energy: High-level generic plant assumptions

The aim is to derive a cash flow model from which all manner of metric and 'output' could be obtained and presented. Some of which are discussed in the WP4 scoring

Item	Comments/Actions/Owner
Project Length	
Project Start (financial close - date contracts signed)	Assume 2012
Project life	EDF Energy & CPI (WP3): Optimal economic/technical length interaction
	Potentially assume 25 year project life
Electricity and Heat Strategy	
Electricity sales	Assume sales to the grid
Heat sales (demand and customer mix)	Heat modelled to plant 'gate' only - heat demand not modelled
Operational strategy (how much and when run which equipment -> drives elec sales price)	EDF Energy/CPI (WP3): simple capacity factor assumption to be made to derive a ta
Plant flexibility (to meet heat demand profile)	EDF Energy/CPI (WP3): Heat demand will not be modelled, so only flexibility of fuel i elec output are considered
Generation	
Plant type	CPI (WP3)
Plant heat efficiency	CPI (WP3)
Plant electrical efficiency	CPI (WP3)
Plant availability	CPI (WP3)
Plant capacity	CPI (WP3)
Capex/repex	
Capex equipment	Caterpillar (WP2)
Capex price & spend profile	Caterpillar (WP2)
Capex risk/contingency	Caterpillar (WP2)
Capex useful life (and therefore replacements required, proportion of repex/lifecycle required)	Caterpillar (WP2)
Enhanced capital allowance applied to capex or not	EDF Energy/Caterpillar (WP2)
Pricing (& volumes)	
Gate fee for landfill waste	EDF Energy - with Cranfield & Shanks (WP1)
Volumes for different recyclables	EDF Energy - with Cranfield & Shanks (WP1)
Prices different recyclables	EDF Energy - with Cranfield & Shanks (WP1)
Volumes for compost/organic material (@ different grades)	EDF Energy - with Cranfield & Shanks (WP1)
Prices for compost/organic material (@ different grades)	EDF Energy - with Cranfield & Shanks (WP1)
Standing tariff for heat per customer type	EDF Energy - will model single variable heat tariff at the plant 'gate'
Variable tariff for heat per customer type	EDF Energy - will model single variable heat tariff at the plant 'gate'
Variable tariff for electricity per customer type	EDF Energy - will model single variable electricity tariff ('to the grid') at the plant 'gate
Sales price of electricity to grid	EDF Energy - will model single variable electricity tariff ('to the grid') at the plant 'gate
ROC sales price	EDF Energy - will allow for input in the model (to be modelled as zero at ETI request)
ROC volume	EDF Energy - will allow for input in the model (to be modelled as zero at ETI request)
RHI sales price	EDF Energy - will allow for input in the model (to be modelled as zero at ETI request)
RHI volume	EDF Energy - will allow for input in the model (to be modelled as zero at ETI request)
FiT sales price	EDF Energy - will allow for input in the model (to be modelled as zero at ETI request)
FiT volume	EDF Energy - will allow for input in the model (to be modelled as zero at ETI request)
LEC sales price	EDF Energy - will allow for input in the model (to be modelled as zero at ETI request)
LEC volume	EDF Energy - will allow for input in the model (to be modelled as zero at ETI request)
LECs (or equivalent) end date	EDF Energy - will allow for input in the model (to be modelled as zero at ETI request)
REGO sales price	EDF Energy - will allow for input in the model (to be modelled as zero at ETI request)
REGO volume	EDF Energy - will allow for input in the model (to be modelled as zero at ETI request)
Triad price	EDF Energy
Triad volume	EDF Energy
Connection fees paid into project (heat)	EDF Energy - only model a single variable tariff for heat, thus exclude connection fee
Opex	
Waste transport costs	EDF Energy - with Cranfield & Shanks (WP1)
Sorting costs	EDF Energy - with Cranfield & Shanks (WP1)
Sorted waste transport costs	EDF Energy - with Cranfield & Shanks (WP1)
Tech processing costs	Caterpillar (WP2)
Tech running costs	Caterpillar (WP2)
Tech maintenance costs	Caterpillar (WP2)
Plant running costs	EDF Energy
Plant BOP	EDF Energy
Admin/office costs	EDF Energy
Fuel	
Fuel type	CPI (WP3)
Fuel calorific value	CPI (WP3)
Fuel emissions factors	CPI (WP3)
Waste Cost	EDF Energy - with Cranfield & Shanks (WP1)
Fuel cost (back-up/alternate fuel sources; e.g. gas)	EDF Energy/Caterpillar (WP2) - if Caterpillar state back-up required
Fuel transportation cost	EDF Energy
Heat Network	
Network loss factors (heat)	Excluded
Capex and opex cost for DE network	Excluded
Greenhouse gases (Savings and other)	
Emissions volumes	CPI (WP3)
Carbon emissions methodology (vs. base case etc)	EDF Energy
Carbon costs applicable	EDF Energy to allow for input
Other emissions	
Other emissions volumes	CPI (WP3)
Cost of prevention of release of other GG	EDF Energy/Caterpillar (WP2)
Financial & modelling	
Upfront costs (costs to close)	All parties
Funding methodology	EDF Energy - model pre finance
Ownership structure	EDF Energy - model pre finance
Finance structure	EDF Energy - model pre finance
Bank debt rate	EDF Energy - model pre finance
Terminal value	Assume no terminal value beyond project life
Tax rate	EDF Energy - model pre tax
VAT rates	Assume UK large business VAT rates - required for accurate initial cash flows
Working capital	EDF Energy - with Shanks for waste and recyclables (WP1)
Capital allowances	EDF Energy - model pre tax so not directly relevant, but useful to include
Interest rate on cash balance	EDF Energy - model pre finance
Interest rate on overdraft	EDF Energy - model pre finance
Indexation	
indexation factors (capex, opex, labour etc)	ETI to provide guidance

Boundaries of the Project (Appendix B)

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
- Technologies not on list below including further post-processing of waste derived liquids/gases into transport fuels

Pre-Processing

Stabilisation		Storage	Size Reduction
Drying	Torrefaction		Milling

Processing

Anaerobic Digestion

Assessment Criteria	Mesophilic		Thermophilic	
	Batch	Continuous	Batch	Continuous

Gasification

Down Draft	Updraft				Plasma
Fixed Bed	Fixed Bed	Fluidised Bed			
		Air	Steam	Oxygen	

Pyrolysis

Rotary Kiln	Surface Contact

Post- Processing

Filter	Cyclone	Oil Scrub	Water Scrub	Electro Static Precipitation	Plasma

Power Generation

IC Engine	Gas Turbine	Fuel Cell (Generic, unspecified type)

Meeting Notes (Appendix C)

Below are the notes from the workshop on the 22 September with Caterpillar, EDF Energy and the ETI. The ETI presented on their distributed energy programme and Macro DE requirements with the outcomes of the discussion documented below.

General

- Distribute the ETI presentations discussed yesterday. [AK] - Complete and attached.
- Caterpillar to liaise with the ETI [Mark] on the approach for developing future CAPEX costs.
- Energy from Waste is focused on power and heat conversion up to 10MWe. The production of transport fuels from energy from waste is excluded however information on liquids and gases produced from the waste processing technologies can be used by the ETI transport team.
- Heat will be modelled to the gate of the plant thus as a product and the volume and quality outlined. This will allow the data to be used by ETI.
- Confirm WP1 will be documenting current usages of waste by waste type. This should be presented in table that can then be used and added to in the UK benefits case. Table should outline waste type, volume, CV, current usage (technology & volume), timeframes for usage, and appropriate technical assay information (ash content, silica, water, halides, alkalis, etc) TBC

Technology System - Evaluation Criteria

- Technology system has 4 individual component technologies – Pre-processing, waste processing technologies, post-processing and power & heat conversion.
- Update the Technology System Assessment Criteria to align with the ETI objectives – Affordability (CAPEX/OPEX), CO2e reductions, Energy security, Robustness. [BS / ZvR]
- Baseline comparisons will be based on the status of the existing technology system / sub-component
- Benefits technology improvement should incorporate benefits of the ETI investing in acceleration of the technology improvements - Qualitative assessment of the R&D timescale. Further work is required to understand how this is evaluated, but is will be undertaken by the ETI. [BS]

UK Benefits case - evaluation criteria

- The UK Benefits Case is essentially targeted at the board and is a holistic assessment of the program area (EFW), in terms of its overall potential to impact on the ETI core focus areas (80% GHG reduction, energy security, affordability, robustness and additionality). The Project must generate and compile sufficient data, analyse it and present it in such a manner as to enable the ETI to make decisions at the end of the Project regarding future programme scope. The requirements are aligned as stated in the RFP and the presentation material attached. The costs modelling and financial assessment underpinning this will be developed based on evaluating benefits for a generic plant for the selected technology, determining the number of potential sites and no. potential sites x generic plant.
- Comparison will be between the 3-5 technology system improvements not an existing baseline for UK benefits case, unless it becomes clear later in the project that a simple base-line needs to be set in terms of clarifying the opportunity space to the board for setting the context not for detailed comparison.
- Affordability criteria
    - o This will be predominantly a cost based assessment- CAPEX and OPEX. ~~Detailed~~ DH network costs and modelling to be excluded.
    - o Review approach being undertaken for development of CAPEX and OPEX costing beyond 2010 by ETI (in terms of inflation index) based on the Energy Systems Model (ESM). [AK]
    - o Develop a high level model of the costs of preparing targeted waste, transport to site. Transport Document on overview of this approach. [AW]

  - Undertake a Generic commercial assessment of plant – operational cash flow however excluding financial incentives and based on ETI price / revenue curves only if they are all ready established within the ESM. [AK to confirm]. Assessment of financial viability given today's incentives useful as context for board (on-going discussion closer to project conclusion)
- CO2 reduction & Environmental
  - Energy consumption is embedded within the black-box component models. CPI will provide information on CO2 emissions and energy consumption at a systems level. [BS to inform CPI of this requirement].
  - Transport of waste will be undertaken on per mile (costs, energy and CO2e). EDF Energy and Cat believe this should be done using a standard 40 tonne truck. To be discuss and confirmed with Shanks. [BS/ FSP]
- Energy Security
  - Security of fuel supply - Waste stock availability should incorporate seasonality and the sheet updated. [FSP] Complete
  - Technology supply chain assessment should be revisited. It is unclear how this assessment would be undertaken. Generally if there is a market the supply chain will develop.
  - Robustness
  - Diversity should incorporate commentary on the fuels the plant can operate beyond waste (e.g. biomass). [FSP] Complete
  - Circulate the draft deliverable for Task 4.1 Monday 28 September. [FSP]

Appendix F: Technology development opportunities for EfW

Low cost gas clean-up of gasification gases

The carbon and cost modelling show that the use of gasification could enable CO_2 emissions reductions of:

- UK CO_2 (equivalent) savings from gasification of dry wastes as modelled relative to landfill is tabulated below (kTCO2e):

	Gasification (for each plant)	Number of Plants	Gasification (Total for Each Plant Scale)
City	392	36	14,156
Town	39	437	17,152
Village	4	2,089	8,194
Rural	0.4	2,089	819
UK Total			40,321

- The TRL estimated to be ~3-4. Estimated by consortium that development to a TRL of 6 may be achievable in around 5 years and cost £50-100 million.
- System level capital cost target based on modelling work for financial viability is < 250£/t with a > 25% target for total efficiency to electricity (or other products with equivalent or greater value).

These savings are the absolute emissions values (not accounting for all or part of the waste being considered CO_2 neutral), and are based on a system efficiency of 21%. Further savings are possible through increasing the system conversion efficiency and lowering the specific carbon intensity. For these benefits to accrue, the system cost and efficiency must be sufficient to enable an economic return as illustrated by the technology performance lying below the NPV = 0 line in **Figure 3.4** in report. The efficiency of the plant may also be taken here as the total power output generated over a period relative to the cost of operating the plant. For gasification, the derived gases commonly contain 'tars' and other contaminants including Sulphur and Nitrogen species and trace metals, as a function of their concentrations in the feedstock materials. In this case there is a link between the feedstock materials and the scale and complexity of the gas cleaning required and so controlling feed mixes through blending provides one element of an integrated approach to reducing the costs of gas cleaning. To achieve this, developments are required in feedstock monitoring and waste fuel standards.

The range and type of contaminants in waste gasification gases present a greater technical challenge than AD biogas and are a development opportunity with a number of options. As contaminant levels will vary with feedstock blend and with time, it is important to understand this variability and apply feedstock blend controls and monitoring to ensure that the most cost effective gas cleaning approach can be utilised. It is also necessary to ensure good process control as the levels of certain species, such as NH_3 (Ammonia), will vary with changes in operating parameters. Given the criticality of the gas cleaning stage to enable the efficient use of the gas to realise the carbon benefits of using wastes, the development of robust, low cost waste-derived gas clean up technology has been identified as the highest priority development opportunity as it enables the downstream utilisation of the gas in all options.

Current gas cleaning systems (where applied) have been shown to operate successfully for periods of time. However, blockages caused by tars and further corrosive damage from gas contaminants requires considerable periods of shut-down as maintenance is carried out. Ultimately this impacts the cost of energy generated (as the energy generated per hour is reduced, and hence the required revenue to achieve profitability for that energy is increased), to the point where plant operation is no longer economically viable. These techno-economic factors are the cause of the majority of plant failures to date.

Where current gas cleaning systems may be tailored to the contaminants emanating from a specific, well characterised feedstock (e.g. pulverised coal), a gas cleaning system designed for mixed wastes would need to remove varying levels of contaminants, depending on the composition of the actual input feedstock, which is also likely to change over time as cost and regulatory drivers push for the removal (or inclusion) of certain materials in the waste stream to be processed. Although technologies exist to remove individual gas contaminants, there are little empirical data and evidence from industry that the combination of contaminants can be effectively cleaned to enable the use of the gas in sensitive, but efficient, equipment. Where such a system could be developed from standard gas processing technologies, this is likely to be prohibitively expensive for widespread adoption.

The gas cleaning system cleans the gas produced by the main process utilising mixed wastes as a feedstock (producer gas) to enable the gas to be used in downstream applications. This is differentiated from flue gas cleaning following the complete combustion (oxidation) of the wastes (or derived gases), for which technologies exist and are widely in operation to comply with emission regulations. These flue gas treatment technologies are not directly applicable to the treatment of product gas as, as the mix of contaminants and the chemical species involved are very different in the reducing product gas environment.

To date, financial drivers from the waste and energy industries have not been sufficient to attract large scale investment in this technology area. These drivers for waste disposal, energy generation and carbon reduction are, however, now focusing on specialised gas cleaning (combined with process optimisation) for the efficient use of waste gasification gases, as illustrated by the increasing volume of analysis and assessment of these technologies currently being published.[1]

A wide range of products, including tars and corrosive chemical elements and compounds, result from the gasification of mixed waste feedstocks. The successful development of a robust, low cost gas cleaning system will likely involve innovative, low energy integrated gas cleaning approaches to reduce residual contaminants in fuel gases sufficient to meet the inlet requirements of the downstream systems. Such schemes may involve smart use of particulate filtration with injected solids and the use of catalysts. Strategies for recovering the energy content contained within the tars may include the processing of tars for alternative uses or through their cracking for recycling into the gas stream. The identification of the carbon benefits associated with town and village scale gasification suggests that system scalability will be a critical success factor. Similarly, system efficiency is a key enabler for carbon savings; given that thermodynamic limitations dictate the efficiencies of the gasification and downstream technologies, any further energy

[1] For example, Review of Technologies for Gasification of Biomass and Wastes, NNFCC 09-008

load demanded by the gas cleaning system will directly impact the system efficiency. Therefore, the requirements of the gas cleaning will have to balance the variability of the feedstock with the downstream use of the product gas to develop optimised systems at the required scale.

If successfully developed, as well as enabling the generation of power (and heat) through gas engines and turbines it is likely that any gas cleaning system could be applied to the production of other products, fuels and chemicals though further downstream processes such as Fischer Tropsch.

In considering the TDOs the TRLs, risks and affordability and carbon reduction dimensions must be taken together. These are summarised in **Table 1** below.

Table 1: Drivers for low cost gas clean-up

TRL scale	The TRL of a gas cleaning system is difficult to quantify due to the range of technologies usually combined. These are usually of high TRL technologies from associated industries (i.e. cyclone filters, scrubbers etc. which are all widely deployed (TRL 9) in other process industries). However, many systems also include experimental technologies (designs or use of different scrubbing liquids, solid sorbents, activated carbons, etc.), which may be deemed to be a TRL 3 (being tested at lab scale). The lack of an apparent break-through system suggests that at a system level (whether comprising of only high TRL technologies or a combination of low, mid and/or high TRL technologies), the overall TRL may in actuality be deemed to be “low” (TRL 3-4). Given a full development programme including process design, modelling, testing and validation, a TRL of 6 may be achievable in around 5 years, such a programme is estimated to cost £50-100 million and will require access to appropriate ‘real world’ gases either from an existing or purpose-built facility.
Risks	The nature and cost-effectiveness of gas cleaning is critical. Drivers for increased efficiency as well as manufacturing capabilities are driving for more stringent gas quality requirements from downstream equipment (e.g. catalysts, fuel cells and engines), which in turn drives further demands for higher levels of gas cleaning. These drivers have led to much work in the area of gas cleaning, both in the UK and globally, as evidenced by the Technology Landscape Assessment and Conversion and Resource Efficiency work Despite these efforts, a highly robust and cost effective gas cleaning system for small scale applications utilising mixed wastes as a feedstock appears elusive. The risk in attempting to develop such a system is that significant challenges may be encountered.

Small and micro scale AD plants

The carbon and cost modelling show that the use of AD could enable CO_2 emissions reductions of:

- UK CO_2 (equivalent) savings from the AD of wet wastes relative to landfill ($kTCO_2e$):

	AD (for each plant)	Number of Plants	AD (Total for Each Plant Scale)
City	223	40	8,839
Town	22	509	11,332
Village	2	2,455	5,467
Rural	0.2	2,455	547
UK Total			26,186

- TRL estimated to be ~4. Estimated by consortium that development to a TRL of 6 may be achievable in around 3-5 years, although development costs are unknown.
- System level capital cost target based on modelling work for financial viability is < 50 £/t with a > 25% target for total efficiency to electricity (or other products with equivalent or greater value).

To deliver the potential carbon savings identified, technologies are currently under development and are in the early stages of market deployment, but there are clear opportunities for further process and technology development, especially for technologies and process which are more efficient than the current ~13% gas yield. Current batch processes usually have an adaptation time of ~3-6 weeks between feedstock types. Whilst the rate of transformation of microbes cannot be readily altered, the use of continuous AD process is likely to enable compact and cost effective deployment at smaller scales. The technology is scalable and economies of scale of downstream usage are considerable, but reactor costs would require significant reductions at smaller scales, or much greater conversion efficiencies, for cost effective plants to be developed for village and rural scales (less than 5kt/year). In terms of feedstock diversity and contributing to energy supply, AD is only applicable to appropriate biogenic wastes, and is most efficient when applied to high moisture content materials to allow the microbes to transport. If scaled down to a domestic level, sewage that is currently managed in domestic septic tanks would also be available for treatment, and the methane emissions there from would be captured.

While the primary use for the digestate residue is soil beneficiation as a fertiliser, where this is not possible or acceptable the residue could be used as an additional feedstock for parallel gasification or pyrolysis processes after drying or blending to meet feedstock moisture constraints.

Other factors that need to be considered with AD plants are summarised in **Table 2** below.

Table 2: Drivers for small and micro scale AD plants

TRL scale	AD is a well-established technology that has been deployed around the world for many years. The AD process itself may be deemed to be at a high TRL, although small scale AD systems, especially those operating continuously or in a controlled, high efficiency manner, are still under development and may be judged to be at TRL of ~4. The potential for acceleration is considerable, with a requirement for evidence of a reliable medium term operation at an appropriate cost to enable commercial deployment. An increase in TRL to ~6 is estimated to take around 3 - 5 years of demonstration and development activity. An AD plant is expected to have an operational life of 25 years,

	although there are examples of plants operating for over 45 years resulting from a robust planned maintenance regime. The core technology replacement cycle is long, with adjacent equipment, such as gas cleaning and the power generation engine requiring more regular service. Additional requirements to inject the outlet gas into the UK gas grid would be expected to drive further technological solutions, adding technical risk and reducing the system TRL scale.
Risks	Some small and micro scale AD technology improvements are currently in development such as the CPI and ECO innovation project. Some regulations currently do not permit deployment in the UK.

Medium, small and micro scale gasification processes for wastes

The carbon and cost modelling show that the use of gasification could enable CO_2 emissions reductions. Some of the key features include:

- UK CO_2 (equivalent) emissions savings relative to landfill for gasifying all dry wastes are tabulated below (kTCO_2e):

	Gasification (for each plant)	Number of Plants	Gasification (Dry) (Total for Each Plant Scale)
City	392	36	14,156
Town	39	437	17,152
Village	4	2,089	8,194
Rural	0.4	2,089	819
UK Total			40,321

- TRL estimated to be ~5. Estimated by consortium that development to a TRL of 9 may be achievable in around 5-10 years, and cost £30-50 million
- System level capital cost target based on modelling work for financial viability is < 250£/t with a > 25% target for total efficiency to electricity (or other products with equivalent or greater value).

The gasification of waste materials in fluidised bed or downdraft gasifiers has been identified as a TDO as there are currently few processes that work using mixed feedstocks at feed rates of 50kt/yr or less. This has also been demonstrated by the scale and operations of pilot plants assessed as part of this project. Units at domestic scale are likely to have value, whilst this type of technology would be highly appropriate to the creation of integrated systems. A further benefit of this scale of technology relates to planning and siting applications, which typically face fewer oppositional issues at smaller scales, particularly when the surrounding community is the direct beneficiary from reduced waste handling impacts (cost, lorry movements etc.), and from low cost heat provision.

Technologies should be developed to support communities generating waste and mixed feedstocks with the aim to develop innovative gasification solutions that reduce capital cost and increase operability of small scale units. Units could be single stream or multiple installations of modular units with lower throughputs. In addition to operating on waste feedstock, the plant could be designed to convert locally sourced coppice, grass and other biomass sources. Developments are likely to incorporate thermal process improvement through the use of alternative oxidants (H_2O, O_2 or CO_2), and optimised process parameters to maximise carbon conversion/gas CV, while reducing/controlling gas contaminant production. While steam should be readily available within most plants, the use of other oxidant gases such as O_2 and CO_2 would need additional process steps. For O_2, this would require the development of small scale, low cost air separation units which would be an enabling technology development in its own right. For CO_2 capture and potential sequestration, one option would be to separate CO_2 from the syngas using membranes or solvents/sorbents, thus simultaneously boosting the syngas CV. Furthermore, there are benefits from an increase in conversion efficiency through improved reactor design to aid heat transfer. Where high levels of tars are produced (as reported in Deliverable 2.2), their cracking to improve overall gas production or their recycling either into the main reactor (for degrading) or to supplement the fuel being used to provide process heat represent significant opportunity for improvements in process efficiency.

A major risk of the use of these technologies is how the physical form of the waste affects the operation and stability in the overall process. Specifically, the feeding of material to the reactor and the thermochemical reactions are the most affected, although there are a number of feeding systems tailored for the specific material being transported. Therefore, to enable more robust technology operation, emphasis should be placed on the pre-treatment of the feedstock to ensure that operational issues are not encountered. This can take the form of moisture control and or physical form homogenisation (e.g. pelletisation), although further work to understand the cost, system efficiency and benefit trade-off would be required to be conducted through directed experimentation. In addition, work will be required to ensure that processes can meet the requirements of the legislative and regulatory system.[2]

Gasification offers flexibility to differing feedstocks (within defined moisture content limits), and the time taken to adapt to another fuel source in a well designed gasification plant will be minimal. Small plants at the town and village scale with appropriate instrumentation and control may offer further flexibility in meeting demand profiles may be achieved through the incorporation of gas storage, either pre- or post- gas cleaning as appropriate.

Other factors that need to be considered for medium, small and micro scale gasification processes for wastes plants are summarised in **Table 3** below.

Table 3: Drivers for medium, small and micro scale gasification processes for wastes

TRL scale	The range of suppliers of gasification equipment at all scales, and the relative simplicity of the core technology leads to assessment that small scale gasification, as a whole, is currently at a TRL of ~5. The use of mixed waste materials poses a challenge for some reactor types due to the variety of physical forms and thermochemical behaviours of the materials present in such a mixed stream. In this regard, fluidized bed gasifiers are more suitable to the processing of mixed wastes), although downdraft gasifiers are more suitable for smaller scales. The use of mixed wastes in downdraft gasifiers may be estimated to be a slightly lower TRL of ~3 and are likely to need pelletised materials to ensure stable gasification and avoidance of bridging. Therefore,

[2] See AEA report in **Appendix B** as part of WP2.

	pelletisation plants operating in parallel are an additional development opportunity. The large scale gasification of very homogeneous materials (e.g. pulversied coal) is widely practiced (e.g. South Africa) and may be deemed to be at TRL 9. To date, the development of smaller scale gasifiers for operation with mixed wastes has not been attractive to investment. Therefore the potential for acceleration is felt to be relatively high, with a consortium estimated timescale for development to TRL 9 or 10 years at an estimated cost of £30m to £50m for initial scoping of project to off-the-shelf technology.
Risks	The development of small scale gasification technologies is largely regarded as being low risk. Although many gasification reactor suppliers have been identified, the technology landscape assessment work carried out for this project shows that the commercial availability of technology at the appropriate scale (using mixed waste as a feedstock) is still pending development (see **Appendices B** and **D**). In all cases, the processes developed are likely to require gas clean-up technologies to enable the efficient use of the gases produced, and so there would be a risk that developed technologies would be limited in application due to the lack of availability of this enabling technology.

Integrated gasification, incineration and AD technology systems

The carbon and cost modelling show that the use of gasification could enable CO_{2eq} emissions reduction relative to the landfill disposal of waste of ($kTCO_2eq$):

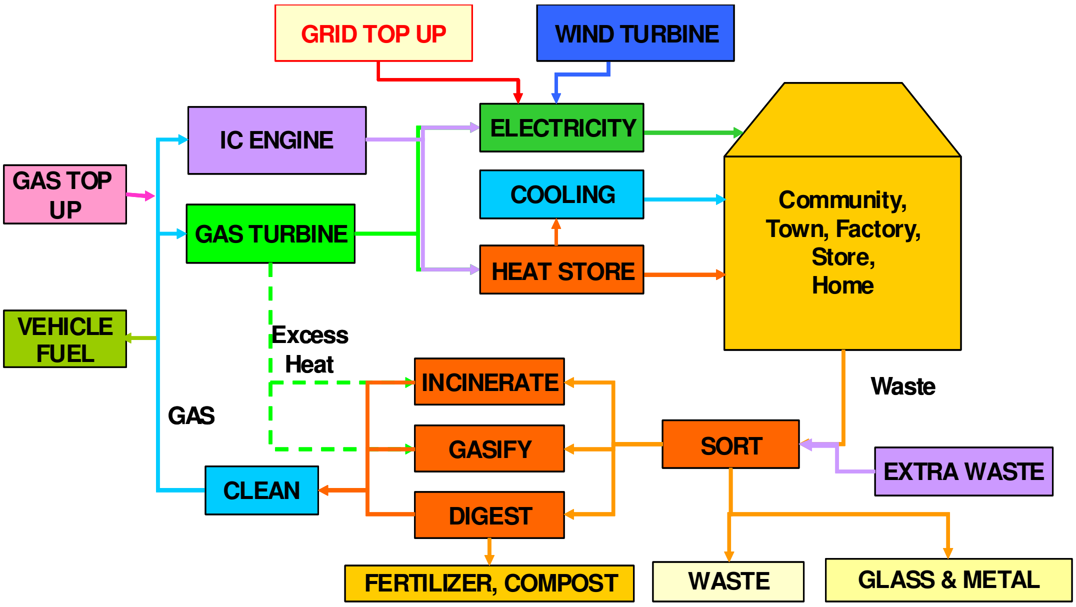
	Integrated Gasification and AD (per Plant)	Number of Plants	Integrated Gasification and AD (Total for Each Plant Scale)
City	615	76	22,996
Town	61	946	28,484
Village	6	4,544	13,661
Rural	1	4,544	1,366
UK Total			66,507

These development opportunities present significant technical developments and associated carbon, energy cost and robustness (security of supply) benefits. These benefits may be maximised through the integration of the component technologies into a highly flexible waste processing and energy generation system. Here, then, there is an opportunity to develop integrated DE systems of technology that can service smaller communities with a particular emphasis on town and village scale systems. Combinations of technology are likely to be AD, gasification, and where appropriate, incineration, with upstream and downstream processing. This approach could reduce emissions for both electricity production and in CHP systems.

Recent technology development has tended to move towards larger scale EfW plants based on the economies of scale that come from large process plants. Large-scale waste processing technology is currently available for city scale installations, which combine waste sorting, AD, composting and recycling with residual disposal. However, large integrated plants do not necessarily provide operational flexibility, as a plant processing 100 kt/pa of fuel will require a continuous process. The evidence indicates that there is an opportunity to develop integrated DE systems of technology that can service smaller communities. The economics will come from lower cost technology driven by a production line approach to large volume production.

One opportunity for integration would be the gasification of AD digestate that cannot be used as a fertiliser or put back onto the land. Small modular plants at the town and village scale with appropriate instrumentation and control offer the required flexibility to meet both waste supply and demand profiles. The opportunity for fuel diversity with a well designed integrated system would be high, and is likely to include a range of separated and mixed feedstocks including MSW, C&I waste, food waste, wood waste, raw biomass and agricultural residues. The integrated plant should be designed to maximise adaptability potential and minimise the time to adapt to another fuel source. Although there is no 'definition' of such an integrated system, a potential technology set with material flow paths is represented schematically in **Figure 1** below.

Figure 1: Schematic representation of an integrated EfW system



The scale at which these systems, and the technologies of which they are comprised, is likely to be influenced by a range of factors, such as the long term availability of waste and community concerns. These factors currently affect waste technologies, and it is likely that smaller scale, advanced technologies would meet with less opposition than those at larger scales. Similarly, feedstock availability would be easier to secure, especially with combined technology systems, which have inherent flexibility to variations in waste materials intake.

It is estimated that the initial costs for a typical town scale integrated project would be around £100m, if the above discussed technologies were commercially available; it is thought that a comparable village scale project would have a capital cost of around £20m based on current technology cost data collated in the AEA and CARE Technology Landscape Assessment reports. Although these systems are based on the earlier identified TDOs, the potential for acceleration of these technologies would increase if the technologies can be demonstrated as working together. A suitably designed integrated system would enable the appropriate technologies to optimise the waste handling capability and the conversion to energy, maximising energy creation and positively contributing to CO_2 abatement.

Other factors that need to be considered for integrated technology systems are summarised in **Table 4** below**.**

Table 4: Drivers for integrated gasification, incineration and AD technology systems

TRL scale	Component technology TRLs are outlined in the preceding sections or are at 8 or 9. The challenge is the development and implementation of integrated systems. Overall system TRL 5 to 6.
Risks	• Development of relevant scale sub-system components is unsuccessful. • Inability to integrate technologies effectively, • Resistance to adoption from larger scale incumbent companies, • Lack of social acceptance by the local communities that would benefit from the integrated technologies, • Lack of proven systems integration in the UK making it difficult to secure finance for projects.

Low cost heat networks

Using the heat produced during the processing of waste materials and/or the power generation from the derived energy enables further carbon savings through offsetting the use of natural gas for heating applications. There are also a number of community CHP plants or community heat supply systems operating in the UK – for instance, in Aberdeen, Milton Keynes, Byker (Newcastle), Nottingham, Sheffield and Woking.[3] However, high level modelling carried out here shows that utilisation of 80% of the heat produced at a city scale would enable an annual CO_2 saving of between 120kt/yr and 150kt/yr[4] from the offset of natural gas. The development of the heat networks to enable these reductions is technologically separate from that to enable energy from waste, although the integration of established CHP technologies such as gas engines and turbines would facilitate heat usage.

Low cost processes to convert syngas into chemicals or fuels

The gasification technologies examined here can be used to produce gas which may also be used as syngas for the production of chemicals or transport fuels. Investigation of the carbon benefits associated with these conversion paths fall outside the scope here. In all cases, due to the capital requirements associated with chemical and fuel production plants (and non-scalability of these plants), these benefits are only likely to be applicable to city scale waste arisings volumes, where a large scale gasification process is being used to produce a large volume of high quality syngas. A number of companies are developing a range of technologies, but

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[3] The assessment of the additional cost of capital required for a plant to develop, or connect to, a heat network are out of scope of this project are under assessment in other ETI activities (The Macro DE project).
[4] See previous footnote.

a more structured public-private partnership to drive value creation may be of value to developing this market further.

Pyrolysis for liquid fuel production

Pyrolysis for the production of liquid fuels has not been explicitly examined due the requirement for a segregated, well characterised feedstock stream, and identified issues associated with the use of the produced oil, even from such streams. These issues include the acidity of the oil (typically pH ~2 - 3), its high viscosity and its temporal instability due to the presence of oxygen (derived from the feedstock) in the oil. Techniques to overcome these shortcomings are under development, such as hydrogenation, and may become more developed and cost effective should hydrogen become a more readily available and lower priced commodity. The development of these upgrading technologies may provide an adjacent TDO, although clarification of the carbon benefits associated with this opportunity would require further investigation.

Other potential areas of improvement

A number of general technology enablers have been identified that could provide additional value. For example, the controlled use of feedstock blending can be used to optimise performance and constrain emitted contaminants to within downstream equipment tolerance and environmental emissions limits, as well as providing operational stability and performance benefits. Such a suggestion is difficult to ascertain without practical experimentation but the evidence here point to different mixtures of materials likely to result in different gas outcomes. In addition, the ability to assess feedstocks through the development of nomographs for different waste material mixtures based on their chemical and physical properties could be of value in the assessment and optimisation of feedstock mixes or blends coming into a facility. These adjacent areas are not development opportunities in their own right, but their consideration should be incorporated into any subsequent activities (see **Section 6** in main report). From all of the opportunities highlighted above and the associated generic enablers, such as feedstock control and monitoring, it is clear that successful EfW systems will only come from a detailed knowledge of waste arisings, the quantification of their properties combined with energy conversion systems which designed as optimised systems of components and not treated as a series of process steps which are 'bolted' together.

Energy security and robustness

The data and discussion above point to significant potential to commercially develop and use EfW technologies. These developments need to be assessed in relation to other factors and real-life situations. In addition to the robustness of the EfW technologies and the alternative uses of waste a major factor influencing the practical and successful development and implementation of EfW centres on energy security.

The UK has around 76GW (gigawatts) of electricity generation capacity to meet annual consumption of about 350TWh (terawatt hours) and winter peak demand of about 63GW.[5] This level of capacity is roughly 20% higher than the expected level of peak demand. The UK has a diverse electricity generation mix. In 2006, 36% was generated by gas-fired power stations, 37% from coal, 18% from nuclear, and 4% from renewables. The remainder comes from other sources such as oil-fired power stations and electricity imports from the continent. Crucially, 80% of the UK's energy sources are imported.

Each person in the UK produces about 1 tonne of MSW per year and about 0.8 tonnes of C&I wastes. These sources of waste amounted to around 90 million tonnes in 2009. If all waste were to be utilised for energy generation, this project projects that around 45 TWhr of electrical power could be generated annually, in addition to over 110 TWhr of heat.

Although EfW technologies have an impact on energy security generally, there are some technology specific dimensions that need to be taken into account. For example, AD can utilise food, paper, card, and slurry based waste and the process can adapt to the varied wastes, but the yield and requirements may change. It can be applied at all scales, but there are currently limitations due to costs and size of the equipment to ensure continued investment. Furthermore, AD could be deployed at farms, villages, towns, cities and industrial/commercial locations.

Thermal chemical conversion systems can be deployed at all scales depending on the viability of the gas cleaning system to enable cost effective operation sufficient for investment at each scale. Gasification enables many markets including biomass, H2 infrastructure including integrated gasification combined cycle (IGCC), and other systems and provides the most versatility in its downstream use. Each of these opportunities is highly cost sensitive.

A preliminary analysis of the UK waste, therefore, could be accessed to ascertain the energy security risks. This can be balanced against an assessment of potential energy generated by technology systems. But a number of dimensions will need to be considered, such as technology system diversity, other end uses and systems in which the improved component technology could be deployed, other feedstocks which could be processed by the system, and the capacity scales and ranges over which component technologies and systems could be operated.

[5] Meeting the Energy Challenge, Department of Trade and Industry (2006).

Appendix G: Pre-treatment and gas cleaning

Economic imperatives for waste disposal and power generation underlie a global interest in applying gasification process to mixed solid wastes (plastics, paper/card, wood, food and textiles etc. such as typically arising in raw, mixed form from domestic, industrial and commercial sources), as well as in using the produced gas as a fuel in efficient engines and turbines for power (and heat) generation.

When considering its decomposition and the use of any derived fuels (gas), the full composition of the feedstock should be considered. A typical comprehensive elemental break-down of a mixed domestic waste stream as measured in the UK National Household Waste Analysis Programme (NHWAP) in 1994 is presented in **Table 1**. Although subject to the inherent variability in any waste stream, these values correlate well with similar European studies and more recent data, as presented by Burnley [2007].

Table 1: Average Elemental composition of household waste (NHWAP survey, 1994)

Element	Average
Oxygen	30 %
Carbon	24.5 %
Hydrogen	5.25 %
Silicon	3 %
Iron	3.8 %
Sodium	0.7 %
Aluminium	1.15 %
Calcium	1 %
Nitrogen	0.55 %

Element	Average
Sulphur	0.08 %
Chlorine	0.59 %
Bromine	0.01 %
Phosphorus	0.04 %
Fluorine	0.01 %
Magnesium	0.225 %
Potassium	0.32 %
Manganese	47 ppm
Zinc	71.6 ppm
Lead	140 ppm

Element	Average
Copper	20.5 ppm
Chromium	43 ppm
Nickel	9.025 ppm
Arsenic	5.9 ppm
Molybdenum	0.964 ppm
Antimony	2.15 ppm
Silver	0.173 ppm
Cadmium	1.15 ppm
Mercury	0.07 ppm

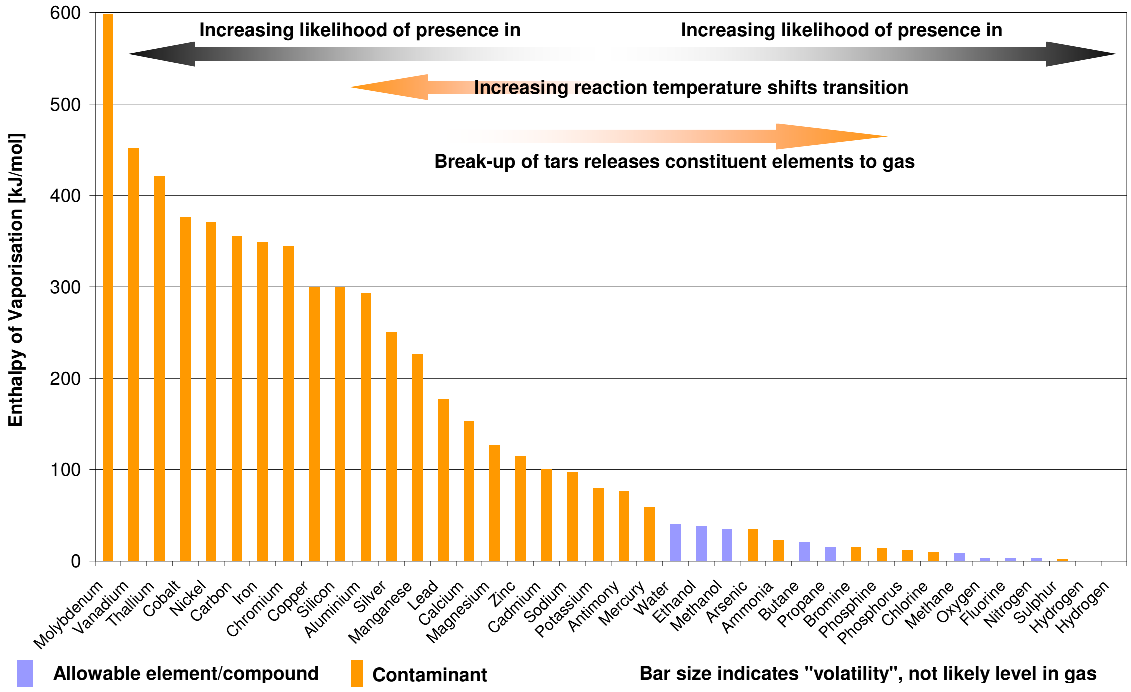
Raw biomass comprises largely of Carbon, Hydrogen, Nitrogen and Oxygen. However, the growing environment (soil type, airborne elements, fertilisers etc.) of the biomass will determine the extent of inclusions of other chemical elements, although levels will generally be lower than for typical waste materials. As such, the requirements placed on gas cleaning for biomass derived gases may be less than those for waste materials.

Gasification is a thermal process where the feedstock material is thermally decomposed in a partially oxidising atmosphere (~700 ℃, insufficient oxygen to support combustion), preventing complete combustion but breaking the material into smaller compounds and elements. These compounds are gaseous if broken down into sufficiently small groupings, or form clumps ("tars") of lower volatility elements and partially broken down parts of the feedstock material. The nature of waste materials and the distribution of heat transfer intensity occurring at differing locations within the reactor mean that in all gasification reactions a distribution of tars will be present in the gas produced. The thermal intensity of the reaction is dependent on the reactor design, feedstock moisture content, air flow rate and flow dynamics, which is dependent on the materials shape and form. The thermal intensity drives heat release rate at the surface of the material, which drives the release rate of each of the material chemical element constituents. As the majority of materials are formed principally of carbon and hydrogen, the gas produced comprises largely of hydrogen and carbon monoxide, with other elements present in the feedstock material also present depending on their concentration in the feedstock and their thermal volatility.

Although the exact volatility of each compound and molecule present in the feedstock material is difficult to define, the enthalpy of vaporisation of each element and the main molecules is presented in Error! Reference source not found.. The high volatility elements/compounds (low heat of vaporisation, right hand side of graph) are those which are released to the greatest extent, whilst the lower volatility elements require a greater thermodynamic driving force to separate, and hence are less likely to be completely decomposed within the finite time and temperature constraints within the reactor, and are more likely to be present in partially decomposed tars or the residual ash. Increasing the intensity of the reaction (e.g. higher reaction temperature, more intense process (e.g. fluidised bed)) increases the likelihood of lower volatility elements being present in the gas.

Where elements are present in tars, the subsequent treatment of these tars is important in determining the levels of the elements in the cleaned gas; where tars are removed from the gas stream (e.g. scrubbing), the component elements are also removed. However, although the break-up of tars is attractive in that it retains their energetic content within the gas stream, where tars are broken up by further thermal treatment (e.g. fluidised bed or plasma treatment) these elements are maintained within the gas stream.

Figure 1: Enthalpy of Vaporisation of Elements and Compounds Occurring in Mixed Wastes



Contaminant	Occurrence	Effect
Ash / Particulates	High – easy removal	• Blockages/constriction of air system • Abrasive corrosion
Tars	Very high, difficult to remove/control	• Sticky deposits, causing blockages, sticktion, clearance tolerance reduction
Alkali Metals	Feedstock dependant, high for wastes and contaminated biomass (soil)	• Gums up fuel valves, turbomachinery and ignition systems (spark plug), gasifier bed material • Contaminates engine oil, after treatment catalyst • Surface corrosion
Ammonia	Feedstock dependant	• Non-adherence with legislated emissions levels
Sulphur / Chlorine	Feedstock dependant, especially high in plastics	• Formation of corrosive acids when in contact with water vapour in gas

Consideration of the entire composition of any gas to be used as an engine/turbine fuel is highly important as contaminants can greatly affect the operational costs of the engine/turbine. Failure to properly clean the raw gasification gas prior to admission to the engine/turbine can lead to; amongst other things:

- Ignition system failure
- Fuel system Damage
- Piston ring/liner issues

- Oil contamination (and resulting bearing failure)
- High emissions of regulated emissions
- Damage to engine catalysts

Ultimately resulting in a shortened engine life and an increased levelised cost of power generated. More details on how each contaminant affects engine/turbine operation is provided in Appendix A to this report.

Feedstock feeding issues were experienced with certain waste mixtures due to "sticktion" and jamming, caused by moisture content and material thermal decomposition effects. However, the feed systems used on the rigs were not optimised for the material mixtures tested and in practice the feed system may be appropriately designed. However, deviations from the designed-for feedstock may present issues in this regard, and increased system robustness might be achieved through feedstock manipulation. Standardisation in feedstock properties, such as the production of RDF (Refuse Derived Fuel) or SRF (Solid Recovered Fuel), or other physical homogenisation techniques such as pelletisation would be expected to help in this regard, although instigate a significant energy penalty, and so would need to be balanced in terms of total system efficiency.

The quantity of output gas was measured to be approximately constant for all material mixtures for each technology. However, the gas composition, including the levels of trace constituents, was found to vary depending on the feedstock composition. The inclusion of paper and card with food wastes in anaerobic digester reactions was found to decrease the initial reaction rate, leading to a decrease in the production of gas contaminant H_2S. For the gasification tests, variable levels of tars and other contaminant compounds and elements were measured. Whilst gas engine operation was successfully shown on simulated, clean gasification type gases, these contaminants would be expected to adversely affect engine operation. The effect of these contaminants is typically to cause blockages and constrictions, and/or to cause corrosive damage. In either regard, the end effect is to cause an increase in the cost of energy generated as engine performance (and hence amount of heat and power generated) is reduced, and the costs associated with maintaining engine performance are increased. The requirement of adequate quality gas in efficient downstream generation technologies such as gas engines and turbines reiterates the paramount importance of cost effective, robust gas cleaning technology to enable effective utilisation of the waste material resources.

Gas cleaning technologies

Although certain designs of gasifier generally produce lower levels of tars than others (due to longer residence time in thermal break-up zone and lower propensity for gas to cool and tars to coagulate in the reactor), practical experience with these technologies has shown that no gasifier design exists that produces a gas that is completely free of tars; the thermochemistry of the fundamental reaction also suggests that this would not be possible, unless a material with a single vaporisation point were being processed (hence applicability of gasification to coal). Hence, the gas is required to be cleaned before it is used in an engine/turbine. The level of cleaning depends on the level of contamination present in the gas (feedstock and reactor dependant) and the acceptable level for the end use (contaminant level/operational cost trade-off). A range of technologies exist to remove specific contaminants from the gas. However, the range and combination of contaminants from the gasification of waste, including elemental chemicals and tars, presents a unique challenge to gas cleaning.

Incineration Flue Gas Treatment

Mass burn incineration of waste materials is a common form of waste disposal, with energy recovery enabled through recovering the thermal energy in the flue gas to drive a steam cycle. Prior to release to the atmosphere, flue gases are required to be cleaned to meet emissions legislation. These gas cleaning requirements differ from those placed on gasification gases for use in an engine/turbine, in that the complete oxidation at ~1200 ℃ of the material (combustion in excess air) produces a flue gas which is free of partially decomposed tars. To meet legislative requirements, NOx, SO_2, particulates, PCBs (Polychlorinated biphenyl) and metals are required to be removed. In modern system, this is achieved through ammonia injection into combustion chamber to remove NOx (selective non-catalyst reduction - SNCR) and bubbling the flue gas through a fluidised bed of lime (to remove SO_2) and activated carbon (attract PCBs and metals) followed by a bag filter to remove particulates and entrained carbon/lime. The lack of tars in the gas prevents both the fluidised bed and filters clogging up.

References

Burnley S.J. [2007] – "The Use of Chemical Composition Data in Waste Management Planning – A Case Study", Waste Management vol 27, pp 327-336

Appendix H: Summary of technology readiness for use with wastes

If the NASA technology readiness level (Safin, et al, 1989) are used the technologies can be assessed as follows

Technology	Technology Readiness Level	Current Operating Scale	Development Opportunities	Pros	Cons
Gasification: Fluidised Bed	6-9	Over 50kt feed/yr	Develop smaller scale low cost units that can handle mixed waste streams	Well established large scale on coal, biomass and MSW	Complex units
Gasification: Downdraft	5-7	Not used on wastes	Small scale units that are simple cheap easy to operate and safe	Very simple	Ensuring safe operation, particularly environmental performance
Pyrolysis	3-5	Not used on mixed wastes	Prove commercial operation on any scale	Good for well defined feedstocks. Affordable.	Need segregated and consistent feedstocks
Incineration	6-9	From 10kt/yr upwards	Smaller economic units with higher energy yields and better heat integration	Very well established technology	Material destruction rather than energy production
Mechanical Pre-treatment	8-9	5 to > 100 KTPA	Negligible	Basic and simple technology in most cases	Quite severe process so maintenance is often a problem.
Chemical Pre-treatment	4-9	From 5kt/yr upwards	High efficiency and low cost	Simple plant equipment that creates a digestible product	Complex to operate
Gas and Liquid Cleaning Technology	3-5	From 10kt/yr upwards	High efficiency and low cost at small scale	Convert mixed and contaminated streams to meet product specification	Expensive to buy and to operate
Integrated Schemes	3-6	Used in some countries but very few UK examples	Prove integrated use of EfW technology at all community	High conversion rate of a range of feedstocks into energy and products	High capital investment in multiple plants that require integration of plant, equipment and control systems

Definitions of technology readiness levels

Technology Readiness Level	Description
TRL 1.	Scientific research begins translation to applied R&D - Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology’s basic properties.
TRL 2.	Invention begins - Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
TRL 3.	Active R&D is initiated - Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
TRL 4.	Basic technological components are integrated - Basic technological components are integrated to establish that the pieces will work together.
TRL 5.	Fidelity of breadboard technology improves significantly - The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include “high fidelity” laboratory integration of components.
TRL 6.	Model/prototype is tested in relevant environment - Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology’s demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
TRL 7.	Prototype near or at planned operational system - Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment.
TRL 8.	Technology is proven to work - Actual technology completed and qualified through test and demonstration.
TRL 9.	Actual application of technology is in its final form - Technology proven through successful operations.