Programme Area: Bioenergy

Project: Energy From Waste

Title: Technology System Improvement Opportunity Report

Abstract:

This deliverable is number 3 of 3 in Work Package 3 and describes the findings and outputs from the technology system modelling work carried out by the consortium. It draws on the outputs from WP1 – Waste Assessment and WP2 – Assessment of EfW technologies. It combines the arising data from each work package into an economic, mass and energy model which takes into account the changing availability of wastes in the UK and aligns technology choices with the likely waste arisings.

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

Deliverable 3.3 Technology System Improvement Opportunity Report

Final

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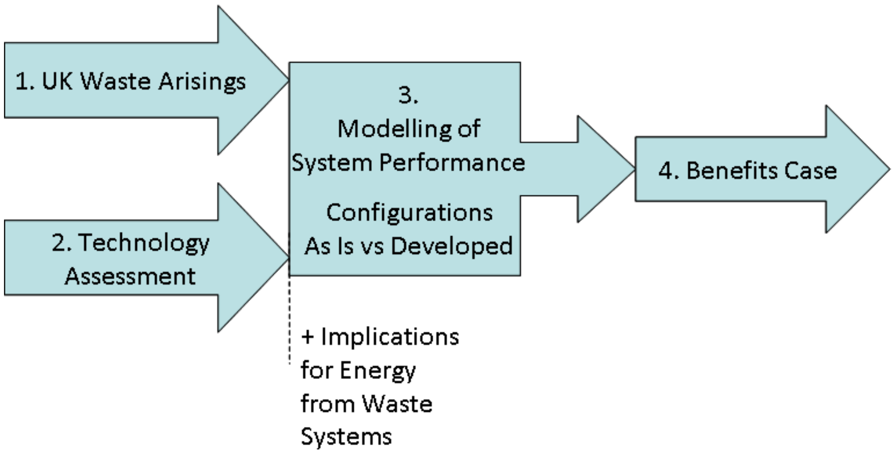
1. INTRODUCTION

This report has been produced by the Centre for Process Innovation (CPI) for the Energy Technologies Institute's (ETI) Energy from Waste (EFW) Project Consortium that forms part of the ETI Distributed Energy Programme. The project structure is shown below in Figure 1. This report is the deliverable from Work Package (WP) 3.3 of the EFW project.

Figure 1. Outline of the Project Structure



As population and affluence grow the world is facing a rapidly increasing demand for its finite natural resources; in particular fossil fuels. Energy demand and the emissions that result from fossil fuel use are rising with increasing population and affluence. There is therefore a need to reduce consumption of fossil fuels without damaging quality of life. For many years the philosophy of Reduce consumption, Reuse resources and Recycle materials has gained strength and is now being built into legislation and regulation. It is now proposed that a fourth 'R' is added to the series to Relate the steps of resource use and recycling together into Resource Integrated system. Fossil fuels are being consumed faster than they are being created and this is releasing carbon that was stored in the fuels into the atmosphere as carbon dioxide and other greenhouse gases. As fossil fuel availability diminishes there is an increasing likelihood of energy shortages.

In addition the increasing population is creating more wastes that have to be stored for a long period of time. In many cases these wastes have a calorific value and could be used as energy feedstocks. There are significant opportunities to both reduce emissions and reduce the use of fossil fuels by developing effective strategies to create energy from waste. This has the multiple benefits of:

- Decreasing the need for landfill,
- Reducing the consumption of fossil fuels,
- Reducing emissions of greenhouse gases,
- Improving energy security,
- Creating more localised distributed energy systems.

A significant part of the EFW approach involves closing loops between waste production and the demand for power and heat.

This report draws on the waste analysis and technology work carried out by Cranfield University in WP 1 and 2. It combines this data with a simplified economic, mass and energy model based on the detailed modelling carried out in deliverables WP 3.1. and WP 3.2. The report takes into account the changing availability of wastes in the UK and aligns technology choices with the likely waste arisings with reference to the energy content, physical form and other attributes.

In this report the waste data are summarised and discussed. These data have been used to create four community scenarios to model EFW systems. The report also summarises the technology analysis that was undertaken between WP 2 and 3 to describe the main features of the technologies and their appropriateness for use in EFW systems.

These base data are combined to create models for each of the four community scenarios that identify the most appropriate feedstock and technology options for EFW systems at each community scale. The scenarios analyse potential throughputs, product yields, profitability and emissions to describe potential operating regimes for the communities. The model outputs have been used to identify technology development opportunities for each scenario.

The report concludes by combining the technology opportunities to identify technology development opportunities that could form the basis of practical development and demonstration work that the ETI could pursue in the next stages of its Distributed Energy Programme.

In addition to the work carried out by the project consortium this report also incorporates the output of a workshop organised by the ETI for interested project stakeholders from academia, the public and private sectors[1].

The output from this report forms a core part of the modelling and UK benefits work reported in the WP 4 benefits case reports.

[1] Notes from ETI Waste to Energy Project Stakeholder Workshop, November 2010

2. WASTE DATA AND FUTURE WASTE VOLUMES

The Office of National Statistics for the UK produced an energy consumption report for the Department for Energy and Climate Change (DECC) in 2010[2]. This showed that total UK energy consumption was 220 million Tonnes of Oil Equivalent (TOE). This is approximately 9.02×10^9 GJ per year.

The waste data produced by Cranfield University in WP1 showed that on average a UK resident produces around 1.8 tonnes of waste per year. This is made up from municipal solid waste (MSW), commercial and industrial waste (C&I) and wet wastes such as sewage sludge and agricultural wastes. In total there is around 90 million tonnes of waste arising each year. If the average calorific value of the energy containing wastes is 10 GJ per tonne and if 50% (assuming high collection efficiency) is converted to usable energy at 70% efficiency (assuming a high proportion of CHP) waste could produce around 11.4 TWh (32×10^7 GJ) annually. This means that although EFW can make a contribution of around 3% to the UK's energy requirement it will always be a small contribution to mainstream energy supply. In fact the DECC 2050 UK Energy Pathways Analysis[3] assumes that energy from waste will not supply more than 1% of UK energy demand. The initial conclusion from the waste data is that EFW will be most beneficial in cases where local distributed solutions can be created. However, it should be noted that advanced technologies capable of processing waste materials are also likely to be able to handle biomass and other feedstocks, thereby supporting further power generation capacity and associated CO_2 reductions.

As part of WP1, Cranfield University gathered and analysed waste data from specific sites across the UK[4]. The sites, owned by Shanks Waste Solutions, are located at Kettering, Blochairn, Broxburn, Aylesbury, Elstow and Milton Keynes. The results from this work have added to the knowledge of what waste arises at these facilities. If this waste could be turned into usable energy each site could supply between 2 MW_e to 10 MW_e depending on the EFW technology used.

The waste types and volumes collected from the sites are variable in both form and composition. The moisture content of these wastes varies with the seasons and weather conditions. In addition materials that have an economic value are extracted from the waste stream for use in material specific recycling processes. Values for the various components of the waste stream vary with the simplicity of segregation and the future use of the material. Table 1 summarises the values in Q3 2010.

[2] Digest of UK Energy Statistics 2010, DECC, 2010
[3] 2050 Pathways Analysis, July 2010, DECC, 2010
[4] Reports for Work Package 1 of this project produced by Cranfield University during 2010.

Table 1 Examples of the Value of Sorted Wastes (October 2010 Prices)[5]

Product	Value (£/t)	Form	Grade
Mixed Paper	75	Segregated	Domestic mill baled
Cardboard	87	Segregated	
Newsprint	120	Segregated	
Sorted Office	168	Segregated	
Domestic Polyethylene	270	Segregated	Baled and delivered
Domestic Polyethylene Clean	370	Segregated and Washed	
Export Polyethylene	100-300	Segregated and Washed	
PET Clear and Light Blue	270	Segregated and Washed	
HDPE Natural	320	Segregated and Washed	
HDPE Mixed	180	Segregated and Washed	
Charity Rags	590	Segregated	Delivered
High grade wood	5		Delivered

Table 1 indicates that certain materials within the MSW and C&I waste stream have economic value. These values change with the supply and demand for the particular products. What is clear is that product values are attractive enough that a proportion of the waste will always be extracted for further processing. This means that the remaining MSW and C&I streams available for EFW processes will vary in composition seasonally and in line with changes in the opportunity cost of material segregation for alternative processing. It is concluded that EFW technologies have to operate with variable and changing feedstock mixes. The variation will be in shape, size and mix and it is likely that the MSW and C&I waste will be the residual material that has no commercial value.

In 2010 some waste streams had negative values (often known as a gate fee) as it was more economic to pay to have the material removed and processed than to pay for landfill tax or fail to meet the local authority trading scheme (LATS) requirements. Therefore the base price for mixed waste is the value of landfill tax minus the cost of transport to the processing site. Clearly the balance between the rising landfill tax, the requirements of the LATS and the rising cost of transport to the processing facility will act together to drive the gate fee for feedstock supplied to processing facilities. Many large-scale incinerator operators have 25 year supply contracts with local authorities to process their waste to avoid landfill and meet the LATS requirements. These contracts are at a cost to the local authority and the gate fee is related to a range of factors including price indices and other economic factors. However, as demand for waste into the energy stream increases the cost of feedstock will rise, especially as waste arisings fall with the forecast increase in the recycling of materials. The changing availability, mix and price of wastes are critical in the choice and adoption rate of EFW technology. In addition, the profitability of existing and planned facilities will also be critical to the uptake of a technology.

The waste collected by Cranfield University has been analysed for calorific value (CV) and elemental composition. It is of mixed form and consists of mixtures of plastics, textiles, food, wood, paper and card. This collection and analysis has been carried out over all four seasons. A summary of the elemental analysis data is presented in table 2 of WP report 1.3 and is repeated as Table 2 below. Though the waste is different in its form it is very consistent in type. Its elemental analysis is even more consistent on a moisture free basis. There is only a small amount of reported work on mixed waste streams. One major report by Battelle is referenced in the table below to compare other waste analysis done on materials used in a gasification process.

[5] Spreadsheet produced by Zane van Romunde, November 2010 using data from LetsRecycle.com

Table 2 Average Elemental Composition of all Waste Samples Taken (Moisture Free)[4]

Weight % basis	Average	Standard Deviation	Battelle Technical Paper[6]
Carbon %	49.4%	0.052	45.52
Hydrogen %	5.6%	0.015	5.75
Nitrogen %	1.5%	0.015	0.29
Oxygen %	42.8%	0.051	37.79
Sulphur %	0.3%	0.004	0.19
Chlorine %	0.4%	0.005	0.43 to 1.54

When converted to a molecular formula the average waste composition becomes $CH_{1.4}O_{0.65}$. This closely approximates to that conventionally given to biomass of $CH_{1.4}O_{0.5}$. There are potentially several reasons for this. Firstly much of the material in the MSW and C&I stream is of biogenic origins such as the demolition wood and paper and card materials. The DECC 2050 Pathways Report[3] indicates that in 2007 65% of the MSW and C&I waste stream was combustible: while 35% was biogenic. Secondly, a large amount of the plastics are polyethylene terephthalate (PET). The monomer formula of PET is $C_{10}H_8O_4$, which would reduce down to $CH_{0.8}O_{0.4}$. Again this is similar to biomass. It has therefore been decided that to maintain a simple approach to the modelling work in WP 3.3 the average elemental composition for all wastes $CH_{1.4}O_{0.65}$ would be used. Additional modelling can be undertaken to assess the effect of changes in waste composition in a follow-on project.

A noticeable factor is the low chlorine content of the materials collected by Cranfield University. Expectations were that this would be significantly higher than found. It is believed that poly vinyl chloride (PVC) is being collected and positively recycled by the manufacturers, such as INEOS, in their processes so it does not appear in the mixed waste stream. Again this is a factor that is hard to predict, as are the other materials, such as polyethylene, that may also be taken out of the supply chain. This illustrates the importance of feedstock flexibility in the conversion processes due to market changes.

The modelling at CPI has been based on the average elemental make up of the waste. This approach is not unique and has also been adopted by other organisations such as the National Renewable Energy Laboratory (NREL) in the US[7]. This approach has allowed the team to model the processes as if the waste material was biomass. In certain special circumstances MSW and C&I wastes may not behave as biomass: e.g. if only polyethylene was processed, a depolymerisation process would be more likely to happen. This is unlikely to occur in a mixed waste stream, so the assumption that waste behaves as biomass is applied throughout.

The conclusion from this work is that chemical composition of the waste can be assumed to be constant but there and there are two major variables that require close management. These are:

- Material shape or form and
- Material moisture content.

[6] Battelle Technical Paper: Gasification of Refuse Derived Fuel in a High Throughput Gasification System. Mark A Paisley, Robert D Litt, and Kurt S Creamer. 1990

[7] NREL Report that uses average waste composition.

Moisture content in the Cranfield University samples varied from less than 10% to a one off value of 71% with the average being around 25% over a year. Clearly this has a major impact on the net CV of the materials being processed as the evaporation of the water has a major burden on the net energy output and above 40% moisture processes become energy users rather than producers. Appendix 1 presents a simple graphical representation of the effect of moisture on net CV, done for gasification. However, as a general rule the industry assume 5MJ/kg of energy for each 10% of moisture content.

EFW plants need to be able to handle materials with varying shape and moisture content. Controlling the moisture content of the materials will be critical to consistent energy production. The product form required varies between technologies. Large incineration plants can handle material over a very wide range of shape and sizes.

However, smaller scale incineration (<$5MW_e$), advanced thermal processes (e.g. gasification and pyrolysis) and anaerobic digestion processes require consistent feedstock size and shape to operate most effectively. As a result, these technologies require pre-treatment equipment upstream of the main processes to ensure the size and moisture content of the feedstock optimises operation. Equipment is available off the shelf for this purpose and can be integrated into process designs. Ensuring the correct shape and size of materials fed to the processes is a critical factor to their consistent operation.

EFW plants also need to be aware of the content of non combustible materials and potential contaminants. Plants need to be designed to handle these materials and the requirements are outlined in the Strategic Environmental Impact Assessment[8].

[8] Strategic Environmental Impact Report, AEA Technology for Work package 4, December 2010.

3. COMMUNITY SCENARIOS

The project team has decided that the best way to assess the technology options against the average waste composition is to create a small number of population scenarios. The scenarios are based on representative sizes of typical UK communities. The objective is to:

- Develop the waste scenario for each case;
- Assess the technology options that can be used to process the wastes in a way that delivers the most effective financial and environmental contribution to the community's energy requirement;
- Identify the technology developments that can improve the waste to energy supply;
- Bring the data together into a potential technology development plan with options for future funding.

Table 3. Community Scenarios

The community scenarios chosen are:

	Population	% of UK Population	Number in the UK	Activity
City	500k	34	5 cities over 500k 26 between 200k and 500k e.g. Leeds	Residential, industrial and service
Town	50k	43	A few hundred towns e.g. Corby	Residential and commercial with light industrial
Village	5k	21	Over 1 thousand villages of this size	Mainly residential
Rural Agricultural	500	2	Very large number of communities of 500 or less	Mixed farming and residential

The scenarios have been chosen to represent the scales of EFW plants that will be required to meet local energy needs. Most of the current effort in EFW is targeted at conurbations on the scale of a city. However, 64% of the population lives in towns or villages. EFW opportunities at this level provide a significant opportunity for technology and system development. They can provide a significant percentage of their total energy requirement. Hence the need for town and village solutions to be part of an integrated low carbon energy supply system.

As part of the work in WP1, a spreadsheet was developed to model future waste arisings in the UK against these community scenarios. In addition to forecasting overall waste arisings the spreadsheet includes a sensitivity analysis on the amount of recycling and re use in the community. These data are summarised in Table 4.

These scenarios are a generalisation but are an acceptable route for simplifying the modelling of a complex problem. The scenarios are used to assess technology options. For the purposes of modelling it is assumed that:

- The technologies will be taken up by communities that can use them;
- The transportation of wastes to a very large regional facility does not occur;
- There will be no planning constraints affecting the EFW developments.

All of these assumptions represent a significant change from the current norm, but it is likely that changes in behaviour will occur in the future.

Waste reduction, reuse and recycling policies combine with trends to have an impact on the scenarios and the conditions have been varied to show changes. There is a growing industry in waste collection, sorting and transfer to treatment and processing facilities. These processes extract and sell high value components of the waste and do some pre-treatment activities. These activities are outside the scope of this report, but they are having an increasing impact on the quality, treatment and content of the wastes being fed to EFW plants. The sorting technologies employed include materials recovery facilities (MRF), solid recovered fuel (SRF) units and refuse derived fuel plants (RDF). This project does not assess the effect of these technologies on waste arising. Consequently, a range of +/- 20% has been applied to the ranges of waste forecast by Cranfield University to cover changes over the next 20 years. The potential range for 2030 is shown in brackets in Table 4.

Table 4. Summary of Waste Scenarios (2030 range of wastes in brackets) [4]

Scenario	Population	Dry Waste (kt/yr)	Dry Waste Energy Content (MJ/yr)	Wet Waste (kt/yr)	Wet Waste Energy Content (MJ/yr)	Comment
City	500k	490 (306-673)	$4.8x10^9$ ($4x10^8$-$5.6x10^9$)	408 (255-560)	$9.2x10^8$ ($7.7x10^8$-$1.1x10^9$)	Urban with little agriculture
Town	50k	49 (31-67)	$4.8x10^8$ ($4x10^8$-$5.6x10^8$)	41 (25-56)	$1.0x10^8$ ($8.7x10^7$-$1.2x10^8$)	Residential and commercial
Village	5k	4.9 (3.1-6.7)	$4.8x10^7$ ($4x10^7$-$5.6x10^7$)	4.1 (2.5-5.6)	$1.1x10^7$ ($9.7x10^6$-$1.3x10^7$)	Residential with little commercial
Rural Community	500	0.49 (0.31-0.67)	$5.1x10^6$ ($4.3x10^6$-$5.6x10^6$)	20	$6x10^7$	Mainly farming with residential

4. TECHNOLOGY REVIEW SUMMARY

The results from WP 2[9] have been used as a basis for the technology modelling. The work done has identified the technologies discussed below as the ones most likely to be used in EFW systems. In all scenarios there are a range of base technology options and these are discussed later. Practical experiments in WP 2 were done on Anaerobic Digestion (AD), Gasification (including Updraft, Downdraft and Fluidised bed) and Pyrolysis. In addition incineration has been included as the current incumbent technology for waste to energy. The work assumes that MSW, C&I and wet wastes to be converted to gas, electricity, heat, power, transport fuels and chemicals.

4.1 Gasification

Gasification has been applied to biomass and coal for over a hundred years, on a variety of scales, from the hundreds of megawatts in induced flow coal units to small units that have powered automobiles in the second world war and the 1970's fuel crisis. Depending on the process technology, gasification takes place between 600°C and 1200°C and has been operated on biomass in the range 0.2 MW_e to 40 MW_e. For the purpose of this document pyrolysis that occurs above 600°C and produces a gaseous product is treated as gasification and are referred to in this document as Advanced Thermal Processes (ATP). At this stage the development of gasification processes from virgin biomass, MSW and C&I are under development and these processes are discussed in detail in the technology review that forms part of Work Package 4. There are also examples of large gasification units running on a combination of coal, wood and wastes[10].

The work carried out by Cranfield University shows that the technologies investigated in this project can operate on waste materials. The data indicate that there is no essential technological difference in processing waste to processing biomass. However, there will be a need for pre-processing of feedstock to ensure the form and moisture level are compatible with gasification process. From the results of the experiments it can be concluded that the same stages of drying, pyrolysing and gasification are occurring.

The main product from the advanced thermal processes is syngas (hydrogen and carbon monoxide mixed with the process gas) with by-products of residual tar, char and ash or slag. All the by-products require further processing or disposal and can represent a significant capital cost. Syngas quality is dependent upon feedstock and process. In most cases there is a need for syngas cleaning and treatment prior to downstream processing. Fluidised bed plants use air or nitrogen in the treatment beds and this dilutes the calorific value of the gas produced. Technology to handle the gas or to remove the fluidising gas is an important part of these processes.

In most advanced thermal processes any char produced is combusted to drive the process. If this is not done another external fuel supply is required and this reduces carbon efficiency. When used on biomass the CV of the gas is of the order of 5000 KJ/Nm^3 if air is the gasification medium. This value is comparable to that estimated from the tests performed by Cranfield University.

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[9] Work Package 2 reports, Cranfield University, 2010.
[10] BGL Units as Schwarze Pumpe, 2000

The advanced thermal processes are efficient when run correctly. From the stoichiometry and thermodynamics, less than 30% of the combustible materials in the feed will be required to drive the process. Optimistically the remaining 70% to 80% is converted into a useful fuel for use in a boiler, gas engine, or Integrated Gasification Combined Cycle (IGCC) power station. With expected efficiencies for the IGCC of up to 45%, while steam cycle combustion and gas engine combustion have efficiencies of up to 35% - The modelling work assumes a gas engine efficiency of 30%. Efficiencies start to drop off around the 40 MW_e dipping into the mid twenties at less than 10 MW_e.

$$\begin{aligned}&CH_{1.4}O_{0.6} + 0.4\ O_2\\&\rightarrow 0.7\ CO + 0.3\ CO_2 + 0.6\ H_2 + 0.1\ H_2O\end{aligned}$$

The syngas produced by the process can be used in a number of applications depending on the gas quality. It can be:

- Converted to energy in a combustion boiler;
- Converted into energy locally by combustion in a gas engine or gas turbine;
- Converted into energy chemically within a fuel cell;
- Converted into chemicals such as methanol or ammonia or fuels using processes such Fisher Tropsch reactions.

The current technologies used for the gasification of biomass, cover a wide range of electrical output. A number of advanced thermal technologies are in development and some are proven on biomass feedstocks although many have experienced operating problems due to a range of design issues. The use of gasification for mixed waste feedstocks is not well proven and we have seen limited evidence on actual performance in application. The advantage of these processes is that they produce syngas from all types of feedstock and gives certainty and capital efficiency to the design of downstream processes.

Based on the finding that MSW and C&I waste are generally similar to biomass, the potential for the exploitation of advanced thermal processes across a range of scales is large. The process design needs to include pre-processing to create a feed that is homogeneous in shape and moisture content. This can require effective process heat integration and may even require additional drying. It should be noted that due to the less homogeneous nature of wastes, the processes may create larger volumes of ash and gaseous contaminants than using pure biomass. The models assume an ash production of 15%.

As gasification is a pre-combustion process, it produces a syngas where it is significantly easier to separate carbon dioxide from the effluent stream for storage in carbon capture and sequestration (CCS) than it is from a conventional incineration plant. This means that plants incur lower capital and operating costs for carbon capture and storage; a factor that may increase the attractiveness of gasification in the 2030 to 2050 timeframe. The carbon dioxide stream is also significantly more attractive for biological capture processes and algae growth.

4.2 Basic Pyrolysis

The pyrolysis process is similar to gasification (and can be performed on similar equipment) but operates in a lower temperature (400°C to 650°C) regime than gasification. For the purpose of this document pyrolysis that occurs above 600°C and produces a gaseous product is grouped with gasification and the two processes are referred to as advanced thermal processes. Pyrolysis occurs in a zero or limited oxygen environment and the process volatilise the feedstock to produce three main products: syngas (a mixture of predominately carbon monoxide and hydrogen), pyrolysis oil (consisting of various aliphatic and aromatic compounds) and a char material that is mostly carbon. The gas is of good quality, but the oils from this process have low calorific value, and are often unstable. This is due to the high oxygen content of the oils. There is also a need to handle the significant amount of char that is produced.

There are two types of pyrolysis;

- Slow pyrolysis (charcoal production) which produces a product split of liquid (30%), char (35%) and syn gas (35%) by weight and;
- Fast pyrolysis produces liquid (75%), char (12%) and syn gas (13%) by weight[11].

The process that is most likely to be of benefit in the processing of wastes is the fast pyrolysis route. In pyrolysis >25 % by weight of the feed material is consumed to drive the process. Due to the absence of a transporting gas the syngas produced from pyrolysis has a higher calorific value than that produced in gasification, but the amount of gas produced is lower.

Most pyrolysis processes are run to produce bio-oils that have a similar calorific value to the original starting material. This philosophy is likely to work with wastes as the composition is similar to biomass. However, the oils have a short shelf life and a tendency to solidify due to the oils being in a non equilibrium state and the oxygen compounds in the mix being catalysed by residual char. The resulting reaction creates a solid or gelled product. The value of these bio-oils may be increased by using catalytic hydro treating to improve their quality and stability. The work performed by Cranfield University has shown that the MSW and C&I waste do pyrolyse as expected.

Again, the energy efficiency of the pyrolysis process will be highly dependent on the moisture content of the feedstock. Pyrolysis can be performed on a variety of equipment from fixed and fluidised beds to rotary kilns.

Pyrolysis is most effective when used with segregated streams such as tyres or specific plastics. It is of less use for mixed and variable feedstocks as the bio-oils produced vary with feedstock quality and quantity. In addition the oxygen content of these bio-oils makes them unstable for use without further processing. Because of this sensitivity to feedstock mix pyrolysis has not been modelled in the scenario analyses later in the report although it is likely to be used in specialist applications such tyre pyrolysis to produce carbon black.

As pyrolysis is a pre-combustion process it produces a syngas where it is significantly easier to separate carbon dioxide from the effluent stream for storage in carbon capture and sequestration (CCS) than it is from a conventional incineration plant. However, there is a need to burn some char to power the process and this releases additional carbon dioxide. The char that remains is mainly solid carbon and is a form of sequestration if the char is not used in other thermal processes.

4.3 Incineration

[11] Large-scale pyrolysis oil production: A technology assessment and economic analysis M Ringer, V Putsche, & J Scahill Technical Report NREL TP-510-37779 November 2006

Incineration from the Greek route literally means to reduce to ashes. This is a process where materials are combusted completely in air releasing heat. There are several technologies available to perform this process including fixed grate, moving bed, fluidised bed and rotary kiln. The facilities can be very large with feedstock capacities of up to several hundred thousand tonnes per annum.

The processes directly use the heat from combustion to produce steam which is then turned into electricity using a steam turbine. An advantage of incineration is that it can handle a large variety of materials with little pre processing. The electrical production efficiencies of these facilities are of the order of 15% to 25%; again this efficiency is affected strongly by the moisture content of the fuel. Large-scale units have high capital costs as they include the cost of large gas cleaning trains, to meet regulated emissions requirements as well as ash and slag collection systems. The plant costs generally follow the 0.6 power law for scale-up with larger plants having a lower cost per tonne. However, much smaller units are being developed that operate down to 10kt/yr of waste, though typically at lower overall energy recovery efficiencies than larger plants.

Incineration has had a poor reputation in the past gained from the weak emissions controls of some facilities and the discharge of dioxins etc. to the atmosphere. This was most likely due to poor process design or short cutting in some facilities. If designed and operated correctly incineration systems work well. However, there is still a large requirement for emissions treatment facilities and these can make up more the 33% of the total plant cost. In summary, incinerators are a good option for waste disposal, power generation and community heat networks.

Investments have been made in large incinerators as they are proven technology and as such are bankable. However, it is worth noting that even investment in proven technology is not simple as plants need long term feedstock supply contracts, planning permission and secure power or heat off-take agreements before investment can be secured. Waste to energy plants also have a poor reliability reputation making investment more difficult to secure.

If newer technology is to secure investment it will need to be well proven at the demonstration scale.

4.4 Multi Stage Processes

Many of the technologies currently under development combine a number of technologies into one process and some of these are outlined in the technology landscape study[12]. Typically these combine an initial pyrolysis process with subsequent gasification or incineration steps. The complexity of these plants is such that they are unlikely to be economically viable unless they are constructed at very large scale and there is a need to ensure that feedstock is secure for the life of the plant. Economics in many European countries are also supported by both supply and demand side incentives such as landfill tax, feed-in tariffs and renewable heat incentives.

4.5 Anaerobic Digestion (AD)

[12] Technology Landscape Study, AEA Technology, 2011

In AD biogenic material is broken down in the absence of oxygen. It normally takes place at ambient conditions using waste slurry of 5% to 10% solids although there are AD plants that handle high solid content biogenic waste. Micro organisms break down the slurry to produce a biogas – mainly methane with some carbon dioxide and a little hydrogen – and a digestate. The digestate is often used as a soil conditioner, fertiliser or can be dried and used in gasification processes. The major contaminant produced in AD that can be harmful to both people and machinery is hydrogen sulphide which, depending on the feed, can be in the hundreds of ppmv. Mediating its production rate and having adequate gas cleaning technology is crucial to the development of AD.

AD processes are long term with residence times around three weeks. Some reduction in the processing time can be achieved by the use of thermophilic organisms that operate at around 55°C.

As the AD process is slow, the plants are large for the electrical output when compared to conventional generating capacity but development activities are underway to develop smaller scale units that have a reduced capital cost.

AD is a desirable part of EFW systems where wastes have very high water content and can be readily turned into aqueous slurries. It is a proven technology that has wide acceptance throughout Europe.

The tests at the European Institute for Energy Research (Eifer)[13] carried out in WP 2 investigated the impact of using paper and card combined with typical AD type wastes such as food materials. The tests and parallel modelling work showed that up to 20% of dry paper and card could be added to food waste without significantly reducing biogas production and the paper and card also acted to stabilise digestion rate and limit the volume of hydrogen sulphide produced. However, paper and card are essentially dry and are best used in thermal processes for energy production.

The modelling of the AD process has been based on an elemental analysis approach and the use of the Buswell equation. The Buswell equation provides a stoichiometric balance converting the biomass to its products.

$$CcHhOoNnSs + 1/4(4c\text{-}h\text{-}2o+3n+2s)H_2O$$
$$\text{---->}$$
$$1/8(4c\text{-}h+2o+3n+2s)CO_2 + 1/8(4c+h\text{-}2o\text{-}3n\text{-}2s)CH_4 + nNH_3 + sH_2S$$

The production of biogas is a function of the amount of the feed that is biodegradable and how much of that material is accessible to the bacteria.

4.6 Limits of Application

The technologies that have been investigated for the EFW project have been operated on a range of feeds and in a range of applications from the kW to MW scale. The processes have limits to their use that are technical, physical or economic.

The different forms of advanced thermal processes have been shown to operate from very low electrical output on biomass using downdraft gasification systems to approaching 50 MW_e when using re-circulating fluidised bed gasification, with the best gas quality resulting when

[13] Work Package 2.2 report, Cranfield University, 2010

pure oxygen is used as the fluidising gas, as the syngas is not diluted with nitrogen. The energy density is higher and more economic for pipeline distribution. However, oxygen is an expensive gas to produce in volume.

Incineration is a technology that requires a substantial amount of energy to start the process and to get the ‘reaction’ mass to self-sustaining conditions. There are heat losses associated with the process. To have a net positive energy balance plant throughput normally needs to be a few tens of thousands of tonnes per year at least. Small incinerator plants tend to have high capital cost per tonne of waste processed.

Pyrolysis is a less intense process than the other thermal processes. It is most commonly used in rapid pyrolysis processes to produce a liquid fuel. This fuel, if similar to that derived from biomass, will require further treatment to allow it to be transportable or used in the best application. Pyrolysis is an endothermic process and requires an external heat source to operate. This can be another fuel or it can be energy created by the combustion of its own char. It is believed that most pyrolysis processes are relatively small in scale.

The ability to switch process conditions using a combination of changing temperature and pressure from gasification to pyrolysis and vice versa depending on the requirements of the market and the feedstock would be a significant technology advantage, but this has not so far been achieved in a commercial plant.

AD has developed significantly in recent years and efforts are being made to develop both smaller and larger plants, but there is still a major opportunity in improving process efficiency. One obstacle to the development of AD is the cost of cleaning up for use in gas engines and turbines or upgrading and blending the gas for injection into the existing natural gas grid.

All the core technologies discussed in this section require additional equipment upstream or downstream of the core reactors to operate effectively. The core processes whether thermal or biological require the feed to be pre-treated to the correct size, shape and moisture content. In most cases this requires crushing or maceration in a mechanical device or steam treatment to disrupt cell structures. Some biogenic feeds also need to be pasteurised prior to treatment. Pre-treatment processes consume energy, but this is not generally an excessive load and it commonly uses excess energy from the plant process. However, incineration does not require pre-treatment. Plants can generally accept combustible material of any form up to moisture content of around 40%.

The largest burden on the thermal processes is management of the moisture content in the feed materials. Decisions need to be made early in project development as to the range of moisture the process can accept. In some cases drying systems are required to keep the output quality consistent. Alternatively there needs to be confidence that the process is flexible enough that it can cope with variation in the feedstock while producing consistent product.

The gases produced from the thermal treatment processes contain tars, ashes and other solids. This has been confirmed by the Cranfield University experimentation. If the gas or fuel is to be used in an engine it must first be cleaned. One notable result from the analysis performed by Cranfield University is the very low levels of chlorine seen in the feedstock samples. This suggests that any PVC is segregated from the waste stream before the MSW and C&I waste arrives at the processing plants. If further samples continue to show that PVC is extracted it can bring significant benefits to plant design and operation with a considerable impact on materials of construction.

The gas treatment technologies that have previously been used for biomass gas treatment have been cyclones, barrier filters of various types, electrostatic precipitators and scrubbers. Whatever the final technology choices the development of cleaning technologies is important. Though these pieces of equipment are potentially not an excessive operational cost burden on the process the extra capital investment may have a significant influence on the economics. If the technology fails during operation then this will have serious implications. As a result gas cleaning is identified as a technology development opportunity in later sections.

Catalytic cracking of the tars may be a viable option, this depends what the desired final product output is; especially if a good clean syngas is required.

A balance needs to be made between what the engine or other energy conversion device can operate to and how much cleaning is needed.

The cost of the EFW processes vary with the type of technology selected and economies of scale. If gasification is taken as an example at the small scale downdraft gasification is a refractory lined 'tin can' that is charged with material and allowed to work down the packed bed. Downdraft gasifiers are low cost, but have physical limits due to the pressure drop of the flow of gas across a larger bed. At the other extreme a dual re-circulating fluidised bed gasifier is a complex unit that has to be large scale to be economic.

The project team has identified that an understanding of the available waste processing technologies, unit sizes and operability would add further to the basis for technology decision making. This piece of work was commissioned in January 2011. In addition there have been studies conducted in recent years that contain useful reference data[14].

[14] Juniper Consulting, Waste Gasification World Review, 2009

Table 5. Summary of Technology Readiness for use with Wastes

If the NASA technology readiness level[15] are used the technologies can be assessed as follows (see Appendix 4 for summary chart of TRL definitions.):

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 at large scale on coal, biomass	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 waste to energy 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

[15] Original NASA TRL Definitions by Sadin, et al., 1989

5. SCENARIO ANALYSIS

To identify the technology development opportunities the project team has combined the background data gathered and applied it to the community scenarios described in section 3. This knowledge includes:

- Knowledge of waste arisings and compositions (WP1);
- The background technology understanding (WP2);
- Results from the experimental technology testing work (WP2);
- Detailed modelling of specific identified processes and technologies (WP3).

A simple process model has been created that integrates technologies at the community scale and is then used to identify development opportunities. The model is described in detail in Appendix 2.

The modelling has been carried out for each of the community scenarios using current waste arisings along and a sensitivity analysis. The base data identifies the yields and costs of EFW for each of the community scenarios under a range of technology scenarios for a single year with established operations. This work has informed the technology development proposals outlined later in the document, but does not give a realistic investment assessment. The community models can be run to assess future waste scenarios, but this is outside the scope of this phase of the project. If required additional modelling can be carried out to assess the effect of future scenarios on technology choices, although as the likely future waste profile is difficult to forecast, the team has taken the view that technologies that have the potential to process variable feedstocks are the most attractive for future development. This is likely to form part of Work package 4.

The overall technology system flow sheet is presented in Figure 2.

Figure 2. Schematic Technology Flow Sheet

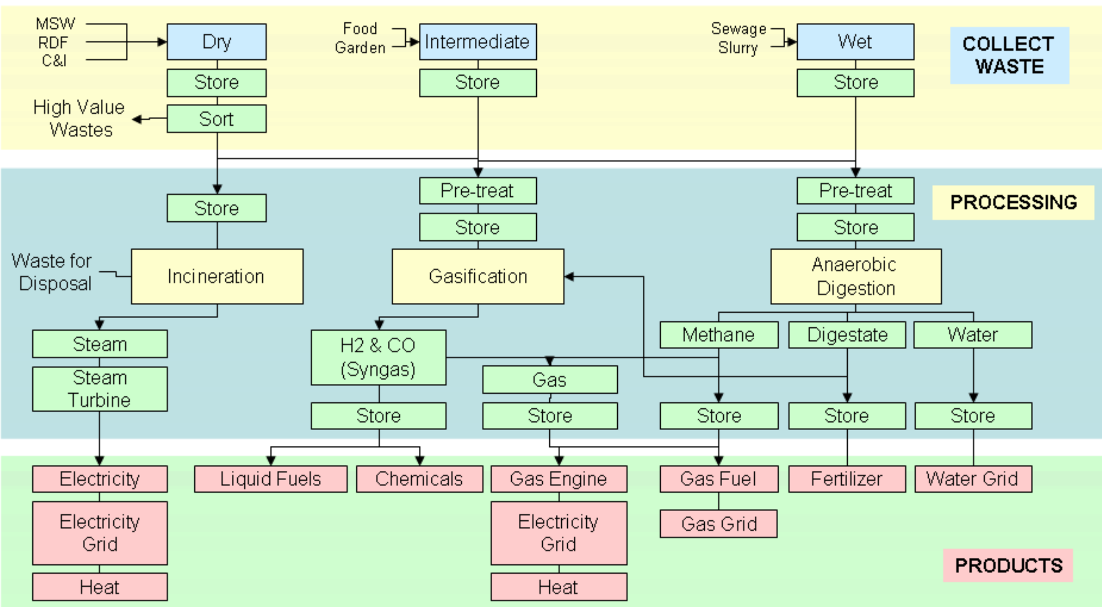


Figure 2 has used to assess the technology scale and requirements for future developments. An economic, energy and mass flow model has also been constructed to assess the community scenarios and also to look at sub-scenarios developed around the operation of a community system. The flow analysis and the model are split into three zones from top to bottom: Waste Collection, Processing and Products.

5.1 Waste Collection

Wastes are classified to be of three main types: Dry, intermediate and wet. For the purposes of this study dry wastes are assumed to be the MSW and C&I fraction that remains after any economically viable materials have been extracted for recycling. Intermediate wastes are garden and food wastes from the MSW and C&I stream. They have been grouped with dry wastes for ease of analysis. Wet wastes are liquid and semi-solid wastes with moisture contents that are consistently above 80%. In the model the waste collection is the entry point for the raw material data which are energy content, tonnage and cost.

5.2 Processing

The processing section covers the mechanical, thermal and biological processing activities that convert the wastes into energy carriers. That is: Steam, syngas, methane, digestate and water. The processing section is the main part of the economic model and requires inputs of capital cost, operating cost and conversion efficiency. The outputs from the section are product and by-product volumes and values along with operating cost and emissions.

5.3 Products

The products section summarises how each of the products and by-products can be further processed to create additional value. The downstream product production is quite specific to a process route and can be followed through in Figure 2. In the economic model this section calculates the final outputs for the integrated systems. It requires capital cost, operating cost and conversion efficiency as inputs and the outputs from the section are: product and by-product volumes and values along with operating cost and emissions. The processes modelled produce a significant amount of low and high-grade waste heat. In this model heat has not been given a value in the base analysis, as typically it is not used in the UK. However, in situations where there is a large local heating demand the use of waste heat for process or district heating can be developed. This has been assessed as a special case and comments are made around its effectiveness in the city scenario model. This modelling is complex as heat use varies with the time and temperature, but if waste heat is used it significantly increases the efficiency of energy use and significantly reduces emissions. A detailed study of heat is being studied in the linked ETI Macro Distributed Energy Programme.

5.4 Discussion

The economic model is not an accurate representation of all the specific processes and supplies a snapshot in time. It is a simplification of the detailed technology modelling undertaken in WP 3.2. The aim of WP 3.3 is to allow the analysis of the community scenarios and the identification of future technology development routes. It is proposed that once the technology targets are selected the follow-on projects will carry out much more detailed studies using the models from WP 3.2 combined with actual operating data or manufacturers data to the model the technology systems in much more depth. In addition the modelling work on distributed energy that is being undertaken in other ETI work streams will be very valuable in supporting the next phases of work under this programme. The model's ability to flex the process routes that are used has not been fully explored in this phase of the project. There is an opportunity to develop the model further and assess the interaction of the chosen technologies under a much wider range of input, operational and output regimes.

The modelling work undertaken here calculates the carbon dioxide, ash and char produced by the processes however these figures are indicative only. The model does not forecast the production of other contaminants to air and water. More detail for emission data, particularly the effect of transport is presented in WP4 through the application of the carbon model to the operating scenarios. Other emissions and pollutant data are presented in the Strategic Environmental Impact Report[10] to support the modelling work here. However there are a number of general comments that can be made about effect of EFW systems on emissions:

- Thermal processes – gasification, advanced pyrolysis and incineration – produce significant amounts of carbon dioxide as they are fundamentally combustion processes. However, the processes meet the zero rating level of the IPCC greenhouse gas inventory manual and the waste incineration directive (WID).
- The use of local distributed EFW systems that use locally arising wastes reduce the need for transport costs and some processing costs, but these are unlikely to have a significant impact;
- The use of waste heat from all types of EFW technology will have a major impact on reducing emissions. The electrical efficiency of the processes ranges between 20% and 40% with the majority of the remaining energy being in the form of waste heat that can raise overall process efficiency to over 80% if it can be used. If this waste heat could be used it would replace gas that would otherwise be burned specifically to produce heat and reduce carbon emissions accordingly.

The following four sections of this report take the input data from waste arisings, the community scenarios and the model to develop flow sheets and simple economic data that transform waste arisings into energy, fuels, chemicals and by-products to show the scale of operations required for each community. No correlation has been carried out between the community's energy demand and the supply that comes from the waste to energy transformation. In all cases it is assumed that the community demand exceeds the output from the waste to energy conversion. As noted in section 1 if the UK's waste was to be transformed into energy it could supply about 3% of the UK's total energy needs.

In addition to creating a basic flow with a simple profit calculation and an outline emissions calculation the cases have also had sensitivities calculated to show the most important factors that would drive both investment and technology development.

The WP4 reports have extended the WP3 modelling to provide 20 year net present value (NPV) calculations and to show the overall impact of EFW on emissions from both communities and for the UK as a whole.

5.5 Guiding Principles for the Community Modelling

Before the scenario modelling was carried out a set of guiding principles were developed based on the waste analysis and technology testing carried out in WP 1 and 2. These principles are:

- Wastes that can be sorted should be sorted where economic;
- Segregated wastes should go to recycling in closed loops that feed waste back to reuse - There are a wide range of established processes;
- Wet (> 80% water) bio-organic wastes will go to anaerobic digestion;
- Incineration is used where there is a need to reduce waste to landfill and where electricity and heat can be used within the community;
- Advanced thermal processes, particularly gasification, are attractive where there are opportunities to use the syngas in a range of processes such as: heat and power, chemicals or fuels;
- Pyrolysis is difficult with mixed wastes and its use would be limited to segregated wastes in most cases.

In many cases incineration and gasification are interchangeable as a route to processing dry wastes in the city and town scenarios. The model has been run twice for these two scenarios so that incineration is the preferred technology in one case and gasification is the preferred technology in the other. The additional complexity of pyrolysis processes means that they have not been modeled separately, but should be seen as variations on gasification.

It is also worth noting that local government waste management contracts generally run for 10 to 25 years. This is because current practice is to build large capital intensive plants that must be able to demonstrate a return over a number of years to secure financing and a long term feedstock supply contract is essential to this. In addition the local authorities that supply waste to the large facilities have to avoid landfill tax and meet the LATS requirements. This leads to waste feedstock prices being distorted by the need to avoid landfill (and the concomitant land fill tax and LATS requirements) and the cost of large capital investments. The result is that waste prices in the UK are negative.

For each of the modelled scenarios the results are reported as a diagrammatic flow sheet, a table that summarises the main inputs and outputs along with a 'simple profit' calculated as:

Income from product sales –
(feedstock cost + operating cost + capital investment/operating life)

The following assumptions are made for plant operating life:

- Incineration: 15 years;
- Gasification (advanced thermal processes): 10 years:
- Anaerobic digestion: 10 years.

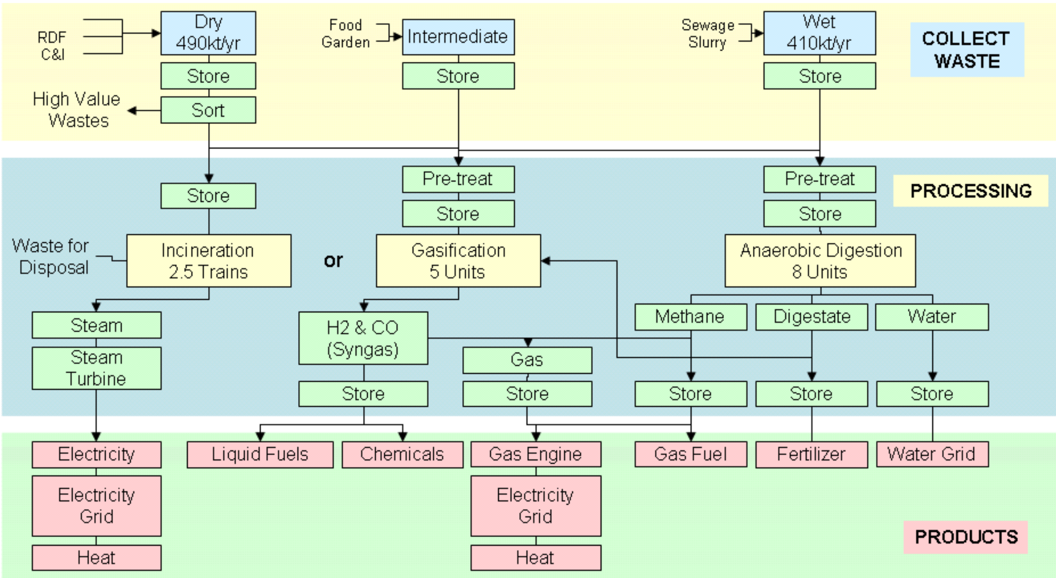
These are indicative figures used for this modelling work. Operating life has been reassessed for the net present value calculations carried out in the WP4 benchmarking cases.

In addition the sensitivities of the simple profit to the major operating variables are also tabled.

6. CITY SCENARIO

Population	500,000	
	Tonnage (kt/yr)	Energy Content (MJ/yr)
Dry Waste	490	6.4×10^9
Wet Waste	408	1.2×10^9

6.1 Product Flow Summary



6.2 Model Outputs

City Operational Summary

Scenario	Capital Investment (£m)	Base Case Simple Profit (£m/yr)	Carbon Dioxide Emissions (kt/yr)	Comments
City (Incineration)	272	10.5	940	All dry waste to incineration All wet waste to anaerobic digestion
City (Gasification and Chemicals)	307	37.9	445	All dry waste to gasification. Syngas split 33/33/33 between electricity, chemicals and liquid fuels All wet waste to anaerobic digestion
City (Gasification for Electricity)	232	8.2	662	All dry waste to gasification. All syngas to electricity All wet waste to anaerobic digestion

Sensitivity of Model Output to Changes in Parameters

Technology	Base Case Simple Profit	Capital	Feedstock Cost	Operating Cost	Product Value	Plant Operating Efficiency
Change	£m/yr (% change in brackets)	Up 20%	Up £30/t	Up 20%	Down 20%	Down 20%
Incineration no heat	10.5	5.1 (51%)	-8.3 (180%)	8.9 (15%)	6.7 (36%)	6.8 (35%)
Gasification with chemicals	39.8	31.8 (20%)	21 (47%)	37.9 (5%)	26.4 (34%)	21.1 (47%)
Gasification to Electricity	8.2	2.2(73%)	-10.6(229%)	6.8(17%)	1.6(80%)	2.5(70%)

6.3 Operating Comments

- The model shows that a city of 500k people where incineration or gasification are twinned with AD to process waste into energy. The model creates enough value to justify investment in the technology system;
- Three cases are shown: Incineration with electricity production, gasification with electricity production and gasification where the syngas is used for a combination of electricity, chemicals and fuels production. This table shows that an established plant can make an annual profit based on electricity production, but significantly better returns can be made if the syngas can be converted to higher value products such as fuels.
- The second table shows the sensitivity of the simple profit to changes in model variables. All sensitivities are shown as negatives, but an equal and opposite effect will occur if the factor moves in favour of the plant. For example a 20% increase in capital for the incineration case reduces annual profit by 50%: Equally a 20% reduction in capital cost will improve annual profit by 50%. This is because capital cost has a significant effect on profitability because the income from electricity sales is low as a result of low conversion efficiency from waste to electricity. A similar change in capital cost has a much lower impact on the gasification case where chemicals and fuels are produced as the capital charges have a much lower impact on profitability as the integrated complex has a significantly higher income. If the gasification plant is run solely for electricity the results and sensitivities are very similar to those for incineration. This shows that for a city, incineration and gasification for electricity production alone are very similar in terms of both capital cost and financial returns.
- If gasification is linked with chemicals and fuels production there is a significant increase in capital investment, but there is a very significant increase in financial returns because chemicals and fuels have a higher value than electricity. In the United States and in the Eastern part of Germany there have been recent investments in gasification based chemical complexes that produce heat, power and chemicals. Most of these plants are coal based, but a number also use a proportion of MSW in the feed. Further exploration of this integrated waste based gasification approach that couples chemicals with energy production is out of the scope of this project, but it is clear that this is a positive route to higher returns and more certainty of financing. This approach is only feasible on the scale of a city;

- The benefits case for incineration and gasification (and other thermal processes) is very strongly linked to feedstock cost, capital cost, product cost and the operating efficiency of the complex. The controllable factors of capital cost and operating efficiency are the main targets for technology development and these are explored in more detail in WP4;
- The work also assumes that technology for both incineration and gasification is available and proven for use on the scale of a city; as such there is probably little opportunity for follow-on ETI projects. The use of incineration to generate electricity from MSW and C&I waste is increasing;
- This model does not attribute a value to heat. There is an opportunity to improve the benefits case for the incinerator, gasifier and AD models by making use of the process heat. This is not widely used in the UK although there are some cities with community based combined heat and power systems. Community CHP is common across Europe. If it is assumed that heat can be used in a CHP scheme the overall efficiency of the process can be improved from 20% (electricity alone) to 80% (electricity and heat). This has no impact on the emissions from the operating plants, but the heat used will replace natural gas that would otherwise be burnt. This displacement of fossil gas would reduce the carbon emissions from a city by over 125kt/yr. This significant improvement is being investigated in the ETI Macro Distributed Energy Project and offers the single largest opportunity for carbon savings;
- Gasification or incineration plant can be integrated with large anaerobic digestion (AD) plants that are located either close to EFW plants or at water treatment works. These could augment the production of gas, electricity or heat;
- The production of chemicals and fuels is an opportunity to develop local facilities integrated with gasification plants to locally manufacture chemicals and liquid fuels in integrated EFW complexes;
- Waste to energy facilities could be operated as one large city plant or as a number of smaller integrated combined heat and power plants distributed around the suburbs.

6.4 Technology Development Opportunities

The base gasification and incineration technologies are available from a number of suppliers but there are technology development opportunities to support their adoption. These are:

- The development of low cost heat distribution networks to make use of heat produced by large incineration and gasification plants. New technology is required to install the heat networks quickly and cheaply with minimal disruption and to install the control systems that give users the freedom they get from existing domestic boilers. This is a major opportunity to reduce emissions by using the waste heat and is a high priority issue;
- AD plants on the scale of a city will produce significant amounts of biogas. Rather than burn this in a gas engine to produce electricity at an efficiency of less than 40% it would be more beneficial to make that gas available either as a vehicle fuel, heating fuel or to augment the natural gas grid. If this is to be put in place there is a need to support the development of low cost gas clean up technologies and the support the implementation of gas injection and grid

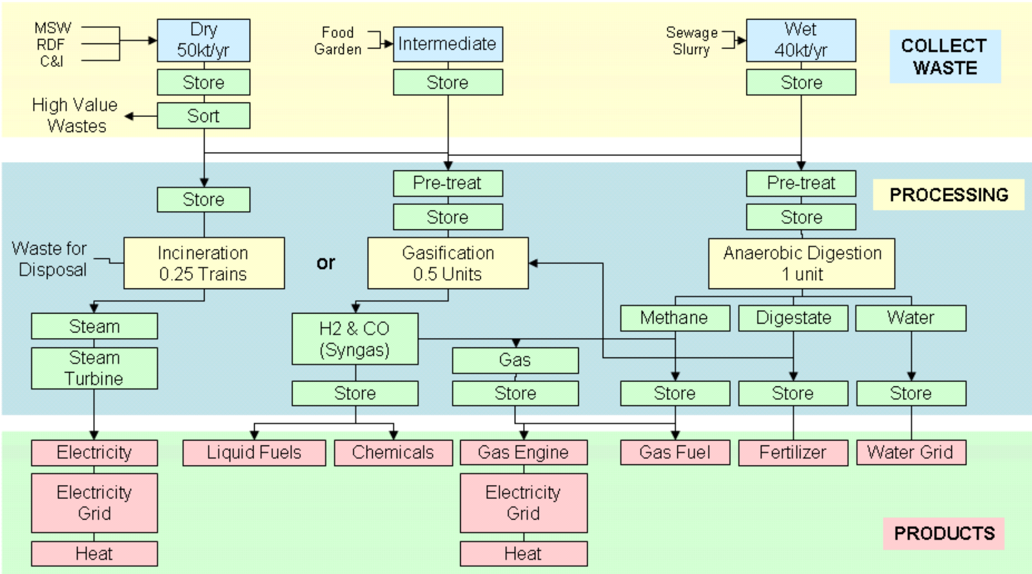
management systems. The process of handling and enhancing digestate is also an opportunity for development;

- As stated earlier there is an opportunity for converting syngas generated from wastes to chemicals and fuels. For this to become viable it would be necessary to develop low cost conversion technologies that have high yields of high value chemicals.

7. TOWN SCENARIO

Population	50,000	
	Tonnage (kt/yr)	Energy Content (MJ/yr)
Dry Waste	49	$6.4x10^8$
Wet Waste	41	$1.3x10^8$

7.1 Product Flow Summary



7.2 Model Outputs

Town Operational Summary

Scenario	Capital Investment (£m)	Base Case Simple Profit (£m/yr)	Carbon Dioxide Emissions (kt/yr)	Comments
Town (Incineration)	27.7	1.1	96	All dry waste to incineration All wet waste to anaerobic digestion
Town (Gasification)	17	1.7	67	All dry waste to gasification. Syngas used 100% for electricity generation All wet waste to anaerobic digestion

Sensitivity of Model Output to Changes in Parameters

Technology	Base Case Simple Profit	Capital	Feedstock Cost	Operating Cost	Product Value	Plant Operating Efficiency
Change	£m/yr (% change in brackets)	Up 20%	Up £30/t	Up 20%	Down 20%	Down 20%
Incineration	1.1	0.5 (55%)	-0.9 (180%)	0.9 (18%)	0.7 (36%)	0.7 (36%)
Gasification	1.7	1.3 (24%)	-0.5 (129%)	1.6 (6%)	1 (41%)	1.1 (35%)

7.3 Operating Comments

- The model shows that there are attractive returns to be made from both gasification and incineration technology application on the scale of a town assuming that a capital cost of £250/t of feedstock can be achieved. However, returns are highly dependent on feedstock price and long term supply agreements will be required to meet investment criteria. In addition capital investment, product value and operating efficiency are also highly important. If capital cost can be lowered and operating efficiency improved returns will increase and also become more stable. The sensitivities to these factors are shown in the tables above;
- This route for EFW for towns is not widely pursued as existing technologies are less well proven at this scale on mixed wastes and because existing waste collection schemes transport wastes to centralised facilities serving more than one town. However, a town of 50k people can support a 50kt/yr incinerator or gasifier;
- Although it could be improved AD technology for this scale of community is easily available and could be installed either at a town waste to energy plant or close to the local water treatment works;
- The largest opportunity for a town of this size is the development of integrated 'town' waste to energy complexes. These would have much in common with the old town gas facilities but would be based on incineration or gasification to syngas in integration with AD. A facility such as this would take the towns wastes and convert it to a combination of electricity, gas and heat which would be used within the local community.

7.4 Technology Development Opportunities

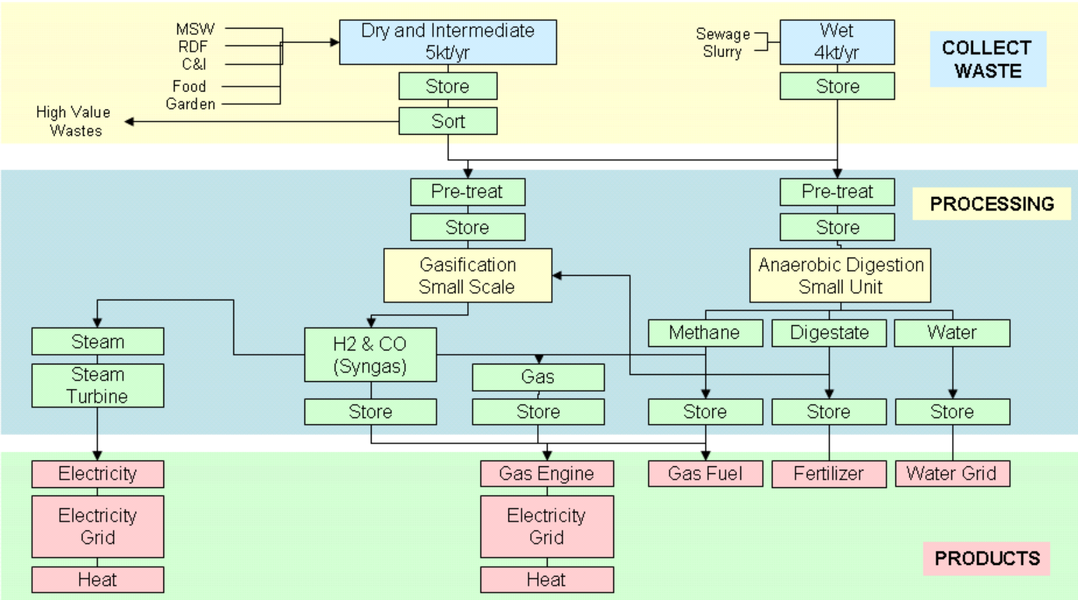
Technology development opportunities to meet the challenge of town scale waste to energy are:

- The development <50kt/yr MSW based gasification or other advanced thermal processes based on downdraft or fluidised bed units for use with variable feeds and moisture contents. The combination of technologies such as MBT, BMT and autoclave plants to partially segregate wastes and create homogeneous feeds for gasification would enhance this opportunity;
- The development of economic gas clean-up, vehicle fuel systems and low cost heat networks as discussed in the city case;
- The largest opportunity lies in the creation and demonstration of integrated advanced thermal, incineration and AD facilities that can act as an integrated system to produce heat, power and gas for the local community;

8. VILLAGE SCENARIO

Population	5000	
	Tonnage (kt/yr)	Energy Content (MJ/yr)
Dry Waste	4.9	$6.4\text{x}10^7$
Wet Waste	4.1	$1.5\text{x}10^7$

8.1 Product Flow Summary



8.2 Model Outputs

Village Operational Summary

Scenario	Capital Investment (£m)	Base Case Simple Profit (£m/yr)	Carbon Dioxide Emissions (kt/yr)	Comments
Village (Incineration)	2.7	0.03	9.4	All dry waste to gasification and electricity All wet waste to anaerobic digestion
Village (Gasification)	1.2	0.2	6.6	All dry waste to gasification and electricity All wet waste to anaerobic digestion

Sensitivity of Model Output to Changes in Parameters

Technology	Base Case Simple Profit	Capital	Feedstock Cost	Operating Cost	Product Value	Plant Operating Efficiency
Change	£m/yr (% change in brackets)	Up 20%	Up £30/t	Up 20%	Down 20%	Down 20%
Incineration	0.03	-0.04 (233%)	-0.16 (633%)	0 (100%)	0 (100%)	0 (100%)
Gasification	0.2	0.2 (0%)	0.1 (50%)	0.2 (0%)	0.2 (0%)	0.2 (0%)

8.3 Operating Comments

- A village of 5000 people does not generate sufficient waste to support conventional waste to energy technology. In most current cases wastes are collected and transported often via transfer stations to shared facilities for processing and disposal. The returns generated from the model are not financially attractive so if the current approach to waste collection and processing is to change new more economic technologies will be required;
- One way to do this could be to innovate to create ‘village’ waste to energy plants to produce heat, power and gas for the community;
- This would require small scale and low cost technologies for gasification, incineration and AD.

8.4 Technology Development Opportunities

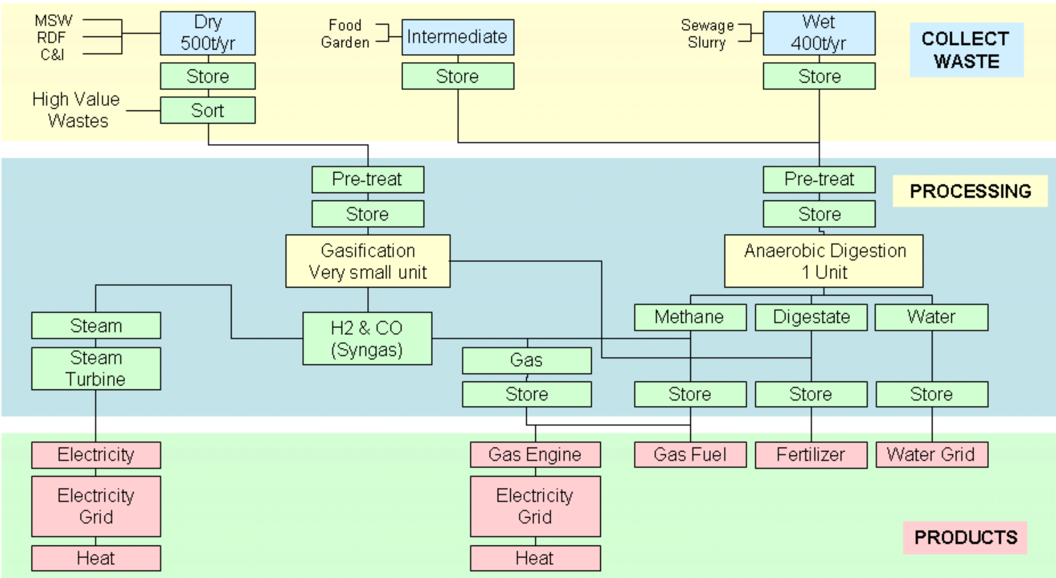
Technology development opportunities for a village are as follows:

- Development of small (<5kt/yr) gasification or advanced thermal units that are integrated with newly developed high efficiency AD plants also processing less that 5kt/yr. This will require the development of AD and small scale downdraft gasification technology;
- Control technology to manage plant operations remotely will be an important factor coupled with locally available operating skills;
- The resulting integrated systems could be used to create syngas and biogas that can be used to produce electricity or heat. At this scale it is not likely that the production of fuels or chemicals would be a cost effective option.

9. RURAL COMMUNITY SCENARIO

Population	500	
	Tonnage (kt/yr)	Energy Content (MJ/yr)
Dry Waste	0.5	6.8×10^6
Wet Waste	20	6×10^7

9.1 Product Flow Summary



9.2 Model Outputs

Rural Community Operational Summary

Scenario	Capital Investment (£m)	Base Case Simple Profit (£m/yr)	Carbon Dioxide Emissions (kt/yr)	Comments
Rural	1.4	0.2	1.2	All dry waste to gasification and electricity All wet waste to anaerobic digestion

Sensitivity of Model Output to Changes in Parameters

Technology	Base Case Simple Profit	Capital	Feedstock Cost	Operating Cost	Product Value	Plant Operating Efficiency
Change	£m/yr (% change in brackets)	Up 20%	Up £30/t	Up 20%	Down 20%	Down 20%
Rural	0.2	0.2 (0%)	0 (100%)	0.2 (0%)	0.2 (0%)	0.2 (0%)

9.3 Operating Comments

- Communities of 500 people do not produce enough waste to supply a local waste to energy plant and wastes are consequently collected and moved to shared facilities;
- However a farming community based on livestock or mixed agriculture can support a 20kt/yr AD plant with animal and food slurries;
- A possible way forward for the community to improve the recycling and reuse of its own waste to energy would be to apply micro scale technologies for a single home or a small number of homes. Target scale would be 2t/yr to 100 t/yr capacity.

9.4 Technology Development Opportunities

- Develop micro domestic scale down draft gasification units with less than 100t/yr feedstock capacity for individual properties or small groups of properties. The resulting syngas could be used to produce electricity and heat;
- Development could also be focused on AD technology to improve its operability and efficiency. It is also worth exploring the use of biogas for use in community vehicles.

10. DRIVERS FOR TECHNOLOGY DEVELOPMENT OPPORTUNITIES

The drivers for technology development split into two groups: Those that are generic to all technology scales and types, and those that are specific to each technology.

In all cases there is a need to develop technology that:

- Reduces the capital cost per unit of investment. This could be through the economies that come from large scale plants or through long production runs of similar units leading to economies from repetition. It should be noted that currently all plants require some support mechanism through either the landfill tax at the supply end or the feed in tariff (FIT) or renewable obligations certificate (ROC) system to be economically viable. A capital cost reduction of over 30%/tonne of feed would be required to remove the need for public sector support mechanisms;
- Improves the yield of higher value products and making use of all by-product streams would be of great value. The technology study and experimental work indicates that all technologies studied have low conversion efficiencies for the transformation of feedstock into energy. In many cases the electricity yield is up to 50% lower than the conventional fossil fuel alternatives;
- Increase the efficiency of energy conversion both electrically and thermally. Pure thermal systems that convert gas into heat for local use can reach conversion efficiencies as high as 85%. This requires a different approach to gas use either in grid or in local heat networks;
- Can handle variable feedstock form and moisture content. This is essential to the successful operation of waste to energy plants. The evidence from the work to date also indicates that mixed wastes have similar elemental composition, but differ widely in form and moisture content;
- Can produce homogenised feedstocks through mechanical, biological or thermal pre-treatment;
- Can meet legislative and regulatory requirements for safe and beneficial operation;
- Are robust, flexible, reliable and are easy to operate.

The other overarching feature of the conclusions that come from the modeling work is that viable solutions for cities are currently available so should not be included in further work. There is a need to develop smaller scale technologies that are appropriate to town or village communities and these should be included in further work. These technologies will need to flexible enough that they can be:

- Turned-up and turned-down without damage to the plant and uneconomic decreases in operational efficiency;
- Turned-on and turned-off as required dependent on season and the amount of waste arisings.

The technologies identified for development for MSW and C&I waste streams are gasification and incineration for dry wastes and anaerobic digestion for wet wastes.

Due to the changing nature of the MSW and C&I wastes in the UK it is expected that composition will be continually changing for the foreseeable future. There is therefore a requirement for technologies applied to this market segment to be able to handle continuously changing feedstock slates, but be able to produce consistent products that can be used in the same downstream equipment. As a result it has been decided that incineration and gasification (included high gas production pyrolysis) are the best technologies to take forward. Basic pyrolysis is considered to be of less interest as it generally requires consistent feedstock to produce consistent product.

In addition to technology development there is a need for the next stages of the project to investigate innovative investment models. Current investment models are tied to large plants that can prove they have secure low cost feedstock supply for enough years to ensure that the investment in the facility pays back with little or no risk to the investor. This approach to financing is unlikely to work with smaller scale distributed technologies and it is suggested that investment options are studied to assess options such as leasing, third party investment based on off-take or supply agreements and outright purchase by individuals or communities.

11. TECHNOLOGY DEVELOPMENT OPPORTUNITIES

In this section the technology opportunities are summarised and then discussed in more detail and suggestions for potential ways forward are proposed. The order of the presentation in this section reflects the priorities defined by the attendees at the ETI stakeholder workshop of the 18th November 2010[1]. The output of the workshop is summarised in Appendix 3. In the table below the higher the number of crosses the greater the support at the workshop.

Table 6. Technology Interest Assessment: ETI Workshop November 2010

	Community Scenario			
Technology	City	Town	Village	Rural Community
Biogas for vehicle use	+++	+++	+++	+++
Biogas for injection into the gas grid	+++	+++	+++	+++
Development of low cost gas clean-up technology	+++	+++	+++	+++
Low cost heat network	+++	+++	+++	+
Integrated gasification, incineration and AD technology systems that integrate innovative technologies	+++	+++	++	+
Develop small and micro scale AD plants below 5kt/yr		++	+++	++
Development of low cost processes to convert syngas into chemicals and fuels	+++			
50kt/yr advanced thermal technology		+++		
5kt/yr gasification or incineration technology			+++	
10t/yr gasification, advanced thermal or incineration technology				+++

The results from the table are discussed and suggestions to develop the technologies further are outlined below. Conclusions are drawn and recommendations for ETI follow-on projects are made in subsequent sections.

11.1 Biogas for use in Vehicles and in the Natural Gas Grid

Development Opportunities

- The use of biogas generated from AD for vehicles or as a supplement to the natural gas grid is well known and is in regular use in some European countries. Some limited minor trials are in progress in the UK, but costs appear prohibitively high to convert biogas to meet the UK gas specification;
- The efficiency of gas use for heat generation in condensing boilers can reach as high as 93%. This is significantly higher the 35% electrical efficiency from gas engines so the use of gas in the grid could be beneficial. If the gas were used in

CHP applications energy consumption efficiency will be further improved to as high as 85%;

- Gasification and pyrolysis processes both produce a syngas of hydrogen and carbon monoxide while AD plants produce methane. Trials to understand the effects of mixed gas streams in the gas grid, gas engines and boilers would be of value to assess the effectiveness of mixed streams in operating systems. An alternative approach would be to investigate the opportunity to machinate syngas to methane for use in natural gas based systems;
- Technology exists to implement both options for gas use but costs appear prohibitively high to convert biogas to meet the UK gas specification.

Next Steps

- An increase in trials is proposed to reassess UK gas specifications to bring them closer to the specifications of European countries where bio gas is regularly injected into the gas grid. The differences are related to the Wobbe index of the gas and how this is put into legislation. For UK gas the index required is 47.2 MJ/m^3 to 51.41 MJ/m^3 while in Germany it is the lower value of 37.8 MJ/m^3 to 46.6 MJ/m^3. Biogas typically has an index of 44 MJ/m^3. In the UK propane is added to biogas to raise the index to meet the specification while oxygen content is lowered. These changes add cost to biogas used in the grid in the UK and the issue for investigation is the cost/benefit balance between changing the specification or investing additional treatment capacity;
- An assessment of the opportunity for using mixed gas streams of methane, natural gas and syngas would generate additional useful operational data that may increase the opportunity for the use of mixed gas streams;
- In addition changes in specification to lower the technological requirements and cost of gas clean-up technologies would be beneficial. An example is the permitted oxygen content in pipeline gas. A number of European countries have a different specification to the UK which makes the injection of biogas more attractive. Others use non-sulphur gas stenchants that reduce the need to sulphur cleaning technologies;
- There is also a need for legislation to allow injection of appropriately formulated bio gas into the grid.

11.2 Low Cost Gas Clean-up

Development Opportunities

- Gasification, pyrolysis and AD produce gas that requires at least some cleaning up before it can be effectively used. The nature of the contaminants have been identified and discussed in the Work Package 2.2 report. These cover a wide range of products from diluent gases to tars and liquids through gases such as HCL and H_2S;
- The wide range of contaminants mean that most common gas cleaning technologies are expensive and can make investment in the waste to energy process uneconomic on all but the largest scales.

Next Steps

- It is proposed that the ETI supports work to characterise the full component analysis of the gases produced from the waste to energy processes and develop lower cost and smaller scale clean-up technology for all types of gas produced from waste to energy processes. However, it should be noted that this work will be dependent the conversion process as well and the gas composition, additives and specification details.

11.3 Low Cost Heat Networks

Development Opportunities

- There are very large amounts of low grade waste heat produced in UK energy systems of all types, particularly from waste to energy incinerators and from the gas engines of AD plants;
- Making use of this wasted heat would significantly increase the UK's energy efficiency and reduce carbon emissions;
- High efficiency incinerators with condensing boilers that supply heat to local networks are in use across Europe and offer an opportunity for further exploration and deployment within the UK;
- There is also a number of community combined heat and power (CHP) plants or community heat supply systems operating in the UK, but these are not commonplace. Examples of existing systems are Nottingham, Aberdeen, Milton Keynes, Byker (Newcastle), Woking and Sheffield.
- The technology for heat distribution does exist but it is costly to fit into new build facilities and expensive when retro fitted to existing communities. However, many European cities (e.g. Paris, Vienna) have installed large district heating systems as the increase in the efficiency and reduction in emissions is seen to offset the investment cost;

Next Steps

- This clear opportunity forms a core part of the ETI Macro Distributed Energy Programme finishing in December 2011. Assuming the results of this programme are positive it is proposed that the ETI supports work to develop and demonstrate lower cost heat distribution systems that are easy to install and are combined with control systems that give home owners and industrial users as much control over their heat supply as they have with an independent gas boiler;
- The use of waste heat and the planned use of heat energy in CHP plants can have a significant impact of GHG emissions as it can raise the efficiency of feedstock use from around 20% to above 80% with a concomitant reduction in emissions. This reduction in emissions amounts to over 120kt/yr of carbon dioxide for each city scale plant.
- Social adoption of heat networks in the UK is low – although this is not true in Europe. There is a need for a regulatory and legislative environment that makes it attractive to join and use a community heat network. Awareness raising would also be beneficial.

11.4 Integrated Gasification or Pyrolysis, Incineration and AD Technology Systems

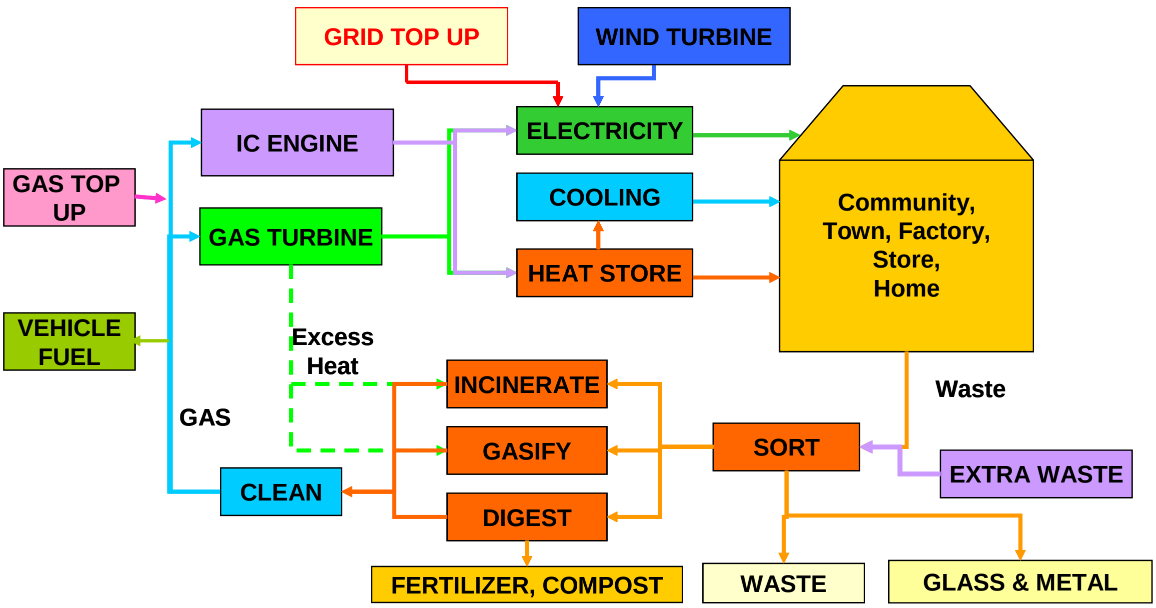
Development Opportunities

- In recent times technology development has tended to move towards larger scale waste to energy plants based on the economies of scale that come from large process plants;
- However, the work in this project indicates that there is an opportunity to develop integrated distributed energy 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;

- Combinations of technology are likely to be AD, gasification, incineration linked with upstream pre-treatment and downstream processing. One opportunity for integration would be the gasification of AD digestate that cannot be used as a fertilizer or put back onto the land.

Next Steps
- There is an opportunity for the ETI to support work that develops and demonstrates the combinations of technology that meet appropriate local needs. It is believed that this offers a significant commercial opportunity if integrated operational solutions can be developed with a particular emphasis on town and village scale systems;
- This part of the programme would draw heavily on the development of the appropriate scale technology discussed in other parts of this technology development section;
- The diagram in Figure 3 is a schematic representation of the type of system that could be developed;

Figure 3 Schematic Representation of an Integrated Waste to Energy System



11.5 Small and Micro Scale Anaerobic Digestion Plants

Development Opportunities
- Anaerobic digestion is a well established technology that has been deployed around the world for many years. However this study indicates that there is an opportunity to develop an economic small and micro AD technology for volumes of waste below 5kt/yr;
- Some technologies are being developed and are in the early stages of market deployment, but there are clear opportunities for further process and technology development;

- The use of local facilities also has significant economic benefits as waste transport requirements are reduced and the technology would fit well with the closed loop system in figure 2 where locally arising wastes are used to generate heat and power for local consumption.

Next Steps
- It is proposed the ETI supports work to develop small AD plants for the community and domestic scale. The replacement of septic tanks with micro units may add value to the disposal of waste material. Work is in progress on a number of projects in this area and it would be valuable to link programmes together to avoid duplication. Those involved include CPI, National Farmers Union, Nation Non-Food Crops Centre and the Renewable Energy Association.

11.6 Viable Processes to Convert Syngas into Chemicals or Fuels

Development Opportunities
- The modelling shows that there are potentially good margins to be had from taking syngas and producing methane, chemicals or liquid fuels such as methanol, ammonia or through Fischer Tropsch reactions;
- This is a niche market that is only appropriate where a large scale gasification process is being used to produce a large volume of high quality syngas;
- There has been much work over the years to develop lower cost conversion technologies for syngas, but despite this the technology is under-developed;
- A number of companies such as Ineos and Oxford Catalysts are developing a range of technologies, but a more systematic public-private partnership to drive value creation may be of value to developing this market further.
- These are out of the scope of this project.

11.7 Medium, Small and Micro Scale Gasification and Advanced Thermal Processes for Wastes

Development Opportunities
- The gasification and thermal treatment of waste materials in fluidized bed or downdraft gasifiers has been identified as a technology development opportunity. There are few if any processes that work using mixed or pre-treated feedstocks at feed rates of 50kt/yr or less. Units right down to domestic scale are likely to have value;
- Data from the waste and energy industry indicates that there is a shortage of commercially viable plant with proven operability on a range of feedstock mix for plants below 80kt/yr of feedstock. It is believed that there is a technology development opportunity to develop small fluidised bed or downdraft gasifiers for this market;
- This type of technology would be highly appropriate to the creation of integrated systems summarized in Figure 3;
- The processes developed are also likely to require gas clean-up technologies.

Next Steps
- It is proposed that the ETI supports the development of this technology for communities generating up to 80kt/yr of waste and mixed feedstocks with the intention of creating a technology programme 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. These units could be significant in the development of community and domestic waste to energy technologies;
- Work will be required to ensure that processes can meet the requirements of the legislative and regulatory system.

11.8 Supply Chain Development and Value Chain Creation

- All the previous technology development ideas will require parallel work to support the development of a supply chain that can create value for the UK. Activities could include:
  - Focused research programmes
  - Technology development facilities
  - Development and proving sites
  - Assistance to help organisations meet new market demands
  - Assistance to create new companies in the market
  - Favourable legislative and regulatory environment
- It is proposed that the a supply chain development programme is run in parallel to any technology development programmes that are created as a result of this project.

Table 7 summarises the technology development opportunities in terms of emissions, cost of production, capital cost of investment and scaleability. These findings form the basis of the conclusions and recommendations in Sections 12 and 13.

Table 7 Qualitative Assessment of Greenhouse Gas Reduction Potential, Cost Implications and Scaleability of the Technology Options

	Qualitative Impact			
Technology	Greenhouse Gas Emissions	Impact on Product Cost	Capital Cost Effect	Scalability
Biogas for vehicle use	Replaces fossil fuel: Emission reduced	Lower cost than conventional fuels	Known technology	Scales to available gas
Biogas for injection into the gas grid	Replaces fossil fuel: Emission reduced	Trials in progress	Increased over local use for heat	Scales to available gas
Development of low cost gas clean-up technology	No effect	Increases cost	Would make use of impure gas streams more attractive	Unknown
Low cost heat network	Replaces fossil fuel: Very significant emission reduction	Use of heat increases income to EFW plant as it supplies additional income	Cost of heat network installation is high, but has been carried out in many towns and cities	Scaleable, but is most successful in large high density conurbations or industrially
Integrated gasification, thermal processing, incineration and AD technology systems that integrate innovative technologies	Replaces fossil fuel: Very significant impact if CHP	Should match fossil alternatives	Will depend on application, but likely to be comparable with conventional technology	Technology is available for city scale installations, but not for towns and villages
Develop small and micro scale AD plants below 5kt/yr	Replaces fossil fuel: Emission reduced	Will be lower that fossil fuels in remote locations	Supplies to remote location: Likely benefit	Small scale technology required
Development of low cost processes to convert syngas into chemicals and fuels	Replaces fossil feedstocks: Emission reduced	Unknown: Commercial plants not developed	Unknown: Commercial plants not developed	Unknown
50kt/yr gasification or advanced thermal technology	Replaces fossil fuel: Very significant impact if CHP	Should match fossil alternatives	Will depend on application, but likely to be comparable with conventional technology	Technology not available for wastes
5kt/yr advanced thermal processes including gasification and incineration	Replaces fossil fuel: Very significant impact if CHP	Should match fossil alternatives	Will depend on application, but likely to be comparable with conventional technology	Technology not available for wastes
10t/yr advanced thermal processes including gasification and incineration	Replaces fossil fuel: Very significant impact if CHP	Should match fossil alternatives	Will depend on application, but likely to be comparable with conventional technology	Technology not available for wastes

POTENTIAL DEVELOPMENT RISKS

11.9 Physical Form, Moisture Content and Impurities

Though chemically waste is similar to biomass materials and the modelling project has assumed that it performs the same thermodynamically, the physical form of the materials may have impacts that cannot be predicted. The biggest risk to the technologies is how this physical form will affect operations and stability in any process. Whether these difficulties are in the reactor itself or associated feed system or gas treatment. As discussed in the WP 2.2 report Cranfield University had difficulty with certain materials in feeding the pilot gasifier. More confidence needs to be developed in the non incineration processing of these materials.

11.10 Feedstock Prediction

The ability to assess feedstocks that can be used in a project would be critical for the success of future EFW programmes. The development of criteria or nomographs for different materials based on their chemical and physical properties could be of value in the assessment and optimisation of feedstock mixes or blends.

11.11 Technologies

The technologies that seem most ripe for further development for use with mixed MSW and C&I wastes are the gasification and AD processes. Pyrolysis is also worth further development for segregated streams. The construction of a facility that can test and develop technology is recommended. The facility must be at a scale that can iron out processing difficulties. The project should not limit itself to just the processing but have the ability to create the added value products such as methanol or fuel oil.

11.12 Next Phase Modelling

The modelling done in WP3 is an a necessarily high level, but as the distributed energy programme develops and options are narrowed down there will be a need to develop more detailed models that will show how materials will behave in the processes but also develop enough knowledge to be predictive in what the outputs will be. It will give an assessment of what the best product is for the waste that is to be handled.

11.13 Controllable and Uncontrollable Variables

The project has feedstock cost, feedstock quality, product value, capital investment and process efficiency as the major variables driving business profitability and emissions production. These variables split into to two groups: Controllable and uncontrollable variables. These are summarised in the table below.

Variable	Controllable/ Uncontrollable	Effect on Profitability	Effect on Emissions	Comments
Feedstock cost	Uncontrollable	Higher price lowers profitability	None	Set by a combination of legislation and market conditions
Product value	Uncontrollable	Higher price increase	None	Set by regulation and

		profitability		market conditions
Feedstock quality	Controllable	Balance quality and price to manage returns	Higher yields of products lowers emissions	Blending of feedstocks and feedstock flexibility allows this to be managed
Capital investment	Controllable	Lower capital increases profitability	None	Need to guard against loss of function as capital reduced
Process efficiency	Controllable	High conversion to high value products increases profitability	High conversion to high value products reduces emissions	

Controllable variables offer the best opportunities for successful technology development.

12. CONCLUSIONS

- Each person in the UK produces about 1 tonne of MSW per year and about 0.8 tonnes of Commercial and Industrial (C&I) wastes. These figures include wet wastes such as slurries and sewage. These sources of waste amounted to around 90 million tonnes in 2009 and could be used to generate up to 3% of the UK's energy need each year.
- If wet wastes, garden wastes and food wastes are to be used to produce energy there are a limited number of options with the most attractive being anaerobic digestion. Although in certain circumstances garden and food wastes can be included in the MSW stream and would be treated as described below.
- The evidence is that the amount of residual MSW and C&I waste produced each year is reducing as recycling rates increase and the mix of materials within the MSW is changing. This reduction is linked to a combination of: the commodity value of recyclable materials and increased efficiency in material use.
- Elemental analysis of MSW and C&I waste indicates that although it contains different mixtures of materials the elemental composition of the dry waste is consistent. However, it is noted that it changes in its form (shape) and its moisture content.
- It is concluded that MSW composition will continue to change in both volume and mix over time, but that the elemental composition is likely to remain the same.
- Any waste to energy technologies must therefore be able to cope with wastes in various forms and with a moisture content of up to 40%. This need to have the flexibility to handle a range of materials reduces the number of technology options. These are most likely to be medium to high temperature thermal processes.
- The project has focused on two main thermal technologies that theoretically have the capability to handle mixed wastes and have the capacity to deal with changing form and moisture content. The technologies are:
    - Incineration at temperatures up to 1200°C.
    - Advanced thermal processes between 650°C and 1200°C – with a particular emphasis on fluidised bed and downdraft gasifiers for general use.
- Pyrolysis has also been discussed as an option, but this should only be developed for the treatment of MSW and C&I waste if novel fuel flexible technologies can be developed as it is more appropriate for consistent feedstock streams. Pyrolysis routes that produce gas or are combined with gasification steps are appropriate technologies and are included as advanced thermal processes in this report.
- The project modelling using a number of community scenarios to define waste arisings shows that most UK communities produce tonnages of MSW that are less than the current economic scale for incineration and gasification plants. EFW – including CHP - technologies that work economically on the scale of a town or village are a major development opportunity.
- The modelling work undertaken in WP 3.3 is based on the current available waste data. Additional work could be undertaken to create further data sets that assess the effect of changing composition and changing recycling levels on energy from waste generation. This work could be undertaken in follow-on projects and draw on the outputs of WP 3.2. However, this additional modelling will not affect the technology development ideas generated from this work package.

- As the electricity production from current technologies is of the order of 20% to 25% a significant amount of the energy content of the waste is lost.
- It is concluded that distributed waste to energy plants of an appropriate size to local communities could bring significant benefits in efficiency and reductions in transport costs.
- The modelling also shows that the economics of waste to energy plants are very highly geared to the cost of the feedstock, the capital cost of the plants, the efficiency of conversion of the waste to useful energy, the product value and the local use of waste heat. It is concluded that any future waste to energy development project must address the operational efficiency of the process plants with a major focus on the conversion efficiency of the processes to electricity or fuels and the local use of heat produced by the plant.
- The emissions from waste to energy plants arise from the transport costs of bringing wastes to the plant, distribution loses once energy is produced, the efficiency of heat use and the conversion efficiency of the plants themselves. It is concluded that the best way to reduce emissions from waste to energy is to have local plants that are of an appropriate size and scale to the local community with high conversion efficiencies and local use of heat.
- It is concluded that there is a need to develop advanced thermal and incineration plants of an appropriate size and scale for local communities with high waste to energy conversion efficiencies.
- Anaerobic digestion plants have been identified as the best route to process wet bio wastes. Although AD technology is well established it has low efficiency for the size of plant. It is concluded that AD for energy production should be targeted with a view to increasing the yield of gas per unit of feedstock.
- AD plants produce methane rich gas that is akin to natural gas and in the UK this is typically burnt to produce electricity. It is concluded that lower emissions will result if AD plant conversion efficiency is increased and if the biogas produced is injected into the UK national gas grid.
- It is concluded that although SRF plants and autoclaves are becoming increasingly common there is a continuing need for all technologies identified to improve technologies that prepare feedstock to a consistent shape and moisture content.
- The gas produced by gasification and AD contains contaminants and it is concluded that there is a need to clean-up technologies before these gases can be used effectively.

13. RECOMMENDATIONS

It is recommended that the ETI develop programmes in the following areas.

13.1 Within the Next Phase of the Waste to Energy Project

13.1.1 Integrated Gasification, Advanced Thermal, Incineration and AD Technology Systems

This project indicates that there is an opportunity to develop integrated distributed energy 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, incineration with upstream and downstream processing. This approach could reduce emissions for both electricity production and in CHP systems. There is a need for the ETI to sponsor work to develop and demonstrate the combinations of technology that meet appropriate local needs. It is believed that this brings a significant commercial opportunity.

13.1.2 Medium, Small and Micro Scale Advanced Thermal Processes for Wastes

The advanced thermal treatment of waste materials in fluidized bed and downdraft gasifiers or in combination with pyrolysis has been identified as a technology development opportunity. There are few if any processes that work using mixed feedstocks at feed rates of 50kt/yr or less. Units down to domestic scale are likely to have value. It is proposed that the ETI creates a technology programme to develop innovative gasification solutions that reduce capital cost and increase operability of small scale units. These units could be significant in the development of community and domestic waste to energy technologies.

13.1.3 Small and Micro Scale Anaerobic Digestion Plants

Anaerobic digestion is a well established technology that has been deployed around the world for many years. However this study indicates that there is an opportunity to develop an economic small and micro AD technology for volumes of waste below 5kt/yr. It is proposed the ETI supports work to develop small AD plants for the community and domestic scale. The replacement of septic tanks with micro units may add value to the disposal of waste material.

13.1.4 Low Cost Gas Clean-up

All thermal processes and AD produce gas that requires at least some cleaning up before it can be effectively used. Technology exists to do this, but it is prohibitively expensive for widespread adoption. It is proposed that the ETI supports work to develop lower cost and smaller scale clean-up technology for all types of gas produced from waste to energy processes.

13.2 Opportunities for Exploitation in Other Projects

13.2.1 Biogas for use in Vehicles and in the Natural Gas Grid

Biogas from AD processes has been proven in vehicle and grid use across Europe and trials are being run in the UK. Technology exists to implement both options for gas use but costs appear prohibitively high to convert biogas to meet the UK gas specification. In addition slight changes in specification that lower cost gas clean-up technologies would be beneficial. An example is the permitted oxygen content in pipeline gas. A number of European countries have a different specification to the UK which makes the injection of biogas more attractive. Others use non-sulphur gas stenchants that reduce the need for sulphur cleaning technologies. There is a need for legislation to allow injection of appropriately formulated bio gas into the grid.

13.2.2 Low Cost Heat Networks

There are very large amounts of low grade waste heat produced in UK energy systems of all types, particularly from waste to energy incinerators and from the gas engines of AD plants. The technology for heat distribution exists but it is costly to fit into new build facilities and expensive when retro fitted to existing communities. However, if the heat is used in CHP installations on the scale of a city it will save over 120kt/yr of carbon dioxide. It is proposed that the ETI Macro Distributed Energy programme is used to develop lower cost heat distribution systems that are easy to install and are combined with control systems that demonstrate that home owners and industrial users have as much control over their heat supply as with an independent gas boiler. Social adoption of heat networks in the UK is low – although this is not true in Europe. There is a need for a regulatory and legislative environment that makes it attractive to join and use a community heat network.

13.2.3 Low Cost Processes to Convert Syngas into Chemicals or Fuels

The modelling shows that there are potentially good margins to be had from taking syngas and producing methane, chemicals or liquid fuels such as methanol, ammonia or through Fischer Tropsch reactions. There has been much work over the years to develop lower cost conversion technologies for syngas, but despite this the technology is under-developed. A number of companies are developing a range of solutions, but a more systematic public-private partnership to drive value creation may be of value to developing this market further.

13.3 Overarching Industry Development Opportunities

All the previous technology development ideas will require parallel work to support the development of a supply chain that can create value for the UK. Activities could include:

- Focused research programmes
- Technology development facilities
- Development and proving sites
- Assistance to help organisations meet new market demands
- Assistance to create new companies in the market

- Favourable legislative and regulatory environment

It is proposed that the ETI runs a supply chain development programme in parallel to any technology development programmes that are created as a result of this project.

14. POTENTIAL FOLLOW-ON PROJECTS

14.1 Integrated Gasification, Advanced Thermal, Incineration and AD Programme

- Create a reconfigurable test and development site for the proving if waste to energy technologies;
- This should be at a scale of at least 10kt/yr of throughput for the development and demonstration of technology systems and should have a dedicated infrastructure and operations team;
- This demonstration facility could be followed-up with a full scale resource efficiency demonstration at a town or village scale – Up to 75kt/yr throughput;
- The aim of this work would be to develop appropriate scale mixed feed plants and systems for advanced thermal gasification, incineration and AD with appropriate upstream and downstream technologies to improve capital efficiency and productivity.
- This will include network management to link into larger grid.

14.2 Small Scale Plant Development

- This project indicates that there is a technology and market opportunity to develop gasification and AD at domestic or very small community scale.
- The replacement of septic tanks with micro AD units may add value to the disposal of wastes.
- The development and application of small scale gasifiers based on existing trials and ideas is an additional opportunity.
- There are also opportunities to create development links with producers of small scale plants in other countries.

APPENDIX 1 SUMMARIES OF TECHNOLOGY ASSESSMENT EXPERIMENTS

The materials tested performed in the processes generally as expected, some feeding difficulties were experienced which is only to be expected from such variable materials. The table below shows the major gases evolved from the processes investigated. These values with one or two exceptions are in the range that one would be expected from biomass. On a theoretical basis the gas concentration from gasified biomass would approximately be Carbon Monoxide 40%, carbon Dioxide 20% and Hydrogen 40 % with a few percent methane. Due to the experimental nature of the equipment used and more heat losses than expected more air was used to drive the processes through combustion, leading to higher CO_2 concentrations and nitrogen dilutions.

		As Analysed Vol%				N2 free Basis Vol %			
		CO	CO2	CH4	H2	CO	CO2	CH4	H2
P	**Demolition Wood**	1.6	1	1.2	3.5	22	14	16	48
U	**Demolition Wood**	5.4	7.9	1.6	3.2	30	44	9	18
FB	**Demolition Wood**	6.9	8.9	2.1	2.4	34	44	10	12
D	**Demolition Wood**	6.7	9	0.9	3.1	34	46	5	16
P	**Demolition Wood and Textiles**	4.7	2.9	3.8	7.4	25	15	20	39
U	**Demolition Wood and Textiles**	5.6	8.3	1.4	2.7	31	46	8	15
FB	**Demolition Wood and Textiles**	7.6	10.2	2.3	2.4	34	45	10	11
D	**Demolition Wood and Textiles**	8.3	14.4	1.7	3.4	30	52	6	12
P	**Demolition Wood and Plastic Film**	2	1.2	2.1	5.1	19	12	20	49
U	**Demolition Wood and Plastic Film**	5	3.4	6.6	12.2	18	13	24	45
FB	**Demolition Wood and Plastic Film**	5.1	9.2	2.8	1.6	27	49	15	9
D	**Demolition Wood and Plastic Film**	3.6	6.8	1.7	1.4	27	50	13	10
P	**Textiles and Plastic Film**	0.8	1	2.4	4.2	10	12	29	50
U	**Textiles and Plastic Film**	2.1	7.6	5.9	0.2	13	48	37	1
FB	**Textiles and Plastic Film**	4.6	9.8	3.7	2.3	23	48	18	11
D	**Textiles and Plastic Film**	3.8	7.4	1.7	2	26	50	11	13
P	**Paper & Card and Dense Plastic**	2.5	2.6	3.3	4.6	19	20	25	35
U	**Paper & Card and Dense Plastic**	4.2	10.8	2	1.6	23	58	11	9
FB	**Paper & Card and Dense Plastic**	6.9	11.4	4.1	2.9	27	45	16	11
D	**Paper & Card and Dense Plastic**	5	12.3	1.9	2.8	23	56	9	13
P	**Food and Paper &Card**	5.1	8.2	3.1	8.2	21	33	13	33
U	**Food and Paper &Card**	9.6	10.9	0.4	2.8	41	46	2	12
FB	**Food and Paper &Card**	6.8	13.4	2	2	28	55	8	8
D	**Food and Paper &Card**	3.1	6.7	0.5	2.4	24	53	4	19
	P Pyrolysis U Updraft Gasifier FB Fluid Bed Gasifier D Downdraft Gasifier								

When using refuse derived fuels values of gas concentrations produced on equipment operated by Battelle operated for the Pacific North Western laboratories, albeit on a high throughput fluid bed gasifier with char combustion and the absence of oxygen are as in table. As mentioned in the WP 2.2 report the analytical capability to measure higher hydrocarbons in the gas mixtures was not available during experimentation. This is unfortunate as higher hydrocarbons may well have been produced.

	Vol %
H2	15.7
CO2	11.1
C2H2	11.2
C2H6	1.3
CH4	16.3
CO2	43.9

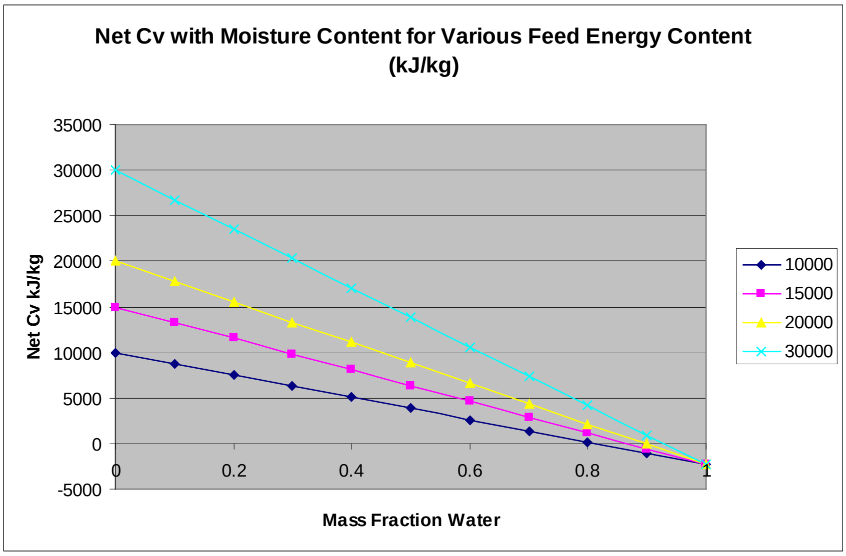
Literature values for the gasification of biomass that have been quoted. These show that the data collected in the minimum experimentation period available shows that the work corroborates with other previous studies

	Vol % dry				
	H2	CO	CO2	CH4	N2
Fluid Bed Air Blown	9	14	20	7	50
Up Draft Air Blown	11	24	9	3	53
Down Draft Air Blown	17	21	13	1	48
Down Draft Oxygen Blown	12	48	15	2	3
Multi Solid Fluid Bed	15	47	15	23	0
Twin Fluidised Bed Gasification	31	48	0	21	0
Pyrolysis	40	20	18	21	1
A.V. Bridgewater Biomass Gasification for Power Generation 1994					

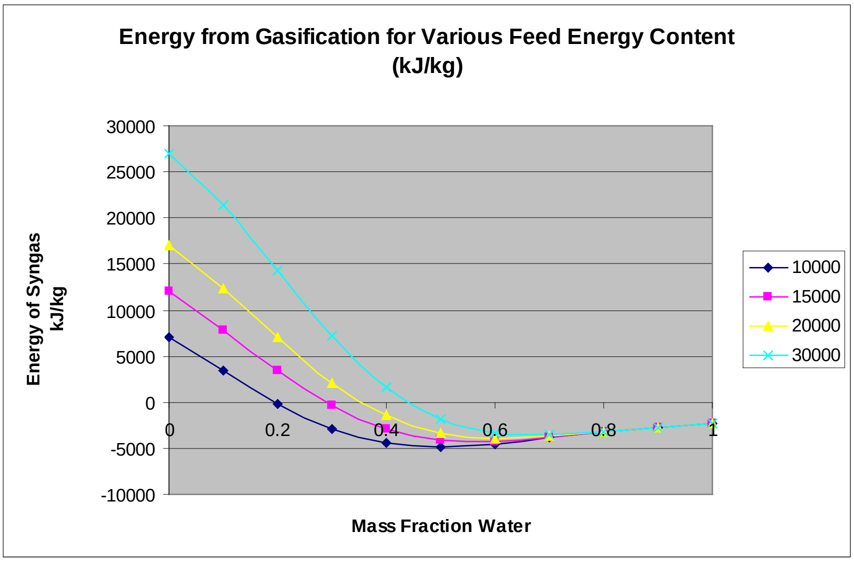
The similarity of the average elemental analysis of the feedstock to biomass and the similarity of the gas evolutions to that produced previously in other projects and studies on biomass has driven the modelling with respect to the thermal conversion processes to two conclusions. Firstly to use an average elemental composition in the feeds to the processes that is similar to that of biomass. Secondly that the processes will perform similarly to those of biomass (which was the basis upon which they were originally developed) although it should be noted that ash production is higher and contaminants cover a broader range of elements in wastes.

As detailed in the 2.2 report the type of technology used governs the by-products and residues produced in terms of tars and ash etc. It is not particularly feedstock driven. It was noted that the demolition wood and plastic film combination seems to produce more methane than would be expected. This may be an effect of breaking down long chains in the polymers.

The calorific values of the gases and other products is calculated by the spreadsheets thus developed, but the most impact on the processes in terms of net energy plus or minus will be the moisture content of the feed or the level of treatment of the feed to convert it into a form suitable for processing, such as comminution or pelletisation. Below is a simple chart of how net CV changes with moisture content and the burden this can place on a process.



Net Cv with Moisture Content for Various Feed Energy Content (kJ/kg)
Net Cv kJ/kg
35000
30000
25000
20000
15000
10000
5000
0
-5000
0
0.2
0.4
0.6
0.8
1
Mass Fraction Water
10000
15000
20000
30000



Energy from Gasification for Various Feed Energy Content (kJ/kg)
Energy of Syngas kJ/kg
30000
25000
20000
15000
10000
5000
0
-5000
-10000
0
0.2
0.4
0.6
0.8
1
Mass Fraction Water
10000
15000
20000
30000

APPENDIX 2: MODEL DESCRIPTION

This Appendix describes the system model that has been used in WP 3.3. The table below shows every line of the model and a note is provided to describe the purpose of each line. This description can be used in conjunction with the model itself to run a range of scenarios based on a number of simple variables.

This WP 3.3 systems model is different from the technology component models generated in WP 3.2[16], but it can be used with the WP 3.2 models and data can be transferred between the two. The WP 3.2 models are detailed models of various technology types while the WP 3.3 model looks at community scenarios.

The WP 3.3 model summarises the scenarios described in Sections 6 to 9 of this report and is used to produce waste to energy scenarios for these communities. The WP 3.3 has two versions: One that focuses on an Incineration approach and one that focuses on a Gasification approach. There is the option to split waste between processes at various points in the model as described below. The WP 3.3 model also produces scenarios for the City, Town, Village and Rural community and has the facility to assess the sensitivity of the model results to capital cost, feedstock price, operating costs and process conversion efficiency. The effect of these variables is discussed in the body of the report.

The WP 3.3 model operates by the user inserting a set of major data variables. The model then generates a scenario based on these variables. The user then has the option of investigating the effect of changes to any of these variables on the energy production, carbon dioxide emissions and simple profit of the whole system or any element within it.

Once a scheme or operating scenario has been developed with this model detailed runs can be made using the relevant models from WP 3.2 and data inserted into the WP 3.3 model to improve the accuracy of the model scenarios. Alternatively summary data can be taken from specific process suppliers and inserted in the model to validate decisions or develop higher quality model outputs.

The WP 3.3 model therefore provides a simple approach to assessing the waste to energy opportunities for a community type. This base model can be enhanced with additional data to develop the most viable scheme for and particular community scale. It can also accept enhanced data sets from either the WP 3.2 model or from actual data from process suppliers. Finally the WP 3.3 model can also be used to assess the sensitivity of the chosen scenarios to changes in the major process, operational and environmental variables.

The table below is an annotated printout of the WP 3.3 model. It does not reflect a particular model run, but is provided to describe how the model operates. The calculation approach to each line is discussed. Green cells are variable and can be changed by the user while White cells are calculations.

The overall aim is to define realistic schemes and approaches that can be verified with more detailed modelling and to identify the best opportunities for further technology development, application and investigation.

[16] See Work Package 3.2 report and the accompanying models.

Work Package 3.3 Model Description

ETI WASTE TO ENERGY MODEL
Version: 5
Date: 28/11/2010

CITY OF 500K PEOPLE

WASTES

	Units	Data	Comments
Dry Waste Weight	kt/yr	490.00	Dry waste is taken to be waste with moisture content below 25%. This is an entered variable. Data used in Work package 3.3 came from Work package 1.
Dry Waste Energy	MJ/Yr	4.79E+09	This is an entered variable. Data used in Work package 3.3 came from Work package 1. This value can be changed with the Dry Waste Weight if the calorific value of the specific waste is known.
Cost of Dry Waste	£/t	-30.00	Variable entered by the user based on local knowledge.
Wet Waste Weight	kt/yr	408.00	Wet waste is taken to be waste with moisture content above 25%. This is an entered variable. Data used in Work package 3.3 came from Work package 1.
Wet Waste Energy	MJ/Yr	9.18E+08	This is an entered variable. Data used in Work package 3.3 came from Work package 1. This value can be changed with the Wet Waste Weight if the calorific value of the specific waste is known.
Cost Wet Waste	£/t	-10.00	Variable entered by the user based on local knowledge.
Split			
Incineration	%	0.00	The user enters the amount of waste going to incineration based on weight percentage.
Gasification	%	100.00	Calculated by difference.
		100.00	

DRY WASTE SECTION

	Units	Data	Comments
Incineration			Section modeling an Incinerator
Capital/kt	£k/kt	500.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package 3.2 models.
Plant Capital	£M	0.00	Calculated from mass throughput and capital costs.
Plant Operating Cost	3% Capital/Yr	0.00	Assumes 3% of capital per year.
Plant Feed	Kt/Yr	0.00	Calculated from total dry waste mass throughput and split between technologies.
Plant Feed	MJ/Yr	0.00	Calculated from total dry waste energy content and split between technologies.
Feedstock Cost	£M/yr	0.00	Calculated from mass throughput and price per tonne of feed. N.B. this is negative is the supplier pays a gate fee.
Plant Efficiency	%	20.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package

			3.2 models.
Yield Electricity	KWh/Yr	0.00	Calculated from plant efficiency, technology split and throughput. Using a conversion from MJ to kWhr of 0.28.
Electricity Price	£/KWh	0.06	Variable entered by the user and including benefits from renewable obligation certificates (ROC) or feed in tariffs (FIT).
Value of Electricity	£M/Yr	0.00	Calculated from electricity production and price.
Simple Profit	£M/Yr	0.00	Calculated figure based on Value of Electricity minus the sum of (feedstock cost, operating cost and capital divided by 15). Capital figure is to simulate 15 year payback.
Wastes and Emissions			Assuming 100% combusted
Carbon Dioxide	kt/yr	0.00	Calculated based on stoichiometry with 1.9t of CO_2 produced per t of waste. Can be changed within the calculation cell if required.
Ash	kt/yr	0.00	Calculated assuming 1% of feed turns to ash. Can be changed within the calculation cell if required.
Gasification			Section modeling a gasifier. Significant changes occur depending on the type of gasifier.
Capital/kt	£k/kt	250.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package 3.2 models.
Plant Capital	£M	122.50	Calculated from mass throughput and capital costs.
Plant Operating Cost	3% Capital/Yr	3.68	Assumes 3% of capital per year
Plant Feed	Kt/Yr	490.00	Calculated from total dry waste mass throughput and split between technologies.
Plant Feed	MJ/Yr	4.79E+09	Calculated from total dry waste energy content and split between technologies.
Feedstock Cost	£M/kt	-14.70	Calculated from mass throughput and price per tonne of feed. N.B. this is negative is the supplier pays a gate fee.
Plant Efficiency	%	80.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package 3.2 models.
Yield Syngas	Kt/Yr	392.00	Calculated from plant efficiency, technology split and throughput. Calculated on a mass basis.
Syngas Price	£/t	0.00	Variable entered by the user. Set as zero if downstream plants are integrated with the syngas plant. If syngas is supplied as a merchant product a value will be entered here.
Value of Syngas	£M/Yr	0.00	Calculated from mass produced multiplied by price.
Simple Profit	£M/yr	-1.23	Calculated figure based on Value of Syngas minus the sum of (feedstock cost, operating cost and capital divided by 10). Capital figure is to simulate 10 year payback.

Wastes and Emissions			NB Links CO2 production to efficiency rest of feeds is assumed to be char
Carbon Dioxide	kt/yr	248.92	Calculated based on an approximation of syngas production and assuming syngas is not burnt. Calculation used is 635kg of CO_2 per t of waste. This can be changed on the calculation cell if required.
Char	kt/yr	98.00	Calculated assuming all feed that is not converted to syngas remains as char. This is an approximation and the calculation can be changed as required. E.G. Char is often used as a fuel in syngas production processes.
Split Syngas			Section assessing the value of syngas in varying production routes.
Electricity	%	33.00	Variable entered by the user. The user chooses the downstream processing route for the syngas.
Chemicals	%	33.00	Variable entered by the user. The user chooses the downstream processing route for the syngas.
Fuel	%	34.00 100.00	Calculated by difference.
Downstream			
Electricity by combustion			Option 1 is to use syngas for electricity production.
Capital/kt	£k/kt	100.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package 3.2 models. Lower than incinerator as this is just generation unit.
Plant Capital	£M	12.94	Calculated from mass throughput and capital costs.
Plant Operating Cost	3% Capital/Yr	0.39	Assumes 3% of capital per year.
Plant Feed	Kt/Yr	129.36	Syngas feed calculated from split between technologies.
Plant Feed	MJ/Yr	1.26E+09	Calculated from syngas energy content and split between technologies. N.B. Comparison data shows that for the purposes of this model on a like for like basis syngas energy content and waste energy content can be assumed to be equivalent.
Feedstock Cost	£M/yr	0.00	Calculated from mass throughput and price per tonne of feed. This will be zero in a system integrated with a syngas production unit.
Plant Efficiency	%	40.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package 3.2 models.
Yield Electricity	KWh/Yr	1.42E+08	Calculated from plant efficiency, technology split and throughput. Using a conversion from MJ to kWhr of 0.28.
Electricity Price	£/KWh	0.06	Variable entered by the user and including benefits from renewable obligation certificates (ROC) or feed in tariffs (FIT).
Value of Electricity	£M/Yr	8.50	Calculated from electricity production and

			price.
Simple Profit	£M/yr	6.82	Calculated figure based on Value of Electricity minus the sum of (feedstock cost, operating cost and capital divided by 10). Capital figure is to simulate 10 year payback.
Wastes and Emissions			Assumes full combustion of syngas
Carbon Dioxide	kt/yr	163.64	Calculated based on stoichiometry with 1.295t of CO_2 produced per t of waste. Can be changed within the calculation cell if required. Assume all feed is burnt, but conversion to electricity is the variable.
Ash	kt/yr	1.29	Calculated assuming 1% of feed turns to ash. Can be changed within the calculation cell if required.
Chemicals			Option 2, Use syngas to produce higher value chemicals such as methanol or ammonia.
Capital/kt	£k/kt	500.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package 3.2 models.
Plant Capital	£M	64.68	Calculated from mass throughput and capital costs.
Plant Operating Cost	3% Capital/Yr	1.94	Assumes 3% of capital per year.
Plant Feed	Kt/Yr	129.36	Syngas feed calculated from split between technologies.
Plant Feed	MJ/Yr		Not used.
Feedstock Cost	£M/kt	0.00	Calculated from mass throughput and price per tonne of feed. This will be zero in a system integrated with a syngas production unit.
Plant Efficiency	%	35.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package 3.2 models.
Yield Chemicals	kt/yr	45.28	Calculated from plant efficiency, technology split and throughput.
Chemical Price	£/t	550.00	Variable entered by the user based on data acquired from external sources.
Value of Chemicals	£M/yr	24.90	Calculated from production tonnage and price.
Simple Profit	£M/yr	16.49	Calculated figure based on Value of Product minus the sum of (feedstock cost, operating cost and capital divided by 10). Capital figure is to simulate 10 year payback.
Wastes and Emissions			
Carbon Dioxide	kt/yr	84.08	Assume all non chemical is CO_2. Very general worst case assumption.
Liquid Fuel			Option 2, Use syngas to produce fuels such as higher alcohols of fuel blending components.
Capital/kt	£k/kt	350.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package 3.2 models.

Plant Capital	£M	46.65	Calculated from mass throughput and capital costs.
Plant Operating Cost	3% Capital/Yr	1.40	Assumes 3% of capital per year.
Plant Feed	Kt/Yr	133.28	Syngas feed calculated from split between technologies.
Plant Feed	MJ/Yr		Not used.
Feedstock Cost	£M/yr	0.00	Calculated from mass throughput and price per tonne of feed. This will be zero in a system integrated with a syngas production unit.
Plant Efficiency	%	55.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package 3.2 models.
Yield Liquid Fuels	kt/yr	73.30	Calculated from plant efficiency, technology split and throughput.
Fuel Price	£/t	450.00	Variable entered by the user based on data acquired from external sources.
Value of Liquid Fuel	£M/yr	32.99	Calculated from production tonnage and price.
Simple Profit	£M/yr	26.92	Calculated figure based on Value of Product minus the sum of (feedstock cost, operating cost and capital divided by 10). Capital figure is to simulate 10 year payback.
Wastes and Emissions			
Carbon Dioxide	kt/yr	59.98	Assume all non chemical is CO_2. Very general worst case assumption.
Simple Profit from Incineration	£M/yr	0.00	Simple profit for incineration copied down from higher up the model.
Simple Profit from Gasification	£M/yr	49.01	Sum of the simple profit for each of the gasification and downstream treatment processes.
TOTAL SIMPLE PROFIT OF DRY PRODUCTS	£M/yr	49.01	Sum of the Incineration, Gasification and downstream processing profit/loss.
TOTAL WASTE AND EMISSIONS FROM DRY PRODUCTS			
Carbon Dioxide	kt/yr	496.64	
Char	kt/yr	98.00	Note that this is consumed to power further processing so much is destroyed and turned to CO2
Ash	kt/yr	1.29	
WET WASTE SECTION			
Capital/kt	£k/kt	65.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package 3.2 models.
Plant Capital	£M	26.52	Calculated from mass throughput and capital costs.
Plant Operating Cost	3% Capital/Yr	0.80	Assumes 3% of capital per year
Plant Feed	Kt/Yr	408.00	Calculated from total wet waste mass throughput from the data at the top of the model.
Plant Feed	MJ/Yr	9.18E+08	Calculated from total wet waste energy content from the data at the top of the model.
Feedstock Cost	£M/yr	-4.08	Calculated from mass throughput and price per tonne of feed. N.B. this is

			negative is the supplier pays a gate fee.
Plant Efficiency	%	13.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package 3.2 models.
Yield Gas	MJ/yr	1.19E+08	Calculated from plant efficiency and throughput.
Split			
Gas	%	20.00	Variable entered by the user showing a balance between the use as gas and the conversion of gas to electricity.
Electricity	%	80.00	Calculated by difference.
		100.00	
Electrical Conversion Efficiency	%	40.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package 3.2 models.
Yield Electricity	KWh/Yr	1.07E+07	Calculated from AD plant yield energy value using the Buswell equation and multiplied by the split going to electricity production.
Electricity Price	£/KWh	0.12	Variable entered by the user and including benefits from renewable obligation certificates (ROC) or feed in tariffs (FIT).
Value of Electricity	£M/Yr	1.28	Calculated from electricity production and price.
Yield Gas	KWh/yr	6.68E+06	Calculated from AD plant yield energy value using the Buswell equation and multiplied by the split going to electricity production.
Gas Price	£/t	0.06	Variable entered by the user and including benefits from renewable obligation certificates (ROC) or feed in tariffs (FIT). Currently none for gas, but this may change with the advent of the renewable heat incentive.
Value of Gas	£M/Yr	0.40	Calculated from gas production and price.
Digestate Output	Kt/Yr	354.96	Residual tonnage after energy yield, but calculated on a mass basis.
Solids Content	%	10.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package 3.2 models.
Dry Solids	Kt/Yr	35.50	Calculated from digestate tonnage and water content.
Digestate Value	£/t	30.00	Variable entered by the user based on general knowledge, data from a specific process or data from the Work package 3.2 models.
Digestate income	£M/Yr	1.06	Calculated from the price and the dry tonnage.
Simple Profit	£M/yr	3.38	Calculated figure based on Value of Product minus the sum of (feedstock cost, operating cost and capital divided by 10). Capital figure is to simulate 10 year payback.
Wastes and Emissions			
Carbon Dioxide	kt/yr	10.20	250kg of CO_2 per tonne of dry feed is produced. Assume feed is 10% solids
TOTAL VALUE OF WET	£M/yr	3.38	Sum of the simple profit for all parts of the

PRODUCTS			wet product chain.
TOTAL CAPITAL INVESTED	£M	273.28	Sum of all the capital invested in the total waste to energy system including incineration, gasification, downstream processes and wet processing.
TOTAL VALUE OF OUTPUTS	£M/yr	52.39	Sum of all the simple profits for all stages of the total waste to energy system including incineration, gasification, downstream processes and wet processing.
TOTAL WASTES AND EMISSIONS			
Carbon Dioxide	Kt/yr	506.84	Sum of all the carbon dioxide emissions for all stages of the total waste to energy system including incineration, gasification, downstream processes and wet processing.
Char	kt/yr	98.00	Sum of all the char production for all stages of the total waste to energy system including incineration, gasification, downstream processes and wet processing.
Ash	kt/yr	1.29	Sum of all the ash production for all stages of the total waste to energy system including incineration, gasification, downstream processes and wet processing.

APPENDIX 3: OUTCOME FROM THE ETI WORKSHOP IN NOVEMBER 2010

Key Factors/Questions to Consider for Robustness/ETI/UK Benefits Case

Waste Scenarios from 2020 to 2050

- Availability of certain types of waste (e.g. plastics, etc)
- Co-mingling of wastes or segregation of wastes?
- Growth in certain potential areas, such as agricultural residues
- Synergy effects of combining certain types of waste (e.g. slurries with agricultural residues)
- Technology developments for “wet waste” versus “dry waste”, costs/effectiveness of drying for example
- “Value” of energy from waste versus Replace, Reduce, Reuse, Recycle Framework
- Spatial availability of wastes (regional availability of certain wastes)/waste hubs, etc
- Technologies that produce liquid bio-fuel rather than heat/power
- Co-production of energy as well as materials (plastics, cement mix, etc)
- Need to ensure that all types of waste are included in the model (sewage, slurries, agricultural residues, etc)
- Long-term of availability of each feedstock to ensure running the project....

Opportunity Costs and Systems Costs

- Waste as a “free resource” is unlikely to continue in the longer term
- Costs of transport/pre-processing/aggregation are significant in the overall systems costs (20 to 70% of costs)
- Opportunity costs should be considered for each waste stream (e.g. plastics – value of upgrade/recycle, for slurries/agricultural residue – costs as fertiliser, etc)

Feedstock prices

- There are a number of considerations or “world” which could evolve to 2050
- Price for waste could be based on “opportunity costs”, GHG reduction plus transport costs, and/or biomass pricing (with a discount based on moisture content, impurities, etc)

- Note that current biomass pricing in more advanced markets is based crudely on moisture content, ash, and level of certain impurities

Storage

- Role of storage in value chain
    - Storing of biomass feedstock (10days – 3months?)
    - Storing of product (e.g. gas, for using as load-following), combining with OCGT for balancing with wind?

Technology and Technology Readiness Levels 3 to 6

- ETI "demonstration" is not a fully commercial demonstrator, this is a pre-commercial prototype or systems demonstration (provisionally £10 to 15mn)
- This could be separate or part of an integrated project
    - Integrated project could include district heating and gas engine/turbine/fuel cell for example, fuelled from the gasification
- Need to consider how we represent "technology potential" in the modelling work that Steve and Jalaja are delivering. E.g. cost improvement, efficiency improvement, GHG reduction improvement. What are the potentials? What is the difference?
- Incineration as base case for dry waste, AD as base case for wet waste
- What scales do these technologies work at?

Capital costs and operations costs

- Huge sensitivity to certain key impurities (ash, alkali, Cl, ammonia, etc)
    - Could mean adding additional pre-processing or post-processing equipment
    - Need to consider sensitivities depending on differing types of feed material

Robustness/Feed material

- Should consider how all types of "waste" play out in technology combinations, as individual and combined streams
- Consider "robustness" in terms of the ability of technologies to readily be able to utilise other feedstocks during 15-20 year operating cycle (e.g. wood-chips, srf, miscanthus, etc)

Gaps in the model/sensitivities

- Gaps clearly exist in terms of "operations costs" confidence – these need to be explored and articulated clearly
- This could certainly play out when comparing differing technology sets, especially in considering differing types of impurities
- How do we consider aggregation and transport costs?
- Supplementary data from lab and field trials of technologies in published/grey literature
    - As much as possible, source data to be referenced and gathered based on lab/field trial data as well (and error bars given around uncertainty)
- Other technologies
    - Fast pyrolysis
    - Torrefaction for pre-processing?
- Feedstock variability, consistency and control
    - We will need to comment on this and consider how important this could be
    - Considering that we could not "close the mass balances", then there were two conjectures provided, namely:
        - That there was material that "stayed within parts of the equipment"
        - The feed quality/mix was not homogeneous, hence contents was varied throughout
        - Technically autoclaving may create more homogeneity, or we segregate stocks and "blend" in certain proportions

Leverage of existing infrastructure/location of waste sites

- E.g. sewage works
- E.g. current incinerators
- E.g. current grid/gas connectivity

Business/Benefits Case

- Benefits case activities were provisionally defined back in December 2009 with EDF/CAT, it would be good to share these definitions with the consortia
- As part of benefits case, the potential rigour/replicability and materiality of opportunities was to be included (E.g. what is the scale of the opportunity in the UK)

Note:

- Will need to "bring" local authorities with us
  - Interesting to see that only Glasgow really has an integrated system of wet and dry waste central collection and separation
  - Environment Agency
- Will need to "bring" waste groups with us – to consider energy
  - Veolia
  - Shanks
  - Ineos

Brain-storm of types of technology demonstrators (TRL 3 to 6)

Consider "deeper modelling" to improve understanding prior to build
Consider separation of wastes into three or four value streams

- Wet waste with energy value
- Dry waste with higher energy value (e.g. for gasification)
- Dry waste with low energy value (e.g. for incineration)
- Waste for other valued products
  - Plastics for recycling
  - Timber for re-use
- Play the "arbitration" based on value of feed-stocks at the time (combine bio-gas and syn-gas?)

Wet waste

- Low temperature of bio-processes
- Synergies?
  - Is there anything in TRL 3 to 6?
    - AD - continuous AD, small-scale, mixed feed
    - AD – combined ag residue/wet waste combinations

Dry waste

- Fluidised bed gasifier with pre-processing and post-processing
  - Simple
  - Broad range of pre-processing and post-processing to ensure equipment runs
  - Monitor ranges of fuel types

- Syn-Gas can be utilised in conjunction with power/CHP and/or transport fuel combinations – could allow for flexible model to "play the arb"
- Could consider capturing CO2 in conjunction, could consider bio-char
- Incineration can do all, however at 11-13% efficiency
- We need to beat this benchmark
    - Could be achieved by some level of segregation?
    - Robustness?
- May need to consider both in hubs
    - Incineration for "real crap"
    - Gasification/other technologies for higher end material

Note

- Business case at the moment is driven by tonnes of waste converted, rather than efficiency/effectiveness of what we are trying to achieve.

Frames to consider including in the scenarios themselves

1. Current infrastructure versus optimised matching of technology
    - Current infrastructure world vs Optimised matching of technology combinations based on producers (consumers, C&I, rural farms, etc)
    - Need to integrate transport costs/aggregation costs as well as appropriateness of technology combinations to waste combinations in terms of:
        - Segregated combined hubs (incinerator, ad, gasification, and waste upgrade)
        - Or at a smaller scale in terms of single/dual technology combinations
2. Segregation versus combinations of fuels
3. Differing waste availabilities and pathways to 2050
    - MSW (especially plastics)
    - C&I
    - Agricultural residues
    - Slurries, manure, wet wastes
4. Consideration of spatial aspects of waste volumes and categorisation where energy content/volumes may be high
    a. MSW
    b. C&I
    c. Agricultural residues
    d. Slurry/wet waste

    Number of regions and combinations across UK

Key questions

- Scenarios need to be tested both in terms of technology stream modelling (Steve/Jalaja) as well as EDF business/scaleability/robustness test, and use the questions considered at the workshop to answer the qualitative aspects for each of the scenarios/technology sets

- **Test/validate schemes against real data, such as ARBRE, EDF, and DEFRA schemes**

- **Scenarios and preliminary thoughts should be tested in a workshop in November to include externals such as WRAP, DEFRA, REA, Carbon Trust, NFU, NNFCC, BBSRC, EA, Tony Bridgwater, Jim Swithenbank, etc**

  - Which technology sets come out most powerfully within the scenarios above in terms of robustness, GHG reduction, efficiency, costs, and value
  - Is there something meaningful that the ETI could do to inform the above?
  - Need to consider the potential impact of technology improvements here (costs, efficiency, etc) as we consider 2020, 2030, 2040, etc
  - What is the materiality of these options in terms of availability of future waste streams, and spatial distribution of this waste material?
  - Sensitivity analysis needs to be performed on each of the scenario outputs, especially around waste prices/availability, effect of impurities on capital/opex, etc

- **Engagement with other groups (local authorities, etc) in early Jan/February**

***Consideration of counter-factuals (**E.g. Pyrolysis and syn-gas to transport fuels, Plastics for other options)

APPENDIX 4: 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.