Programme Area: Bioenergy

Project: Energy From Waste

Title: UK Benefits Case Report: Syn Gas for Fuels and Chemicals

Abstract:

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 ETI has commissioned a series of supporting pieces of work to augment the full project reports. This report discusses the opportunity of using syngas produced from the gasification of wastes for the production of fuels and chemicals. A separate report studies the use of pyrolysis to produce vehicle fuels. Pyrolysis is not discussed further in this report.

In general liquid fuels and chemicals have a higher value than electricity and heat and as a result it is inferred that margins are likely to be greater and returns higher if wastes are converted to fuels and chemicals rather than heat and power. The work of the core ETI EFW Project focused on the conversion of wastes into energy and heat. This additional report focuses on fuels and chemicals.

The report looks at the technologies that could be used for converting wastes to fuels and chemicals and their state of technology readiness. It also considers the scale of operation required for these types of plants and draws on the economic models developed in the core ETI EFW project to explore potential returns.

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

UK Benefits Case Report:
Syn Gas for Fuels and Chemicals

Version 1.2

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Graham Hillier and Steve Donegan

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Contents

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.[1] The ETI has commissioned a series of supporting pieces of work to augment the full project reports. This report discusses the opportunity of using syngas produced from the gasification of wastes for the production of fuels and chemicals. A separate report studies the use of pyrolysis to produce vehicle fuels. Pyrolysis is not discussed further in this report.[2]

In general liquid fuels and chemicals have a higher value than electricity and heat and as a result it is inferred that margins are likely to be greater and returns higher if wastes are converted to fuels and chemicals rather then heat and power. The work of the core ETI EFW Project focused on the conversion of wastes into energy and heat. This additional report focuses on fuels and chemicals.

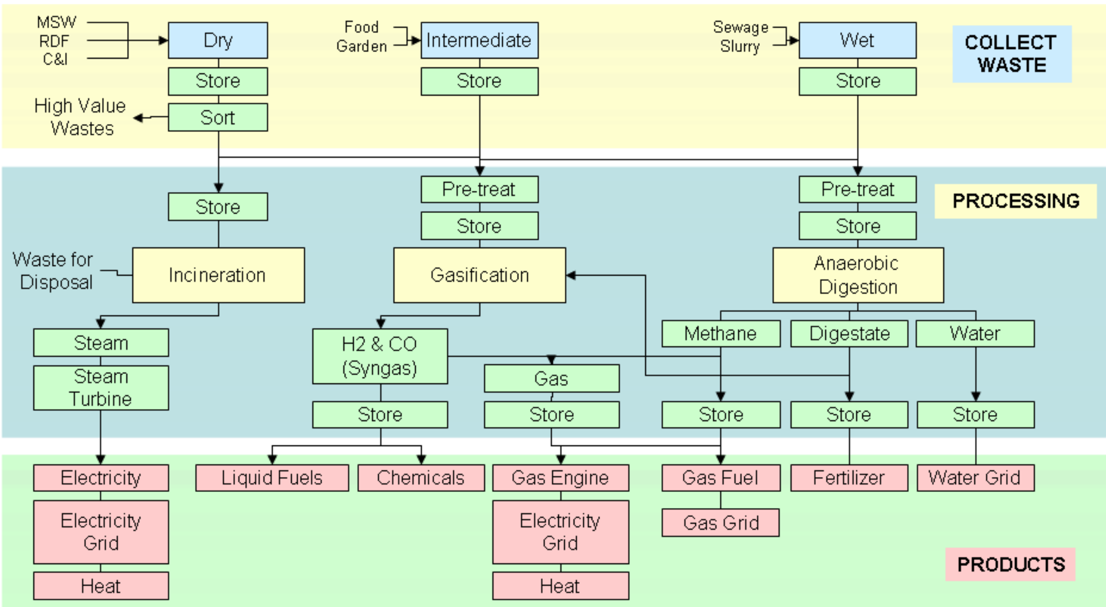
The report looks at the technologies that could be used for converting wastes to fuels and chemicals and their state of technology readiness. It also considers the scale of operation required for these types of plants and draws on the economic models developed in the core ETI EFW project to explore potential returns. Conclusions are drawn and proposals made for potential projects that could further explore the opportunities for waste to fuel and chemicals.

[1] ETI Energy from Waste Programmes Reports, June 2011.
[2] CPI Report for ETI: A review of Biomass to Liquid Fuels via Pyrolysis, August 2011.

2. BASIS OF MODELLING

As used in the core ETI EFW project work the technology flow sheet shown in figure 1 has been used as the basis of the modelling and assessment.[3]

Figure 1 - Schematic Technology Flow Sheet



In this report the gasification leg through to fuels and chemicals is studied. Small modifications have been made to the economic, energy and mass flow model that was used in the work package 3.3 of the core projects to assess process effectiveness.[4]

The wastes assessed in this case are assumed to be dry wastes with an average moisture content of 20%. Wastes can include biomass, polymers, paper, card textiles and other materials that can be gasified to syngas.

The economic model has been simplified from the ETI EFW Work Package 3.3 version and has been updated to reflect publicly available data for capital and product costs. The model calculates the final outputs for the integrated system from waste through to fuels and chemicals. The model requires feedstock volume, feedstock cost, capital cost, operating cost and conversion efficiency as inputs and calculates product and by-product volumes and values along with operating cost and emissions as outputs. The processes modelled produce a significant amount of low and high-grade waste heat. In this model the waste heat is not reintegrated into the process, but it should be noted that in many fuel and chemical process plants waste heat would be reused in the process to improve operating efficiencies wherever possible.

The economic model is not an accurate representation of all the specific processes; it is a simplification for the purposes of comparison. The model's ability to flex the process routes has not been fully explored in this project. There is an opportunity to develop the model further and assess the interaction of the chosen technologies under

[3] ETI Energy from Waste Programme, Work Package 3.3 Report, May 2011.
[4] Excel Modelling Spreadsheet for Syngas to Chemicals, August 2011.

a much wider range of input, operational and output regimes in future programmes if desired.

It should be noted that the products modelled in this project are in the mature market stage. Thus profitability is to a greater extent dependent on the world capacity to meet supply and demand. This means that, unless there is a significant under capacity, the product profitability is highly dependent on the balance between the cost of feedstocks, the value of the product and the efficiency of the process. The modelling approach has been used to generate scenario data that shows the significance of the main variables.

2.1. Guiding Principles for the Modelling

The guiding principles applied in the core ETI EFW[1] project report continue to apply to processes that produce fuels and chemicals. The 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;
- 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.

This project report looks at the integrated production chain from waste to synthesis gas (syn gas) by gasification. The gasified syngas is then converted into fuels and chemicals in production plants that are downstream on the syngas production facility. The economic model has been constructed in this way and all the main variables can be changed to assess their impact on the process.

For each of the modelled scenarios a 'simple profit' is calculated as:

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

The Excel based economic model has been supplied as part of the project[4].

3. DESCRIPTION AND STATUS OF THE TECHNOLOGY

Syngas chemistry is well known and has been in use to produce a number of common fuels and chemicals from natural gas or coal for a number of years. This section covers the following aspects:

- Feedstock requirements for gasification;
- Status of large scale gasification technology:
- The common products produced through a syngas route;
- Novel process routes that are yet to be established;
- The opportunity to move to a syngas based system for the production of fuels and chemicals for general use.

3.1 Feedstock

The conclusion from the core technology work in the ETI EfW project was that the chemical composition of waste can be assumed to be approximate to that of biomass, but there are two major variables that require close management. These are:

- Material shape or form and
- Material moisture content[3].

Moisture content in wastes has been shown to vary from less than 10% to 71% with the average of around 20%. Clearly the moisture content 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. Gasification 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 syngas production. The product form required varies between technologies.

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.

As identified in the core ETI EfW project there is a need for the development of technology to create consistent feedstock sources in both shape and form for all gasification processes. The conclusions drawn in the core report are relevant to the processes to produce fuels and chemicals and the conclusions drawn around feedstock shape and form apply to these processes.

3.2 Large Scale Gasification Technology

One of the features of current production plants for fuels and chemicals is that they are generally built on very large scales and it is expected that the economies of scale coupled with downstream use or distribution systems will ensure that this continues in the future. In Work Package 3.3 of the ETI EFW project it was noted that the conversion of wastes to fuels and chemicals would not be feasible unless large volumes of wastes were consistently available to feed capital intense fuel and chemical complexes. The result is that facilities using less than 500kt/yr of feedstock are very unlikely to be developed. As a result it is assumed that only large scale gasification technologies would be used for integrated fuel and chemical complexes.

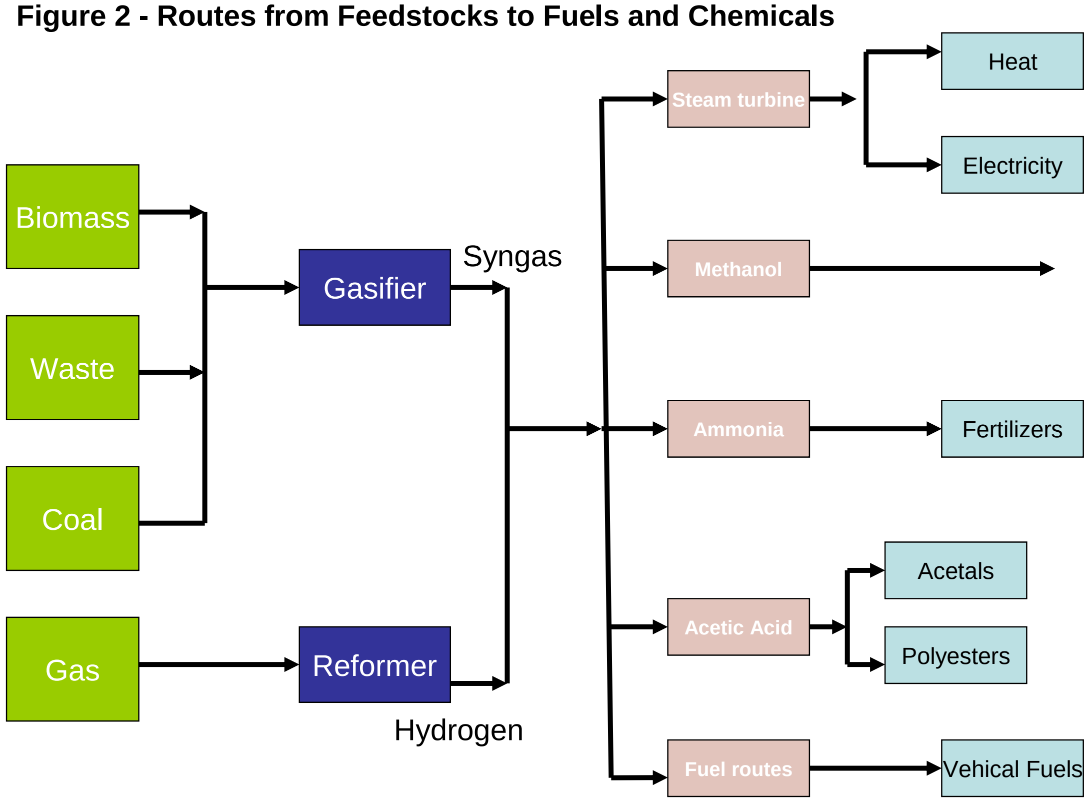
Typical new plants produce of the order of 1 million tonnes per annum. For example: The capacity of the new methanol plant for the new Al Jubail (AR RAZI 4) Methanol Plant, Saudi Arabia approximately 850,000t/yr.

The main technologies for the production of syngas by gasification are fixed bed, fluidised bed and entrained flow gasifiers. Descriptions of how these technologies work and their variations are contained in the main ETI EFW Work Package 3.3 report and the technology review reports. An assessment of their technology readiness levels is also included. It is assumed that this type of technology will be used in fuel and chemical complexes. It has a technology readiness level (TRL) of 8 or 9 for use with coal and a similar level for units that co-fire a proportion of their feedstock as waste or biomass. There is no evidence of large scale commercial gasifiers using 100% percent waste feedstock. This is because of the technical issues associated with changing waste, moisture content and form. It is also related to the difficulty of securing a large enough feedstock supply for long enough to make investment viable.

3.3 Common Products and Technologies Based on Syngas Processes

A number of commonly used fuels and chemicals are currently produced through syngas routes based on natural gas or, in a few cases, coal. The production routes, including energy, are summarised in Figure 2.

Figure 2 - Routes from Feedstocks to Fuels and Chemicals



The common chemical reactions are:

3.3.1 Methanol – Widely used chemical reagent that is also be used as a fuel and can be blended with conventional liquid fuels. Over 40% of methanol is used in the production of formaldehyde for adhesives, plastics, paints and explosives. Current global production is about 41 million tonnes per year.

Production at present is a combination of several reactions:

$$CH_4 + H_2O \rightarrow CO + 3\ H_2$$

Endothermic steam-methane reforming (SMR) to syn gas (carbon monoxide and hydrogen)

$$2CH_4 + O_2 \rightarrow 2CO + 4\ H_2$$

Exothermic reaction with oxygen for auto SMR to syngas

$$CO + H_2O \rightarrow CO_2 + H_2$$

Exothermic Water gas shift reaction used to moderate the H_2 concentration in the syn gas

$$CO + 2\ H_2 \rightarrow CH_3OH$$

Catalysed syngas reaction to produce methanol

This is the major use of Fischer Tropsch catalysed reactions.

If waste/biomass was used as the feed material a theoretical equation of methanol production can be developed.

$$CH_{1.4}O_{0.6} + 0.6\ H_2O + 0.07\ O_2 \rightarrow 0.66\ CO + 1.32\ H_2 + 0.34\ CO_2 \rightarrow 0.66CH_3OH + 0.34\ CO_2$$

This approach would consume water in the steam phase. CO_2 would be produced. The amount depends on the energy efficiency of the process.

3.3.2 Ammonia – Widely used chemical that is the mainstay of the synthetic fertilizer industry. 80% of ammonia is used in fertilizer production, but is also used for explosives, anaesthetics, food, fire extinguishers and as a refrigerant. Current global production is about 155 million tonnes per year.

Ammonia is still produced commercially using the Haber process which was developed in the early 1900s. It is the reaction of hydrogen and nitrogen at elevated temperatures and pressures.

$$N_2 + 3\ H_2 \rightarrow 2\ NH_3$$

Ammonia production depends on plentiful supplies of natural gas and other fossil fuels for the production of the hydrogen using similar reactions to those detailed above in the methanol production equations. This is a finite resource and one potential development is to provide the hydrogen from a waste gasification process. The ammonia process uses a catalyst which is highly sensitive to contaminants and those such as sulphur and arsenic can cause permanent poisoning. The cleaning and purifying of the hydrogen is a significant part of the whole ammonia process. This is likely to be a more difficult task with the variability and exiting known difficulties of gasification processes based on wastes and biomass.

3.3.3 Other Hydro carbons

In a similar way that methanol can be produced in catalysed Fischer Tropsch reactions, other hydrocarbons can be produced. It has been shown that alkanes and alcohols can be created in this type of reaction to C_{10} plus. These molecules can be used directly as fuels (e.g. ethanol and butanol). In addition they can be used as the building blocks for other more complicated aromatic products. This approach would be inserting products into the existing chemicals supply chain. The waste feedstock or biomass would be replacing a crude oil.

3.3.4 Novel Syngas Processes Routes that are Under Development

It is believed that the majority of the work in syngas technology is in the catalyst development and the combining of the steam reforming and the Fischer Tropsch (FT) process, the reforming is exothermic and the FT is endothermic so in theory the two reaction stages can be integrated for optimum energy usage. The FT process is quite sensitive to temperature so the management of the temperature and heat across the catalyst bed is critical.

Other work and development is in the creation of guard bed catalysts to clean up syngas entering the main reaction process. These are to protect the main catalyst from low levels of impurity and contamination that can arise in the syngas. As discussed in the main ETI EFW reports low cost technology to clean-up syn-gas produced from biomass and wastes is a vital step in the process development. This is particularly true in the case of catalysed reactions to produce fuels and chemicals. It is understood that organisations such as Johnson Matthey are actively researching catalyst development for use on waste and biomass derived products.

3.3.5 The opportunity to Convert to a syngas based system for the General Production of Fuels and Chemicals

From the previous discussions it can be seen that there are already syngas based routes for the production of fuels and chemicals. Admittedly these are fossil fuel based processes using natural gas or coal. As noted the catalysts used in these existing processes are extremely susceptible to contaminants in the feed gas and require a high level of purity.

There is potential for development projects to develop gas cleaning processes for the purification of the waste derived gases suitable for use in existing FT processes. In addition the development of guard bed catalysts or catalysts that are resistant to the contaminants produced by the waste gasification process is also a target. These findings reiterate some of the difficulties highlighted in the 3.3 and 4.1 reports in the core ETI EFW project. Although the effect of syngas contaminants in the production of fuels and chemicals are different and of greater importance than those for energy production there is no doubt that gas cleaning is an essential part of the process that requires further development.

3.4 Summary of Technologies

Table 1 - Summary of Technology Readiness for use with Wastes

If the NASA technology readiness level[5] are used the technologies can be assessed as follows (see Appendix 1 for summary chart of TRL definitions):

Technology	Technology Readiness Level	Current Operating Scale	Development Opportunities	Pros	Cons
Gasification: Fluidised Bed	6-9	Over 250kt feed/yr	Develop technology to use a flexible feed slate of coal, biomass and wastes	Well established at large scale	Complex units
Methanol	8-9	Up to 1 million tonnes/year	Already syngas based, could be developed to use syngas from waste	Very well established and easily available	Currently unable to handle syngas from waste
Ammonia	8-9	Up to 1 million tonnes/year	Already syngas based, could be developed to use syngas from waste	Very well established and easily available	Currently unable to handle syngas from waste
Acetic Acid	8-9	Up to 600 kt/yr	Already syngas based, could be developed to use syngas from waste	Very well established and easily available	Currently unable to handle syngas from waste
Fischer Tropsch Reactions	2-5	Development scale plants	Support the transition from research and development to demonstration	Offer great opportunities to develop syngas chemistry	Currently expensive and underdeveloped. Unable to compete with traditional petrochemical routes
Gas and Liquid Cleaning Technology	3-5	From 10kt/yr upwards	Develop higher efficiency and lower cost technology for all scales	Convert mixed and contaminated streams to meet product specification	Expensive to buy and to operate

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

4. ECONOMIC MODEL

4.1. Pricing and Capital Assumptions

The cost and pricing assumptions are shown in Table 2. For the sake of simplicity current data has been gathered for mid 2011 for an integrated complex that uses 500kt/yr of waste as feed to a gasification plant that can feed into the production of electricity, a fuel (methanol) and a chemical (ammonia). The variables within the excel model can be changed to test sensitivities and the model could be modified for other products. However, methanol and ammonia have been chosen as they are established products with ready markets where pricing and investment data are easily available.

Table 2 - Summarises the Input Data for the Process Modelling

	Mid 2011 Wholesale Price	Capital	Comment
Gasification	No value assumed as syngas is unsalable	£350/kt	Assumptions are as in ETI EFW Project WP3.3
Fuel - Methanol	£265/t	£300/t	Prices are the mid year wholesale prices for 2011. Capital is market data, but with a reduction of 25% as the reformer step is not required.
Chemical – Ammonia	£355/t	£400/t	

4.2. Model Outputs and Sensitivities

The excel model has been run to assess the sensitivity of the simple profit data based on the main variable parameters. These are shown in Table 3. Sensitivities are shown as negatives, but a similar positive improvement would occur if the parameter moved in the opposite direction.

Table 3 - Sensitivity of Simple Profit Output to Changes in Major Variables

Changed Parameter	Base Case	Capital	Feedstock Cost	Operating Cost	Product Value	Plant Operating Efficiency
	£m/yr	Up 20%	Up £30/t	Up 20%	Down 20%	Down 20%
100% Electricity	4.6	-0.9	-10.4	3.3	-1.5	-0.6
33% Electricity /33% Chemicals /33% Fuel	17.4	10.4	8.3	15.8	9	6.4
50% Chemicals /50% Fuels	23.6	15.8	8.6	21.8	14.1	9.8
100% Chemicals	17.5	9.4	2.5	15.7	8.8	5.5
100% Fuel	29.6	22.3	14.6	27.9	19.4	14

Table 4 summarises the capital investment required for the integrated plant scenarios, the simple profit and the payback in years.

Table 4 - Summary of Invested Capital and Payback for a 500kt/yr Waste Fed Production Complex Using Base Case Data

Product Outputs	Total Capital Invested in Complex	Simple Profit	Payback
	£m	£m/yr	Years
100% Electricity	210	4.6	45.7
33% Electricity /33% Chemicals /33% Fuel	268	17.4	15.5
50% Chemicals /50% Fuels	298	23.6	12.6
100% Chemicals	315	17.5	17.5
100% Fuel	280	29.6	9.5

4.3. Comments

- A gasification complex linked with chemicals and fuels production has capital costs that are significantly increased over investments for power generation. However, there is a very significant increase in financial returns because chemicals and fuels have a higher value than electricity and conversion rates for feedstock into valuable products are higher;
- 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;
- It is highly unlikely that an investment will be made in a complex with a throughput of less than 500kt/yr of feedstock as economies of scale are significant;
- The best returns are for waste to methanol production where paybacks come below 10 years. However, investors are most likely to invest in a complex that can handle mixed feedstocks and produce a range of products. By investing in this flexibility of operation risk is reduced as production can be shifted between products to take advantage of changes in feed and product prices. 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.

4.4 Technology Development Opportunities

The base gasification and chemical technologies are available from a number of suppliers but there are technology development opportunities. These are:

- The development of integrated complexes that use wastes or combinations of wastes, biomass and conventional feedstocks to produce heat, power, fuels and chemicals through a gasification route. A schematic of an integrated complex of this nature is shown in Figure 2;

- There is also an opportunity for converting syngas generated from wastes to other chemicals and fuels. There are opportunities to accelerate the development of novel technologies low cost conversion technologies that have high yields of high value chemicals;
- As highlighted in the core ETI EFW reports there is a need to develop gas cleaning processes to make syngas produced from wastes clean enough for chemical processing.

5. EMISSION MODELLING

The complexity of the potential production routes for fuels, and particularly, chemicals produced from wastes is a highly complex issue that cannot be modelled effectively using simple models. As a rule the more biogenic waste that is used in the feedstock the lower the emissions of carbon dioxide to atmosphere. However, the downstream processing and end use of the product can have a significant impact on overall carbon footprint. For example: Methanol could be used as a fuel in which case combustion products would be released to atmosphere at the point of combustion. Alternatively the methanol could go into thermoset resins that are used in plywood and could stay in use in the solid form for in excess of 50 years.

Analysis of this complexity is outside of the scope of this study. In Work Package 4 of the core ETI EFW project the emissions from gasification processes were considered in detail. This analysis is equally applicable to gasification for the production of chemicals and polymers[6].

The additional complexity of downstream processing makes emission modelling complex and difficult and outside the scope of this project. It is proposed that if a waste to chemicals and fuels technology project is taken forward more detailed modelling is carried out to develop an effective analysis approach.

6. DRIVERS FOR TECHNOLOGY DEVELOPMENT OPPORTUNITIES

The coal to chemicals and fuels production chain is well established and all the technology steps are at an advanced level of delivery. The economics modeling in this report indicates that applying this technology approach to wastes is a realistic proposition. However, there are technology development opportunities that are worthy of further investigation. These are:

- Gasification processes that can handle variable feedstock form and moisture content. This is essential to the successful operation of waste gasification processes. The evidence from the work to date indicates that mixed wastes have similar elemental composition, but differ widely in form and moisture content;
- There is a need for gas clean-up technology that can convert syngas produced from waste into a chemical process feedstock of sufficient quality that catalyst reactivity is not disrupted by contamination;
- Develop new technology routes such as Fischer Tropsch catalysts that allow a wider range of chemicals and fuels to be produced by syngas routes;

[6] ETI EFW Project Work Package 4 Report, Benefits Case, June 2011.

- Explore the opportunity for technologies that can operate commercially below the 500kt/yr scale.

7. THE CASE AND OPPORTUNITY FOR ETI INTERVENTION

The analysis presented in this report shows that the production of fuels and chemicals from wastes via the production of syngas has potential as a non fossil fuel route to these vital products. The process steps for some common chemicals, such as ammonia and methanol, are all well known and have been used for many years. There are opportunities to use known reaction routes to develop additional process technologies.

To date the gasification processes have not been proven on 100% waste feeds although many large scale gasifiers have utilised low level waste additions with coal. There are three main areas of opportunity. They are:

- To develop waste sourced syngas complexes for the production of fuels and chemicals. This is unlikely to be a major project for the ETI due to the scale of investment required;
- To support the development of syngas clean-up processes to raise gas quality to that needed for chemical and fuel production;
- To support the development of novel low cost high yield processes for the production of fuels from syngas.

These areas would benefit from the development of gasification technology and gas cleaning technology programmes that were proposed in the core ETI EFW project. This work reiterates the value of the core project proposals.

The UK also has the technological capability to develop low cost high yield syngas to fuels processes. If these opportunities were realised there would be additional benefits from creating a consortium of organisations to work together for this purpose. For example, there are well established organisations in the UK with proven expertise in the following relevant areas.

- Universities – experience with Fischer Tropsch reactions and the development of catalysts;
- Business – the commercial development of catalysts and supply of feedstocks;
- Innovation centres – the practical development of processes to advance syngas to fuels processes to TRL range 4-7.

There are good prospects for the UK to be able to develop and use novel syngas processes but no single organisation is in a position to do so effectively.

A development programme would involve a pilot scale development plant next to a gasification development facility with the emphasis on the syngas to fuel step. Such a programme would cost at least £7m. It is highly unlikely that such an investment would be made by business without an external driver. The ETI could be such a driver by issuing a call for technology if it decides that this technology has a high enough priority when compared to its other technology development options. It could invite a consortium to form to undertake a development programme of work with the following objectives:

- To develop gas cleaning technology – Possibly as part of the core ETI EFW project next stages;
- To develop and demonstrate pilot scale technology for conversion of syngas into chemicals and fuels via FT or other processes to advance them to TRL 7;
- To establish the range of biomass and waste types and pre-treatment processes that are required to supply the process with a particular emphasis on the use of wastes;
- To undertake environmental, economic and engineering studies into the application of these processes in the UK.

The assessment criteria for selecting a preferred consortium should include their capability and intent to further develop and commercialise the outcomes from the work. ETI should expect consortium members to invest their own resources into the project (in cash or kind) although it must recognise that the fundamental role of ETI is to de-risk the development work significantly to enable development to take place.

The benefits of promoting this work would be to accelerate the development of new energy technologies that can convert wastes into chemicals and fuels, thereby reducing emissions of greenhouse gases and consumption of fossil fuels. A successful process would also provide economic opportunities for those involved in its development.

8. CONCLUSIONS AND RECOMMENDATIONS

The review has shown that the component technology steps for the production of fuels and chemicals from syngas produced from gasification have been demonstrated but are at different stages of technical development. However, they have not been assembled into a complete integrated process. Although the process has environmental and economic potential there is a need for significant process development work to be undertaken with emphasis on the following areas:

- To develop gas cleaning technology – Possibly as part of the core ETI EFW project next stages;
- To develop and demonstrate pilot scale technology for conversion of syngas into chemicals and fuels via FT or other processes to advance the TRL to 7;
- To establish the range of biomass and waste types and pre-treatment processes that are required to supply the process with a particular emphasis on the use of wastes;
- To undertake environmental, economic and engineering studies into the application of these processes in the UK.

Such a programme will cost at least £7m. The UK is not commercially active in the production of fuels and chemicals from wastes despite large quantities of biomass and wastes being produced. This programme will require a driver. It is recommended that the ETI considers being that driver. One way is through a technology call to facilitate the assembly of a consortium to undertake this work. The selection criteria should include the capability and commitment of consortium members to commercialise the outcomes.

Appendix 1. 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.