Programme Area: Bioenergy

Project: Energy From Waste

Title: A Review of Biomass to Liquid Fuels via Pyrolysis Oil

Abstract:

There is increasing commercial interest in the pyrolysis of biomass and wastes to form pyrolysis oil, a dark liquid that is sometimes colloquially referred to as bio-crude oil. However, it is not compatible with crude oil or the refining processes used to produce hydrocarbons (including fuels) and petrochemicals. Currently pyrolysis oils are mostly used as a low grade fuel to generate heat and power.
Current processes for the production of biofuels for blending into transport fuels have focused on the use of plant oils or starches as raw materials. These have the potential to compete with food for agricultural capacity. Some technologies have used wastes of varying types ranging from mixed wastes through to plastics and tyres. The development of processes that use lignocellulosic biomass (e.g. wood, straw) would enable waste biomass and forestry materials to be used in this way. Such sources of biomass can be used to produce pyrolysis oil. Laboratory work has shown that pyrolysis oils produced from a range of feedstocks have the potential to be upgraded into vehicle fuels. There is also the potential to extract commercially useful materials from pyrolysis oils providing a renewable alternative to petrochemicals.

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 Benefit Case Report

A Review of Biomass to Liquid Fuels via Pyrolysis Oil

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1.0 Executive summary

There is increasing commercial interest in the pyrolysis of biomass and wastes to form pyrolysis oil, a dark liquid that is sometimes colloquially referred to as bio-crude oil. However, it is not compatible with crude oil or the refining processes used to produce hydrocarbons (including fuels) and petrochemicals. Currently pyrolysis oils are mostly used as a low grade fuel to generate heat and power.

Current processes for the production of biofuels for blending into transport fuels have focused on the use of plant oils or starches as raw materials. These have the potential to compete with food for agricultural capacity. Some technologies have used wastes of varying types ranging from mixed wastes through to plastics and tyres. The development of processes that use lignocellulosic biomass (e.g. wood, straw) would enable waste biomass and forestry materials to be used in this way. Such sources of biomass can be used to produce pyrolysis oil.

Laboratory work has shown that pyrolysis oils produced from a range of feedstocks have the potential to be upgraded into vehicle fuels. There is also the potential to extract commercially useful materials from pyrolysis oils providing a renewable alternative to petrochemicals.

The process to produce pyrolysis oils can be summarised as follows.

- The biomass is collected and prepared using conventional technology
- Fast pyrolysis converts the bulk of the biomass into a gas which is condensed to form the pyrolysis oil. This is practised commercially, mostly using wood.
- The pyrolysis oil is treated to extract chemicals and reduce its moisture content
- The remaining oil is upgraded into a product that can be blended with conventional diesel by a process to reduce its oxygen content

The latter two of these processes need development to make the overall process feasible. Further, the potential to make and upgrade pyrolysis oil from a variety of types of biomass needs to be demonstrated. It should be noted that processes based on single source biomass streams have yet to be commercially successful and the additional challenges of using mixed or variable feedstock streams have yet to be effectively addressed. As a result this report focuses on the use of biomass. Like all waste to energy process the operability, consistency and capital cost of plant are strongly related to the shape and moisture content of the feedstock. This aspect has been covered in the reports from work packages 3 and 4 of the ETI Waste to Energy Programme and is not repeated in detail in this report[1].

The next step in the development of the process for pyrolysis oil to fuels would be to build a pilot plant that can pyrolyse a range of feedstocks, but that can also be used to produce pyrolysis oils and test potential processes for extraction and upgrading of pyrolysis oils. Some university research will be required on the latter. Such a project might take 3 years to undertake and have a cost in the region of £7m.

Two independent assessments of the process economics are considered in a UK context. Both show that even with purchased biomass the process economics appear attractive at current diesel prices. The economics would further improve if the feedstock used is waste biomass with a low price. This confirms that further evaluation of the process is merited economically and justifies investment in a development programme.

Another essential consideration is the environmental performance of the resulting fuels, and in particular their ability to reduce greenhouse gas emissions. The use of cellulosic biomass offers considerable advantages over agriculturally derived biofuels. Horticulture releases potent greenhouse gases and has emissions associated with fertiliser and harvesting. However the use of waste lignocellulosic biomass avoids those emissions. Indeed, it can avoid significant amounts of biogenic methane emissions from diverting it from alternative disposal mechanisms. Greenhouse gas savings can exceed the “credit” due to the mineral diesel displaced. Traditional biofuels only have savings from 10%-50% of the fuel displaced. This is a considerable advantage of biogenic feedstocks.

There is considerable UK potential for the production of fuels via pyrolysis of biomass and wastes; there are tens of millions of tonnes of waste biomass produced each year that could be used. However, the process will not be developed in the UK without some form of intervention to assemble a consortium of organisations to conduct this work. Accordingly it is suggested that ETI may wish issue a technology call for this purpose. The object of such a call should be to demonstrate a process at pilot scale on a variety of different types of biomass and to ascertain the commercial, environmental and technical case for further development. This will require ETI sponsorship of a three year programme of work.

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[1] Reports from Work Packages 3 and 4 of the ETI Waste to Energy Programme, Project consortium Spring 2011.

2.0 Introduction

There is considerable global interest and economic activity in the conversion of wastes and biomass to liquid fuels for road transport in a form that is compatible with current vehicle technology and mineral fuels. The major technologies currently in use are:

- The fermentation of starch (from grain) or sugar (from sugar cane or beet) into bioethanol for blending with gasoline
- The transesterification of vegetable oils into biodiesel

These processes have some significant drawbacks.

- They compete with food production for agricultural capacity
- The agricultural process can generate significant greenhouse gas emissions offsetting the greenhouse benefits of using a renewable energy source
- The economics can be challenging even with the incentives that are frequently available

Processes that can use wastes or waste biomass, such as straw remaining after harvesting grain, or lignocellulosic biomass (e.g. timber) may avoid at least the first two of these disadvantages and be available at lower cost. There is considerable research activity in these processes.

The report mainly considered the simple case of using single source bio-mass as the feedstock using pyrolytic methods. Aggressive heating of feedstock in an atmosphere of low or no oxygen can produce syngas (a mixture of hydrogen, carbon monoxide and methane) which can be condensed to hydrocarbon fuels using a Fischer Tropsch process. These processes are well established in the coal and oil industries. Studies have shown that this technology is likely to only be competitive at very large scales and this would require extensive biomass collection over very large areas.

An alternative pyrolytic approach, and the subject of this paper, is to use less aggressive thermal treatment to vaporise the waste or biomass and the vapours can be condensed into an “oil” known as “pyrolysis oil” or “bio-oil”. This oil is acidic and has a high oxygen content. It tends to have a low calorific value and is not compatible with mineral oils and cannot be used in unmodified engines.

This paper discusses the opportunity for new process technology to develop this pyrolysis oil process so that it can produce products that can enter the diesel road transport fuel supply chain.

The paper draws upon economic, environmental and technical reviews carried out in 2008 by a consortium of four universities and six companies led by the Centre for Process

Innovation which extensively studied the potential and development needs of this technology. In the sections that follow we describe the process and identify the technological challenges and opportunities and briefly review the current extent of commercial deployment. We then consider the economic potential of the process which leads to identification of the key technical questions and assumptions that need to be investigated. The case for the ETI intervention will then be presented, describing some of the investigations that could be commissioned, the order of magnitude for their costs and presenting a high level project programme for consideration.

Large amounts of waste and biomass are produced in the UK as the data in Table 1 shows (source: NNFCC). This excludes the use of commercially grown wood and energy crops as well as polymer wastes. It should be noted that much of the UK resource is increasingly burnt for heat and power (encouraged by various renewable energy incentives) and increased recycling of wood and paper. Hence there are competing demands for this material and it will not all be available for use in a pyrolytic process for fuel manufacture and in some case waste streams are tied up in long term disposal agreements for up to 25 years. However, it can be stated that there are considerable quantities of biomass and biogenic wastes produced in the UK.

Waste	Quantity (million tonnes)
Straw	2.9 (excluding traditional use)
Forestry residues	2.0
Biosolids	1.7
Manure	12.4
Paper and board	26.3
Food	12.3

Table 1: UK Waste Biomass

3.0 Description and Status of the Technology

3.1 Process Description

The basic pyrolysis process is shown in Figure 1 and consists of four stages. The first is the biomass and waste preparation step where feedstocks are collected, dried and reduced to a suitable particle size. As discussed in work package 3.3 of the main waste to energy programme the moisture content and material form have a huge impact on the operation of all downstream plant. Feedstock preparation and pre-treatment has been identified as an area worthy of further innovation and development in WP 3 and AP4[1]. Depending on the location of feedstock preparation plants there is an opportunity for waste heat from the pyrolytic process to be used in the drying process. The choice of biomass feedstock does impact the quality of the resulting oil.

The prepared biomass / waste is then subject to pyrolysis. Pyrolysis can be carried out at a wide range of temperatures and residence times and can be optimised for the production of pyrolysis oil, char or syngas. In principle the gases produced could be subject to catalytic treatment to improve the resulting oil. The gases are quenched to form pyrolysis oil and the remaining gas, which has a valuable energy content, sent for treatment or energy recovery. The condensed pyrolysis oil may require stabilisation to improve its storage prior to upgrading. There is also a need to separate char from the gases and extract it from the pyrolysis unit. The char may have a value as a soil conditioner or as a source of energy for the process.

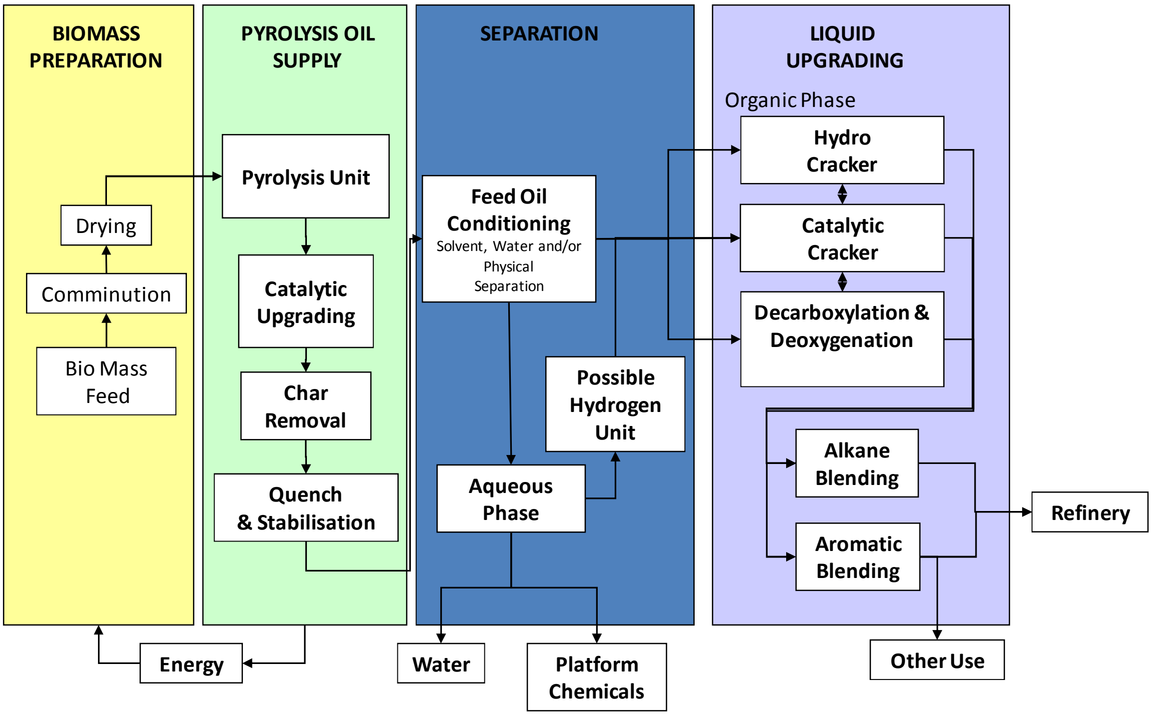

Figure 1: The Pyrolysis Oil Process for Liquid Fuels

The pyrolysis oil contains a significant amount of water but the aqueous content is not immiscible with the organic content and can be difficult to remove. A conditioning and separation step to separate the aqueous and organic phases is needed. The aqueous phase is likely to contain organic chemicals and these could either be extracted and sold as by-products or fed into a reformer to produce hydrogen.

The final step is the upgrading of the remaining oil into fuel. The processed pyrolysis oil will have a significant oxygen content that makes it incompatible and unsuitable for use in the conventional fuel supply chain. The oil needs upgrading by catalytic treatment for which there are a number of process options. The degree of upgrading depends on how the resulting fuel, which is likely to be a diesel blending component, will be introduced into the supply chain. Minimum upgrading will permit it to enter oil refinery processes and maximum upgrading would lead to a fuel meeting the EN590 diesel specification. Increasing the degree of upgrading is likely to increase costs and reduce yields.

3.2 Products and Yields

Typical yields from biomass are shown in Table 2. As discussed in WP 3.3 of the main programme the average composition of the mixed waste stream is similar in elemental composition to biomass. It is concluded that it is reasonable to use the pyrolysis behaviour of biomass to assess the environmental and economic performance of the process.

Material	Yield	
Pyrolysis oil	70% (15-30% w/w moisture content of oil)	w/w dry feedstock
Char	15%	w/w dry feedstock
Non-condensable gases	15%	w/w dry feedstock

Table 2: Indicative Yields from Process Steps

The typical range of composition of pyrolysis oils is shown in Table 3 which demonstrates the range of chemical and physical properties. The high level of oxygen stands out; the corresponding figure for crude oil is less than 1%. The heating value of pyrolysis oil is typically around half that of heavy fuel oil. However, it has much lower levels of sulphur and this is a distinct advantage of pyrolysis oils.

Physical Property[2]	Typical Value
Moisture content	15-30%
pH	2.8 – 4.0
Specific gravity	1.1-1.2
Elemental analysis	
C	55-64%
H	5-8%
O	27-40%
N	0.05-1.0%
Ash	0.03-0.3%
Higher heating value	16-26 MJ/kg
Viscosity at 104 °F and 25% water	25-1000 cP

Table 3: Physical and Chemical Properties of Typical Pyrolysis Oils

3.3 Commercial Deployment of Pyrolysis Technology

A number of pyrolysis oil plants have or are in the process of being built which we tabulate in Table 4. The bulk of the technology is developed in North America and applied for the

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[2] Source: University of Arkansas

production of pyrolysis oil which is then used to produce power; only KiOR are actively seeking to upgrade it into fuels.

Pyrolysis oils have around half the energy density of heavy fuel oil but low levels of sulphur. Several projects have studied its use in firing or co-firing boilers for heat and power (e.g. BIOCOUP). There is some interest in its use in stationary diesel engines for the production of power but this does not appear to be happening commercially. The commercial extraction of chemicals is minimal and it is not currently upgraded into automotive fuels.

Company	Country	Plant
Metso, UPM and VTT	Finland	Pyrolysis oil pilot plant from wood. 90 tonnes oil produced.
BTG	Holland	Facilities up to 5 tonnes wood per hour plant. Demonstrated their process with 45 types of biomass, only 5 unsuitable. Claims to have a catalytic hydrogenation process to upgrade pyrolysis oil.
Anhui Yineng Bioenergy	China	Plant with pyrolysis oil output of 3,000 tonne per year.
Ensyn	USA, Canada	Several pyrolysis oil plants up to 100 dry tonnes per day.
Abri Tech	Canada	Modular portable pyrolysis units 5-50 tonnes per day for agricultural wastes.
Dynamotive	USA, Canada	Several pyrolysis oil plants up to 200 tonnes per day.
Procycling	Canada	3 tonne per hour demonstration plan for pyrolysis oil.
Titan	Canada	Pyrolysis oil and bio-char plant.
Renewable Oil Corporation	Australia	Developing pyrolysis oil plant using Dynamotive technology for 200 tonne per day of wood.
Coll’Energia	Italy	Generates and uses pyrolysis oil from 26 tonnes of wood per day to generate power.
Premium Renewable Energy	Malaysia	Plant under development to use palm biomass to produce heat and power from pyrolysis oil.
Crane & Co	USA	Heat and power from pyrolysis oil from forest residues.
Tolko Industries	Canada	Claims world’s largest fast pyrolysis oil plant (400 tonnes per day wood) to produce and use pyrolysis oil for power.
KiOR Industries	USA	Building 500 tonnes biomass per day pyrolysis oil plant – oil to be processed into diesel and gasoline. To be followed by 1,500 tpd plant.
Karlsruhe Institute of Technology	Germany	12 tones biomass per day pyrolysis unit and 1 tonne per hour pyrolysis oil gasification route with Fischer Tropsch for methanol or dimethyl ether.

Table 4: Pyrolysis Oil Plants

3.4 Technology Development Programme

The purpose of this section is to review the status of the technology overall and the individual stages presented in Figure 1. We do this using the concept of Technology Readiness Levels (TRLs); these are a scale that can be used to assess the maturity of different technologies as they progress from pure research (TRL 1) through to established use (TRL 9). These are introduced in the Appendix but we provide some simple markers here.

TRL 1	Scientific research
TRL 4	First integration of technological components to test the integrated concept
TRL 7	Prototype operating in operational environment
TRL 9	Commercial operation of the technology

Table 5: Summary of Technology Readiness Levels

3.4.1 Selection and Preparation of Biomass

Biomass is routinely prepared by industry using processes of chipping, shredding and drying so we regard these as established processes (TRL 9) and indeed many types of biomass are readily available on the open market. However, the preparation of wastes and mixtures of feedstock to a consistent size and shape is more problematic. In addition, many biomass plants in operation struggle to manage the moisture content of their feedstock to a consistent level. Hence there are some important developments that are required to achieve consistent feed to pyrolysis plants. The following observations are also made.

- The preparation of biomass can be energy intensive and heat integration of drying and pyrolysis could be of value particularly if high moisture content waste biomass is to be used. For example, the BTG process uses spare heat to reduce moisture content from as much as 50% to below 10%.

- The nature and quality of wastes and biomass will impact upon the pyrolysis oil produced and hence yields, separations and upgrading technology. As we shall see pyrolysis oil routes to fuels are expected to offer the largest potential benefit through using waste biomass. To date commercial pyrolysis oil processes are based on consistent supplies of wood chip which offers a consistent raw material. Hence the choice of biomass is of significant importance and needs to be understood through experimental work. Variability in feedstock can have a significant negative impact on plant operability and needs to be addressed in commercially operating units.

- Biomass, which can be bulky, needs to be brought to a processing centre at the pyrolysis plant. Alternatively it could be prepared close to the point of production reducing the transport requirements but foregoing the opportunity for heat integration. There is a need for supply chain optimisation studies to be undertaken but only once there is technical information available to inform the supply chain optimisation. This is a question that can be addressed at a later phase once the overall process technology readiness level reaches TRL 7.

Different pyrolysis technologies require different biomass preparations. Most expect the moisture content to be less than 10% although. The required particles sizes vary from 2mm to 6mm or more. Although the base technology that to process and prepare the feedstock is developed to TRL 9 there is a significant amount of practical trials to do to ensure moisture content and feedstock size and shape are managed for large early stage plants.

It is also worth noting that in many locations there will be insufficient waste to consistently supply a production plant. This could lead to feedstock import or the development of processes that can use more than one feedstock type. In some cases these could be other wastes, but it is possible that full scale plants could require mixtures of wastes with fossil fuels such as coal.

Overall feedstock preparation is at around TRL 6.

3.4.2 Pyrolysis to produce Pyrolysis Oil

The first part of this process is the use of heat to break down the waste and biomass.

Gasification processes that use heat to convert organic material into a gas, have been in use for 180 years. These use high temperatures to convert organic matter into carbon monoxide and hydrogen which can be used as a fuel in its own right or as a chemical feedstock for the production of fuels or chemicals. Gasification of biomass (or coal) takes place at high temperatures (>700°C) which break the chemical bonds in the original material. Lower temperature processes are less destructive at the molecular level. A general consensus appears to have emerged that fast pyrolysis is the most appropriate for high yields of pyrolysis oils. This uses temperatures around 400-600°C and short residence times of the order of two seconds although there are suggestions that staged heating processes result in pyrolysis oils with less tendency to form tars. There are a number of different reactor types that can be used each with their own performance and operating characteristics. The leading technologies are at least at TRL 7; some further when applied to wood chip.

There are variations on the process that add a catalyst to the biomass in the pyrolysis unit to impact the nature of chemicals produced and even to increase the aromatic content and reduce the oxygenates in the pyrolysis oil. Alternatively the gases themselves may be passed through a catalyst system prior to condensation in order to improve the properties of the resulting pyrolysis oil. With the exception of KiOR who are building a commercial biomass to fuel plant using this approach, it is in the region of TRL 3 – 4.

3.4.3 Pyrolysis Oil Separation

Pyrolysis oil is an awkward material to handle. It is acid and corrosive and its constituents are reactive and so the material can change over time with the formation of tars. Distillation is probably an inappropriate process but solvent extraction has been shown, at least at laboratory scale, to be capable of extracting valuable chemicals such as furfural, acetal, acetic and other acids, ketones, N-heterocycles and glycolaldehyde. The moisture content, which can be as high as 25%, is also a problem in downstream use and needs to be removed. Further, the physical and chemical properties of pyrolysis oil depend on the biomass source and pyrolysis conditions and so are variable.

Extraction of chemicals from pyrolysis oil has been less extensively developed than the pyrolysis process itself and is probably at TRL 3. There is a need to develop strategies for robust separation steps that will work reliably in an operating environment and are characterised for a variety of biomass types. Economic recovery of by-product chemicals needs to be assessed and yields of useful materials ascertained. Consideration needs to be given to the optimisation of the pyrolysis process and raw materials for chemical extraction as there are significant known sensitivities to biomass type, impurities and pre-treatment and temperature.

Although extraction of chemicals from pyrolysis oil is the least developed aspect of the whole process for conversion of biomass into fuels it may not be the most critical step. The actual process of upgrading pyrolysis oil into fuel, with or without extraction of chemicals, is more central to the overall development of the process.

3.4.4 Pyrolysis Oil Upgrading

Pyrolysis oil is not compatible with conventional hydrocarbons or internal combustion engines or even oil refinery processes. Hence it needs further treatment before it could be considered for vehicle use and this is frequently referred to as upgrading. The principal requirement is to reduce the oxygen level by some form of deoxygenation or hydro treatment. This eliminates the oxygen as carbon dioxide or monoxide or alternatively hydrogen can be introduced to eliminate the oxygen as water. In any event this will be a catalysed process. The outcome would ideally be a fuel that can be blended straight into conventional vehicle fuel supply chains but a more economic outcome may be a less upgraded material that can be introduced into an existing oil refinery process for the final steps involved in upgrading. An oil refinery location potentially offers other advantages such as a hydrogen infrastructure and gasification processes that can use any by-product materials to generate the hydrogen for the deoxygenation processes. This integration has been studied in the Literature (e.g. DOE, 2005) but has not yet been practiced.

Considerable amounts of laboratory studies have been undertaken into the upgrading of pyrolysis oils and various catalyst systems and processes have been tried and proven to upgrade pyrolysis oils. Several competing technologies and processes have been published but not subject to detailed engineering considerations into their relative attractiveness for scale up or refinery integration. Consideration also needs to be given to the robustness of the processes with regard to different oils and feedstocks.

Taking all these factors into account we conclude that the upgrading process is approaching TRL 4; approaches have been shown to work at laboratory scale but the information needed for process selection and robust process design has not been generated. The next steps are:

- To undertake a systematic review of upgrading technologies to select a preferred approach (including options for adding catalysts to the biomass, catalytic upgrading of the pyrolysis gases and upgrading of pyrolysis oil) with a view to identifying strategies that offer operating flexibility and are practical for implementation on commercial scale plant;
- To gain practical experience with the preferred upgrading technologies in a process development environment;
- To consider their implementation in an operating pyrolysis oil plant including the possibility of integration into an oil refinery complex.

3.4.5 Overall Process

Table 6 summarises the TRL of the major steps in the process to produce vehicle fuels from biomass via pyrolysis oils. Our overall conclusion is that the individual steps have been demonstrated at laboratory scale but have not been integrated into an overall process.

Hence the TRL for the technology as a whole is at level 4. This is slightly ahead of the TRL for the separation and extraction step but from a technical point of view this may be the least critical as some upgrading processes may be able to handle untreated pyrolysis oils.

Process step	**TRL**	**Comment**
Biomass and waste preparation	6	Established processes,
Pyrolysis	7 3	Several technologies in use at pilot and commercial scale. Addition of catalyst to influence pyrolysis oil composition
Separation and extraction of chemicals	3	Pyrolysis oils have been characterised and some experimental work undertaken on extraction
Upgrading of pyrolysis oil to fuels	3 – 4	Laboratory work has demonstrated several approaches but they need developing into a practical process

Table 6: A summary of the technology readiness level of the various steps in the process

We consider that the next step in the development of the process should be to carry out development work on the process as a whole to advance it from TRL 4 to around TRL 6. The object of this work would be two fold; to undertake the technical work to demonstrate a viable process and also to gain the technical and economic data to refine the assessments of its economic viability.

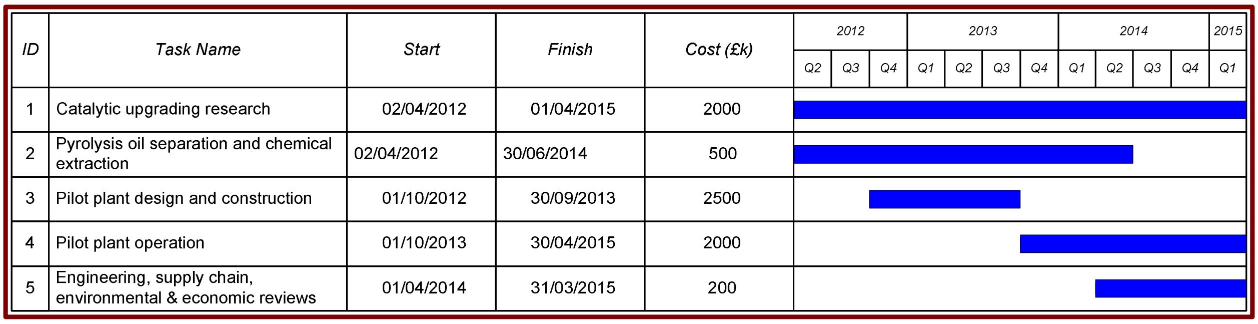
Whilst the area of greatest process development need is in for pyrolysis oil upgrading, the development of this process would benefit from being integrated into the pyrolysis step itself. There are several reasons for this.

- Integration would enable a range of different biomass and waste types to be explored which will lead to a more robust overall process for conversion of biomass into fuels;
- There is a need for gaining experience with the pyrolysis process itself and how pyrolysis conditions impact upon the pyrolysis oil;
- Opportunities would arise for catalytic treatment of pyrolysis gases and also addition of catalyst to the biomass prior to pyrolysis;
- It avoids the need to commission the production of pyrolysis oils from third parties.

The stated objectives need development work at pilot scale (i.e. a few tonnes per day) facility capable of operating 24/7 to gain experience of continuous operations and to assess things like catalyst life. Some laboratory scale work will be needed to develop and screen different catalyst systems and this could be done by industry or in conjunction with a catalyst manufacture.

A three year high level programme to advance the process is show in Figure 2 along with nominal costs. This is likely to require a consortium of organisations to undertake it as no single organisation will have the all the skills and facilities needed to do this work. Research into catalytic upgrading processes runs throughout the whole three years of the project. Project work is also undertaken from the outset on the extraction of platform chemicals from pyrolysis oils. Six months into the project the design and construction of a pilot plant, the principal source of results commences and this operates throughout the second half the project. During the final year we anticipate engineering and economic assessments of the emerging results to refine evaluations of the prospects of a viable process.

The total cost of the programme is in the region of £7m.



ID	Task Name	Start	Finish	Cost (£k)
1	Catalytic upgrading research	02/04/2012	01/04/2015	2000
2	Pyrolysis oil separation and chemical extraction	02/04/2012	30/06/2014	500
3	Pilot plant design and construction	01/10/2012	30/09/2013	2500
4	Pilot plant operation	01/10/2013	30/04/2015	2000
5	Engineering, supply chain, environmental & economic reviews	01/04/2014	31/03/2015	200

Figure 2: Programme for Process Development

4.0 Economic model

A core question is whether the upgrading of pyrolysis oil is an economically effective route to renewable diesel; can it compete economically with conventional mineral diesel? This has been considered by a number of people.

For the purposes of this economic analysis it is assumed that wastes and biomass are freely available. This is the most effective way of assessing process economics. However, it is worth noting that a secure and sufficient feedstock supply will be a pre-requisite to any plant investment. Indications are that this will not be a simple matter in the UK for the foreseeable future.

An assessment of the cost of fuel from pyrolysis oil was published by National Renewable Energy Laboratory (NREL) in November 2010. The report considers two technological scenarios – one with purchased hydrogen to upgrade the pyrolysis oil and the other sacrifices some of the oil to produce the required hydrogen. The salient results from the calculation are shown in Table 7 and are based on corn stover at $75/tonne as biomass and allow for a 10% return on capital investment. The lower capital and production costs allow for substantial capital and operating cost benefits from the learning curve of earlier plants. The higher figure represents the estimate capital and operating costs of the first plant which does not have this benefit which will also adversely impact production rates in the initial period as operating experience is gained.

	Hydrogen purchase	**Hydrogen generation**
Biomass consumed	2,000 tonnes per day	2,000 tonnes per day
Diesel output	220,000 m^3 pa	130,000 m^3 pa
Capital cost	\$200m - \$584m	\$287m - \$684m
Fuel cost	\$2.11 - \$3.41 per US gallon £0.34 - £0.55/litre	\$3.09 - \$6.55 per US gallon £0.50 - £1.05/litre

Table 7: NREL Economic Analysis Results

In a UK context the plant output would also benefit from the RTFC incentive mechanism for biofuels which results in an additional £0.30 per litre. This makes the UK cost in the range £0.04 – £0.75 per litre. The current diesel price is £0.587 (excluding duty) so the process would be viable under most conditions – the exception being the early plant with the hydrogen generation option.

CPI examined the economics of biodiesel manufacture via pyrolysis oils in 2009 and considered the investment returns that could be generated. It was found that at a diesel price of £0.41/l and allowing £0.30 for the RTFC incentive a profit of £0.32/l could be generated with biomass at £100/te on a dry weight basis. Assuming a capital cost of £300m for a large plant of £1,600 m^3 per day diesel capacity it was found to provide a payback period of around 2 years. This is an attractive rate of return that would facilitate investment. Current prices are higher. For example the May 2011 price for wood dried wood pellets is £185/te[3] and July pre-tax diesel price of £0.587/l and this leads to a profit of £0.27/l which still provides a simple payback of less than 2 years. If one was able to use lower price biomass such as waste then margins would increase further still but one must also expect additional operating and capital costs for preparing the biomass and perhaps lower yields.

A plant of this size might consume in the region of 2m tonnes of biomass per year – this is a sizeable amount. It is theoretically available in the UK, but securing a long term supply contract for this amount of waste will be challenging without the collaboration of a major waste supply or treatment company. It would merit a supply chain study to ascertain the availability of biomass.

Allowing for scale, the capital cost estimates used by CPI are lower than for the corresponding US plants in the NREL study but not sufficiently lower to negate the investment conclusion.

The conclusion from these two independent analyses is that the production of diesel via pyrolysis oil does appear to be economically feasible assuming the necessary process development can be completed.

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[3] Source: biomass energy centre

5.0 Environmental model

One of the drivers for producing pyrolysis oils is to reduce the accumulation of greenhouse gas in the atmosphere from the combustion of fossil fuels. Emissions from the oxidation of biofuels are, in contrast, regarded as benign as this represents recycling of carbon dioxide back to the atmosphere. However, life cycle analysis has shown that the net savings can be seriously compromised by emissions generated in agriculture and processing. These emissions can include those associated with the production of fertiliser and also other greenhouse gases most notably methane. Methane can arise in agriculture or the decay of biomass and is a much more potent greenhouse gas than carbon dioxide. It is therefore important to carefully account for greenhouse gases when considering the environmental credentials of biofuel. The UK government commissioned and published software that can be used for this purpose.

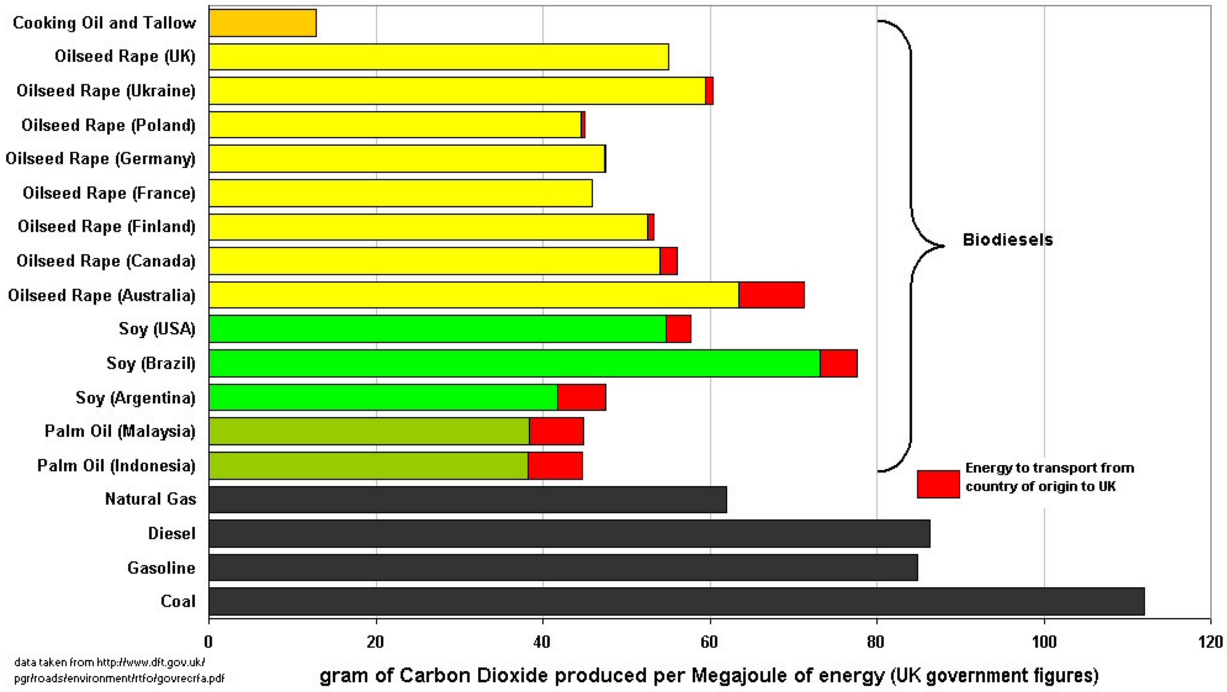
CPI used this software and data provided by E4Tech to assess the greenhouse gas benefits for pyrolysis oil upgrading with several different types of biomass. In each case it was assumed that waste heat was used for drying processes and that any hydrogen requirements were met biogenically through gasification of char and by-products. The outcomes are shown in Table 8 which tabulates the greenhouse gas saving relative to that that would be emitted if the equivalent amount of mineral diesel were used. The focus in these calculations was the use of biomass that would otherwise go to waste in landfill or some other form of decomposition. These alternative disposal processes are associated with significant greenhouse gas emissions (e.g. methane from sewage sludge) and these are avoided if the biomass is used in the pyrolysis process as well as the savings arising from the resulting fuel. These savings can be very significant leading to net savings that exceed 100% of that associated with the equivalent mineral diesel fuel.

Waste biomass also has the potential to be of low or even negative cost to a processing plant although its quality may not be tightly controlled and it may have significant moisture content.

These calculations should be regarded as preliminary and are based on simple mass balances and assumed yields of the type shown in Table 2. The focus is on biogenic wastes and the work has not been extended to polymers or other non biogenic products. Further technical work is required to ascertain the performance of these waste biomass types in the pyrolysis and upgrading processes. However, the results strongly suggest that major savings are achievable. The results can be contrasted with carbon dioxide emissions for other biofuels which are shown in Figure. This figure shows the carbon dioxide emissions for diesel and a number of biofuels. It can be seen that, with the sole exception of fuel from cooking oil and tallow, the reduction in carbon dioxide emissions compared to mineral diesel is only in the range 10%-50%. The bulk of the emissions from bio fuels are associated with the growth and harvesting of energy crops. The greenhouse gas benefits of processing waste biomass into diesel are likely to be significant and favourable compare to other biofuels.

Biomass	Greenhouse gas (GHG) saving	Comments
Sewage sludge	433 – 504%	Decomposed via methane – very poor GHG
Waste wood (construction)	187 – 220%	Landfill – poor GHG
Municipal waste	179 – 211%	Landfill – poor GHG
Food waste	161 – 180%	Landfill with some methane capture
Manure	120 – 140%	Nitrous oxide and methane emissions avoided
Straw	97 – 113%	Attracts some fertiliser GHG value
Roundwood, forestry waste	95 – 111%	Would be left to decompose – no GHG impact

Table 8: Greenhouse Gas Savings



data taken from http://www.dft.gov.uk/pgr/roads/environment/rtfo/govrecrfa.pdf

Figure 3: Carbon Dioxide Emissions for Various Fuels

6.0 The Case and Opportunity for ETI Intervention

The analysis presented in this report shows that the production of fuels from pyrolysis oils is a potential technology from an environmental and economic perspective and also displays promising results from laboratory work. However, the process as a whole has not been sufficiently developed for either single feed or mixed feed inputs to be considered for commercial implementation.

The UK has the technological capability to develop such a process but if it were to proceed with a development of this kind it would require a consortium of organisations to come 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 pyrolysis and the developments of catalysts;
- Business – the commercial development of catalysts and supply of biomass;
- Innovation agencies – the practical development of processes to advance them in the TRL range 4-7.

There are good prospects for the UK to be able to develop and use such a process but no single organisation is in a position to do so. For example, the production of pyrolysis oil is not established in the UK unlike the case in certain other countries most notable the US and Canada.

As already noted in section 3.4.5 a development programme would involve a focus developing a pilot scale plant with emphasis on the pyrolysis oil upgrading 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 consortia to form to undertake a development programme of work with the following objectives.

- To develop and demonstrate pilot scale technology for conversion of mixed biomass and wastes into vehicle fuel via pyrolysis 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 waste biomass;

- To undertake environmental, economic and engineering studies into the application of that process in the UK.

The assessment criteria for selecting the 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 catalyse the development of new energy technologies that can convert waste biomass into 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.

7.0 Conclusions and Recommendations

The review has shown that all the component technological steps for the production of fuels from pyrolysis oil have been demonstrated and are at different stages of technical development. However, they have not been sufficiently developed or assembled into a complete process. Although the process shows environmental and economic potential there is a need for significant process development work to be undertaken with emphasis on the following areas.

1. Pyrolysis of waste biomass

The production of pyrolysis oils from well characterised and controlled types of biomass (e.g. timber) is starting to be undertaken commercially. The resulting pyrolysis oil is mostly used as a fuel for heat and power. There is an opportunity to extend the application of the pyrolysis process to use sources of waste biomass as these have the greatest potential. The characterisation and control of the resulting pyrolysis oil needs to be understood.

There is also the opportunity to treat the biomass or pyrolysis gases to improve the quality of the resulting pyrolysis oils thereby easing their downstream use.

2. Separation and extraction of chemicals from pyrolysis oils

Pyrolysis oils are a complex mixture of organic materials and water (30% w/w). There is an opportunity to extract useful renewable chemicals from the pyrolysis oils and reduce the water content. This has been shown in the laboratory but the process steps need development and to be applied in the context of a continuous plant. There is also the need to develop processes that can handle pyrolysis oils from different types of biomass.

3. Upgrading of pyrolysis oils to fuels

This is the specific critical step that is in need of development work for pyrolysis to fuels to be effective. Various processes have been shown at laboratory scale but not at pilot scale of operation. Methods need to be developed and proven with a range of different pyrolysis oils and practical matters such as catalyst life and regeneration ascertained.

4. Commercial potential

The ultimate object of the work is to develop a process for the production of fuels by the pyrolysis of biomass that could be adopted commercially in the UK leading to environmental and economic gains. Initial indications are that there may be a case but the commercial potential of the process needs further development through engineering, environmental and economic studies using the results of pilot studies.

It is considered that the most appropriate way of meeting these needs would be via a three year development programme

- To develop and demonstrate pilot scale technology for conversion of wastes and biomass into vehicle fuel via pyrolysis to advance the TRL to 7;
- To establish the range of wastes and biomass types that can reliably be used in the process and in particular the use of waste biomass;
- To undertake environmental, economic and engineering studies into the application of that process in the UK.

Such a programme will cost at least £7m. The UK is not commercially active in the production of pyrolysis oils 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.

8.0 Further Reading

This section contains a selective bibliography that expands and complements the information presented in this paper. It is not an exhaustive reference list.

AEA (2011) “UK and Global Bioenergy resource – final report” Investigates the cost and availability of biomass energy in the UK and overseas.

www.biocoup.com An FP6 project investigating how biomass can be used in a conventional oil refinery including routes via upgrading of pyrolysis oils.

Bradley “European Market Study for BioOil (Pyrolysis Oil)” (2006) Climate Change Solutions

www.combio-project.com An FP5 project for the use of pyrolysis oils as a renewable heating fuel.

DOE (2005) “Opportunities for Biorenewables in Oil Refineries” DOE Award Number DE-FG36-05GO15085. A report on the integration of biomass derived materials into oil refineries.

www.empyroproject.eu An FP7 project constructing a pyrolysis oil plant with output capacity of 22,500 tonne per year.

www.eubia.org European Biomass Industry Association.

NNFCC (2009) “Evaluation of opportunities for converting indigenous UK wastes to fuels and energy” A review of the biomass wastes available in the UK.

NREL “Techno-economic analysis of biomass fast pyrolysis to transportation fuels” NREL/TP-6A20-46586.

www.pyne.co.uk A transatlantic consortium for research into pyrolysis

Zhu & Lu “Production of chemicals from selective fast pyrolysis of biomass” http://tinyurl.com/3kk6yns A review of the production of chemicals from fast pyrolysis of cellulose and biomass.

“Pyrolysis and Bio-Oil” University of Arkansas Division of Agriculture. FSA1052. A useful brief summary of pyrolysis and pyrolysis oil and its applications. This discusses the potential for producing and using pyrolysis oils as fuel in heat and power applications.

APPENDIX A: 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.