Pathways to UK Biofuels

June 2010

A Guide to Existing and Future Transport Biofuels

NNFCC Project Number 10-035

Study Funded by DECC and prepared by the NNFCC and the Low Carbon Vehicle Partnership (Low CVP)

Low Carbon Vehicle Partnership

The Low Carbon Vehicle Partnership is an action and advisory group, established in 2003 to take a lead in accelerating the shift to low carbon vehicles and fuels in the UK and to help ensure that UK business can benefit from that shift. The Partnership consists of over 300 organisations from the automotive and fuel industries, the environmental sector, government, academia, road user groups and other organisations with a stake in the low carbon vehicles and fuels agenda.

Low Carbon Vehicle Partnership
83 Victoria Street,
London.
SW1H 0HW
UK

Tel: +44 (0)20 3178 7859 secretariat@lowcvp.org.uk www.lowcvp.org.uk

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NNFCC
Biocentre, York Science Park,
Innovation Way, Heslington
York
YO10 5DG,
UK

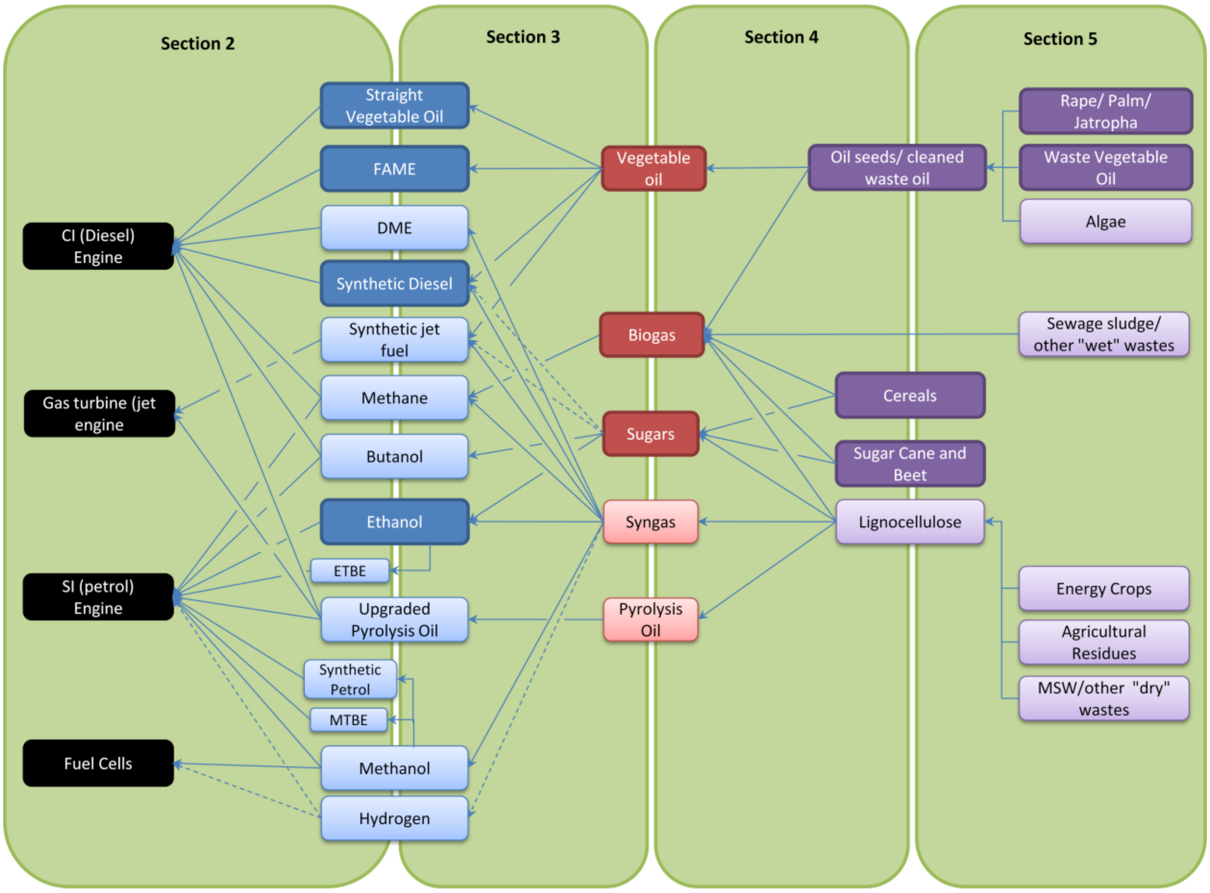
Tel: +44 (0)1904 435182 enquiries@nnfcc.co.uk www.nnfcc.co.uk

1 Introduction

This report has been prepared by the Low CVP and the NNFCC. The purpose is to offer a simple guide to the pathways available for the production of biofuels for transport (Figure 1). It is intended to facilitate strategy planners and policy makers in decision making regarding the future of biofuels in the UK.

The guide includes:

- Existing pathways for the production of biofuels;
- Alternative pathways to current biofuel products that may become commercially feasible in the near to mid-term (in particular before 2020); and
- Pathways to biofuel products not currently in use but potentially feasible in the near to mid-term.



DME: Dimethyl ether
ETBE: Ethyl tertiary butyl ether
MBTE: Methyl tertiary butyl ether

Figure 1. Existing and future biofuel pathways (existing commercial pathways are indicated by the dark colours, dashed lines indicate pathways for which commercialisation is potentially beyond near to mid-term).

Biofuels are liquid or gaseous fuels produced from renewable resources that absorb carbon dioxide via photosynthesis as they grow. When biofuels are burned, only the carbon dioxide absorbed by the biomass is released, so the net production of greenhouse gases[1] in total can be lower than that of burning fossil fuels. Many biofuels can be used, to some degree, within the existing vehicle fleet, and therefore biofuels are an important solution to reducing the environmental impact of both the existing and future transport sector by partial or even full substitution of fossil fuels.

Considering the need for the compatibility of biofuels with existing combustion engine technologies as well as advanced technologies such as fuel cells, section two discusses the characteristics and applications of a range of biofuels. Section three examines the production processes for the manufacture of each biofuel from one of five key intermediaries: vegetable oil, sugar, syngas[2], biogas[3], and pyrolysis oil. Section four examines the options for producing these common intermediaries.

Existing and future biofuel feedstocks are discussed in section five, including cereal and sugar crops, specifically grown energy crops, agricultural and municipal wastes, cultivated and waste oils, and algae.

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[1] There are a number of greenhouse gases. The most significant are carbon dioxide; methane, which has an effect about 23 times stronger than carbon dioxide; and nitrous oxide which has an effect about 296 times stronger than carbon dioxide.

[2] Syngas (or synthesis gas) is a mixture of carbon monoxide and hydrogen which is produced by the gasification of biomass.

[3] Biogas is a mixture of methane, carbon dioxide, and traces of other gas contaminants which is produced by the anaerobic digestion of biodegradable materials.

2 Biofuel Products

Today, there are a limited number of biofuel products available. FAME (biodiesel) and bioethanol occupy the vast majority of the market, accounting for 82% and 18% respectively of the volume of biofuel consumed in the UK between April 2008 and April 2009[4] (a very small amount of biogas was also used in vehicles modified to run on compressed natural gas). However, the potential numbers of biofuel products are high as illustrated by Figure 2. This section describes the characteristics of current and future biofuels, and gives an indication of their potential applications and limitations.

Straight Vegetable Oil

Straight vegetable oil (also known as pure plant oil) is obtained from the crushing of oil producing seeds. It requires no further processing prior to use (except for some applications where stabilisation additives may need to be added), and is therefore cheaper to produce than other vegetable oil based biofuels.

Straight vegetable oil is used as a substitute for diesel fuel but is generally not blended with conventional diesel fuel. Engine modifications are necessary to tolerate the greater viscosity and poor cold temperature performance of the biofuel. Modified vehicles generally require diesel fuel to start up and shut down, switching over to vegetable oil once a suitable engine temperature is reached so separate onboard storage for the two fuels is needed.

Straight vegetable oil is most suitable for specific applications such as bus fleets and return to base truck operations with dedicated re-fuelling stations, as, like all non-blended biofuels, straight vegetable oil does not easily integrate with the existing fuel supply infrastructure.

FAME (Fatty Acid Methyl Ester)

FAME is the most established biofuel substitute for diesel, with about 1029 million litres used in the UK between April 2008 and April 2009[3]. Most of the FAME produced in the UK is made to standard EN 14214 and it is most commonly blended with diesel fuel at up to 7% by volume, although 30% blends, for use in vehicles warranted to use B30 such as some Peugeot and Citroen vehicles, are available in the UK.

The energy density of FAME is similar to that of fossil derived diesel, which means a vehicle achieves approximately the same mileage from a tank of fuel. Blending a small quantity of FAME into diesel improves engine performance, compared to straight diesel fuel, by increasing the oxygen content of the blended fuel. Unfortunately, though, FAME has a poorer cold temperature performance compared to fossil diesel and this can limit the amount of FAME that can be blended into diesel. This is particularly the case for FAME biodiesels produced from the more saturated vegetable oils such as palm oil.

FAME is produced by reacting vegetable oil with methanol in the presence of a catalyst, in a reaction known as transesterification. The vegetable oil feedstock may be extracted from oil-rich crops such as oilseed rape or may be recovered waste oils. The conversion process is relatively mature and the UK has capacity to produce about 525,000 tonnes per annum

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[4] Renewable Fuels Agency, Annual Report and Accounts 2008/09 - http://www.renewablefuelsagency.org/reportsandpublications.cfm

(tpa), equivalent to 65 million litres although actual production rates are somewhat lower. Most FAME used in the UK is imported from Argentina, USA and Germany.

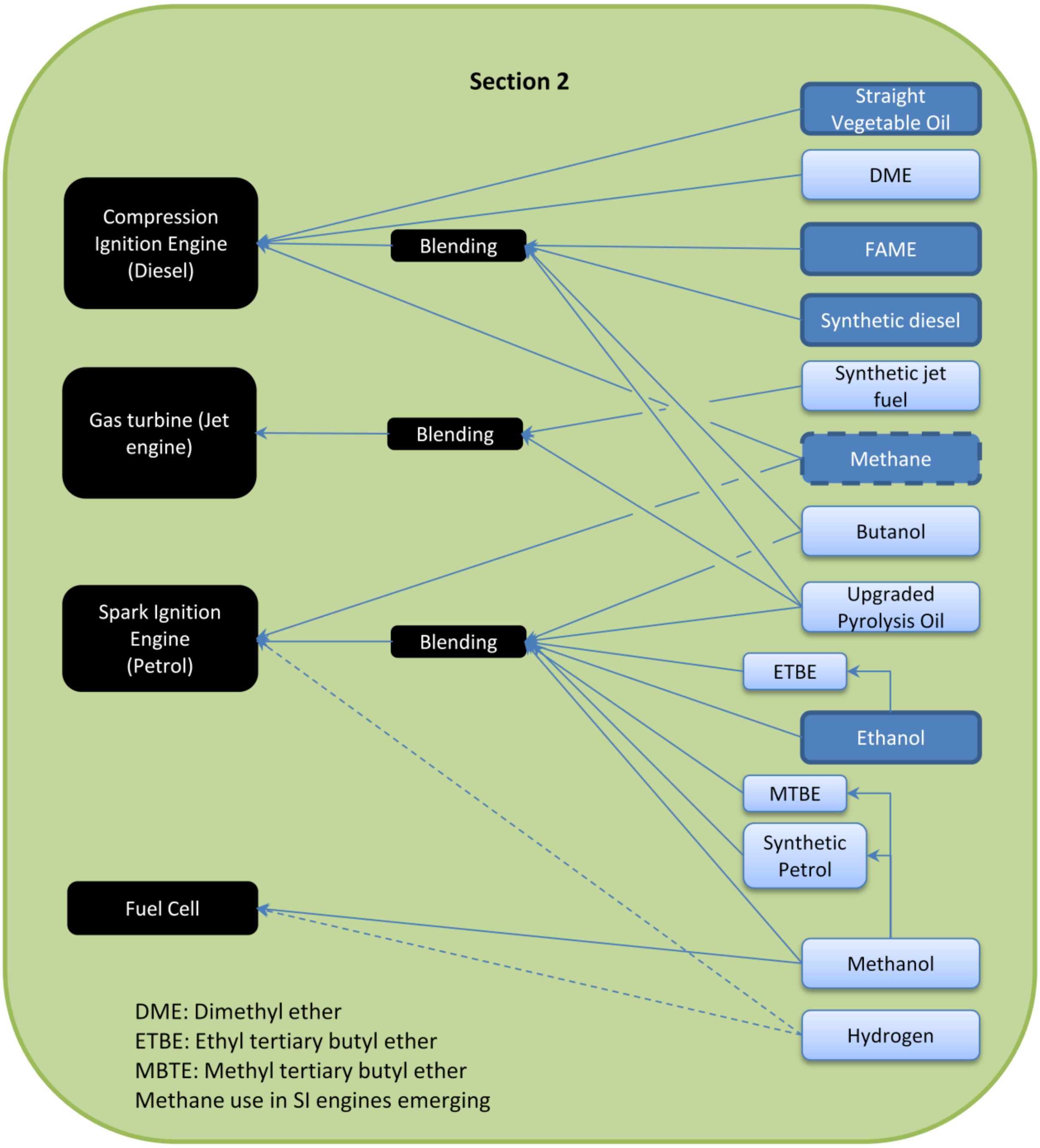

Figure 2. Current and future biofuel products and their applications (existing commercial biofuels are indicated by the dark colours).

Upgraded Pyrolysis Oil

Flash or fast pyrolysis is a process in which biomass is heated to a temperature of about 500^{oC} for a period of about a second in the absence of oxygen to produce pyrolysis oil (also often known as bio-oil). Pyrolysis oil is difficult to use as produced but can potentially be upgraded[5] in existing crude oil refineries or in specific upgrading facilities to produce synthetic diesel and petrol fuels. These fuels are expected to make good petrol and diesel blending components having properties similar in specification to crude oil derived petrol and diesel.

Pyrolysis technologies for producing pyrolysis oil are commercially available from Canada, but the upgrading process to convert the raw pyrolysis oil into petrol and/or diesel requires further research and development. This work is progressing (UOP); the technology is expected to be commercially available from around 2012/13.

Ethanol

Ethanol is the most established biofuel substitute for petrol fuel. About 221 million litres of ethanol were used as a biofuel in the UK between April 2008 and April 2009[3]. Ethanol is most commonly blended with conventional petrol fuel at proportions of up to 5% by volume, as sanctioned by vehicle manufactures and regulated by Fuel Standard EN228. New vehicles may use ethanol blends up to 10% and specially adapted flexi-fuel vehicles can use all ethanol proportions in petrol up to 85% ethanol (E85).

The energy density of ethanol is poor compared to petrol which can reduce fuel economy as illustrated in Figure 3. However, ethanol has a higher octane rating than petrol, potentially improving engine performance, and engine manufactures are developing engines that, by taking advantage of ethanol's octane advantage, will yield improved fuel economy when usingE85.

Today, most ethanol is produced by the fermentation of sugars obtained from sugar crops such as sugar cane or cereal crops such as maize/corn and wheat. This is a mature technology. The UK (June 2010) has an ethanol production capacity of 355,000 tpa, with a further 335,000 tpa under construction and 150,000 tpa planned in the near term. Ethanol may also be produced by the fermentation or catalytic conversion of syngas. Gasification potentially allows all of the biomass to be available for fermentation, rather than just the sugars, and is therefore suitable for a wider range of feedstocks including waste materials, not only those with high sugar content. The conversion of syngas to ethanol is expected to be demonstrated at a large scale during the first half of this decade.

The major barriers to the use of ethanol as a biofuel are its hydrophilic and corrosive properties. These make blends of ethanol and petrol unsuitable for transportation through existing fuel pipelines, as the blended fuel absorbs water which can result in the separation of petrol and ethanol in fuel tanks. To overcome this challenge, ethanol is blended at depots closer to the point of sale; this though can be more costly. The fuel industry expects that the UK will have an ethanol blending infrastructure fully in place by 2011.

An alternative use of ethanol is the manufacture of ETBE (ethyl tertiary butyl ether). ETBE is produced from isobutylene, derived from crude oil or natural gas, and ethanol. Bioethanol derived ETBE has some renewable content. ETBE is currently added to conventional fuels as an octane enhancer and oxygenate to improve the efficiency of combustion and represents an opportunity to increase the renewable content of road transport fuels. ETBE can be

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[5] Upgrading refers to a series of processes which are designed to improve modify the properties of a crude product, in order for it to meet a desired specification. Typical processes include reacting crude products with hydrogen to saturate hydrocarbon structures, and thermal treatment to improve temperature performance.

blended with petrol at up to 22% by volume[6], and has low water solubility compared to ethanol so blends of ETBE and petrol may be distributed through existing pipelines.

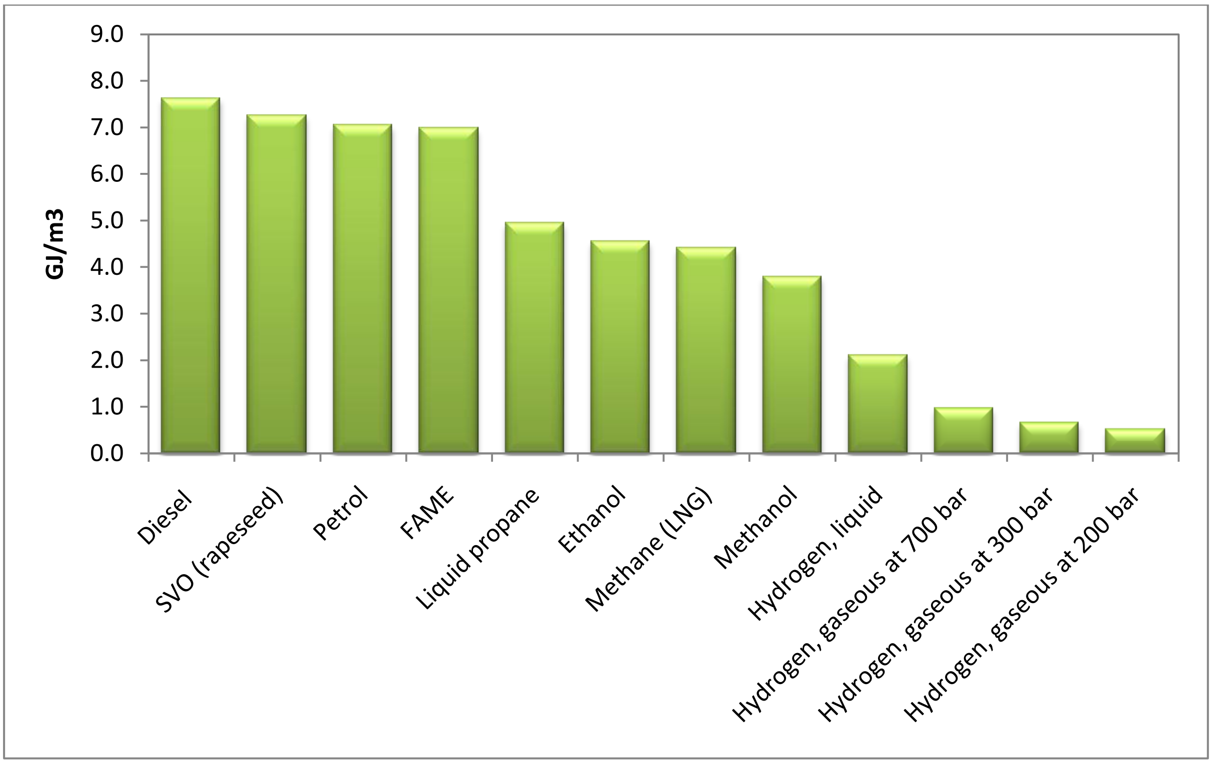

Figure 3. **Volumetric energy density of fuels adjusted for engine efficiency**

Butanol

Butanol has a higher energy density, less corrosive nature and lower water solubility than ethanol. Butanol can be blended with petrol at up to 15% butanol by volume[5] and it is anticipated that butanol will be logistically less challenging to distribute than ethanol. In addition, butanol may potentially be blended into diesel.

Butanol is produced by the fermentation of sugars. The technically mature ABE fermentation process produces butanol as a mixture of alcohols. Alternative high yielding fermentation processes are in the early stages of development, and cost reductions are likely to be necessary before butanol becomes widely available as a commercial biofuel product.

Methanol

Methanol, conventionally derived from natural gas, may be produced by the catalytic reaction of biomass-derived syngas, as performed in the Netherlands by BioMCN from early 2009. Methanol may be blended with petrol up to 3% by volume, under the European Fuel Quality Directive[5]. Alternatively, methanol may be used as a fuel in flexible fuel vehicles designed to accept methanol at up to 85% blend in petrol (M85). However, as illustrated in Figure 3, the energy density of methanol is low.

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[6] Fuel Quality Directive (2009/30/EC): Annex 1. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0088:0113:EN:PDF

An alternative use of methanol is in the manufacture of other biofuels including FAME, synthetic diesel, synthetic petrol, DME, and MTBE (methyl tertiary butyl ether). It can also be used to produce chemicals. At present, natural gas derived methanol is being used in the manufacture of FAME; converting to biomass derived methanol would potentially increase the greenhouse gas savings realised by FAME.

DME (DiMethyl Ether)

DME is produced by the catalytic reaction of syngas or methanol. At atmospheric pressure, DME is a gas, but at a slight pressure, it may be handled as a liquid in a similar way to liquid petroleum gas (LPG) but this requires a dedicated distribution infrastructure.

DME is not blended with diesel fuel and conventional diesel engines require modification for its use, and additional on-board fuel storage. In use, DME produces low emissions of soot and NO_x in comparison to fossil diesel. However, liquefied DME contains approximately half the energy content of fossil diesel fuel. This implies that a new and larger infrastructure and distribution operations would be required for DME to become a common fuel in the UK. This is viewed unlikely in the near to medium term. However, DME could be an attractive option for captive fleets and heavy goods vehicles with dedicated refuelling infrastructure and potential for increased on-board fuel storage.

Synthetic Diesel (FT Diesel & HVO)

Synthetic diesel fuels are mixtures of diesel-range hydrocarbons, which can be made by a number of different processes including Fischer-Tropsch (FT) diesel and hydro-treated vegetable oil (HVO). Synthetic diesel fuels represent a high quality diesel blending component, typically having very high cetane, low or zero sulphur content and clean burning characteristics. These fuels, though, have poorer cold temperature performance and a density that does not meet the current diesel standard. However, these properties are generally overcome by blending with crude oil derived diesel or through further fuel upgrading. Synthetic diesels can be completely integrated into the existing diesel fuel supply infrastructure, and used within existing vehicles provided the finished fuel as supplied to the consumer meets the quality standard EN590.

Synthetic diesel may be produced from syngas using the well-established FT process, from vegetable oils via hydro-treating or alternatively by the less well known MOGD[7] process. Produced from natural gas, FT diesel is already available for sale across Europe, contained in premium diesel fuels such as Shell V-Power. Biomass derived FT diesel is expected to become commercially available in Europe during this decade. Hydro-treating vegetable oil also produces a synthetic diesel fuel. These fuels are commercially produced in Europe, and are known under the names NExBTL, Green Diesel, and BHD.

Synthetic Jet Fuel

Synthetic jet fuel is a drop in replacement for crude oil derived aviation fuel, being completely compatible with existing aviation fuel infrastructure, and suitable for blending with crude oil derived aviation fuel. Synthetic jet fuel is currently produced from coal, and is hence not a biofuel. However, technologies are being developed to produce synthetic jet fuel from biomass. Manufacturing processes are very similar to those for synthetic diesel.

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[7] Methanol to Olefins, Gasoline and Diesel

Several airlines have conducted test flights using biomass derived jet fuels, mostly produced from vegetable oils through the hydro-treating route. A small number of test flights have demonstrated the use of synthetic jet fuel produced via the biomass FT route (i.e., BTL jet fuel).

Synthetic Petrol

Synthetic petrol can be produced from methanol by the MTG[8] or MOGD process. The fuel is a mixture of petrol-range hydrocarbons containing aliphatic and aromatic components, and has a low sulphur content. Synthetic petrol is suitable for use in existing vehicles provided the fuel is upgraded or blended with crude oil derived petrol to meet the fuel standard EN228. It is understood that there are no manufacturing plants for producing synthetic petrol.

Methane

Methane is a gaseous biofuel that is not suitable for blending with petrol or diesel fuels. However, it can be used in vehicles with engines modified to run on compressed natural gas or liquefied natural gas or in combination with a small amount of diesel in dual fuel diesel engines (typically used in trucks). Currently, a small amount of bio-based methane produced from upgraded biogas from anaerobic digestion is used for road transport in the UK, about 400,000 kg between April 2008 and April 2009[3].

Methane can be produced by upgrading biogas produced by the anaerobic digestion (AD) of organic material, or by the catalytic methanation of syngas. In order to use methane as a road transport fuel, it must be cleaned of impurities and either compressed or liquefied.

The availability of suitable vehicles is increasing with some major vehicle manufactures offering compatible vehicles, in particular VW. However, the task of implementing a dedicated refuelling infrastructure in the UK is a significant undertaking. It is, therefore, less likely that, in the near term, methane will be used as a common fuel in the UK, but depot operations for return to base fleets are possible. There are many alternative uses of methane, including heat and power generation, and it is possible to inject biomethane into the existing gas grid and so substitute natural gas in a range of energy applications.

Hydrogen

The major application of hydrogen today is in oil refinery operations and the manufacture of chemicals. However, hydrogen may be used as a fuel in fuel cell vehicles, or in modified internal combustion engines. Around the world, a small number of test vehicles are in operation such as those from Honda (fuel cell) and BMW (internal combustion engine). A number of technical challenges to the commercialisation of such vehicles do though remain to be addressed.

Hydrogen can be produced from a very wide range of sources, including steam reforming of natural gas, water splitting by electrolysis, and via the gasification of biomass. However, challenges to the wide spread use of hydrogen as a fuel remain. The volumetric energy density of hydrogen is very poor and dependent on the pressure at which the gas is stored, as illustrated in Figure 3. Developing appropriate on-board fuel storage is a major technical challenge. In addition, the use of hydrogen as a fuel would require installation of a

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[8] Methanol to Gasoline

dedicated refuelling infrastructure. These challenges are likely to hinder the deployment of hydrogen as a vehicle fuel in the near to mid-term.

3 Biofuel Production Processes

Many of the products covered in Section 2 are currently produced from fossil resources, such as oil, natural gas, and coal. A smaller number are currently produced from renewable resources. Within this section we will describe established and emerging processes to produce biofuels from renewable feedstocks or intermediates, such as sugars, syngas, biogas, and pyrolysis oil. We include processes which are in commercial operation, those at demonstration stage and pilot stage developments, as illustrated in Figure 4.

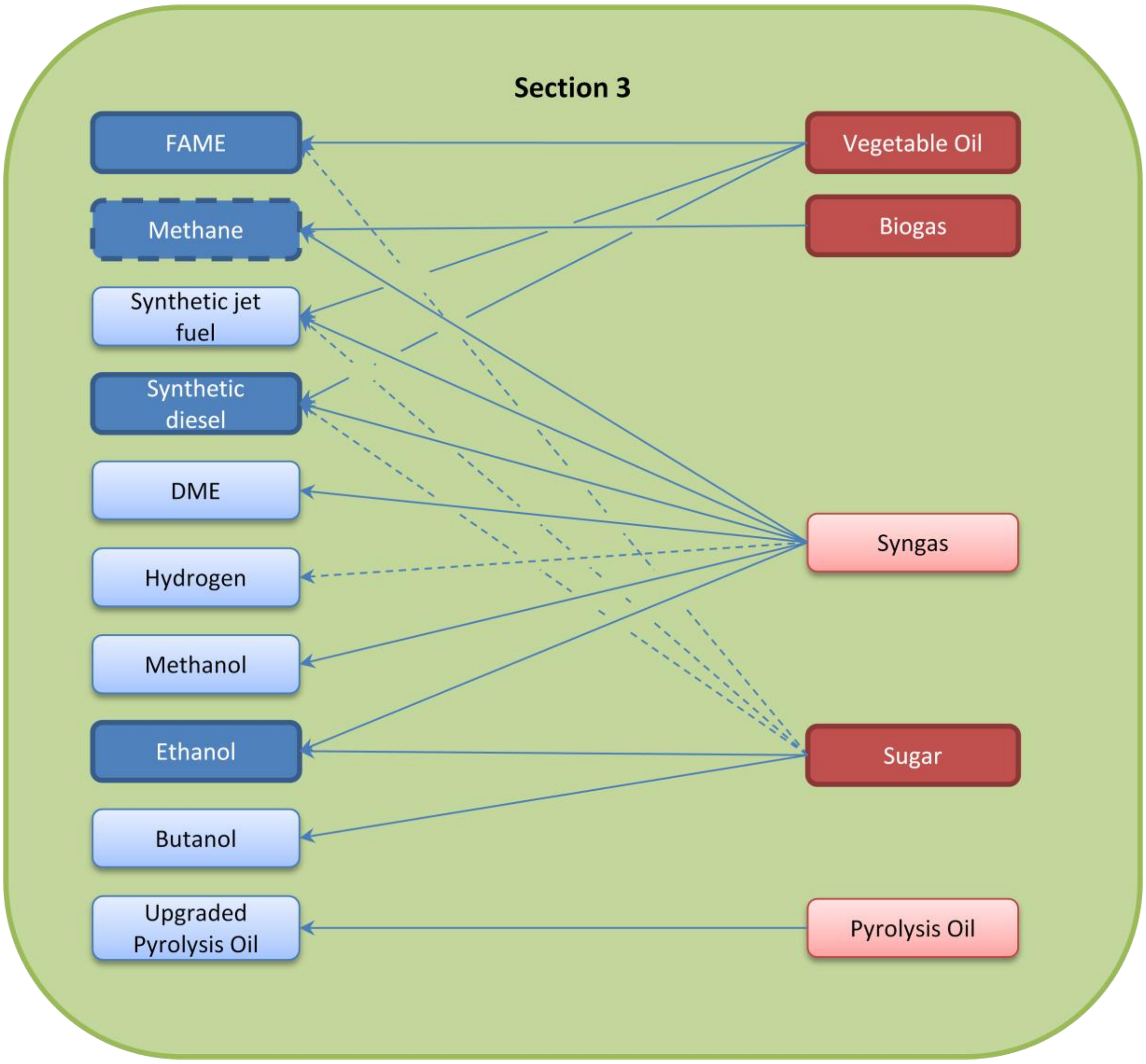

Figure 4. **Biofuel production pathways from intermediates (existing commercial pathways are indicated by the dark colours).**

FAME

FAME is produced by reacting vegetable oil with methanol in the presence of a potassium hydroxide or sodium hydroxide catalyst, in a reaction known as transesterification. The transesterification reaction removes the glycerol molecule from the vegetable oil leaving three long chain hydrocarbons that, combined, are used as a biofuel. Glycerol is produced as a co-product, initially contaminated with methanol and spent catalyst, but it may be purified to achieve a higher value. Glycerol can then be used as a resource from which to produce chemicals or, at lower value, as a fuel itself, for example in CHP. BioMCN in the Netherlands, for example, convert glycerol produced by biodiesel manufacturers into methanol.

The process technology for the production of FAME can be licensed from a number of technology providers, and the capital costs are relatively low as illustrated in Table 1. FAME processes operate at relatively small scale, typically up to 250,000 tpa from about 300 million litres of vegetable oil feedstock per year. FAEE (fatty acid ethyl ether) is a less common fuel with similar properties. FAEE is produced by the substitution of methanol by ethanol in the above process.

Upgraded Pyrolysis Oil

Pyrolysis is a thermal decomposition process which always produces a combination of solid char, liquid oil, and gaseous products. The relative proportions of these products depend on the pyrolysis process conditions used. When the pyrolysis process is optimised to produce primarily a liquid product, the liquid produced consists of a mixture of many chemicals - it is generally called pyrolysis oil or bio-oil. This product cannot be used directly as a road transport fuel but may, in the future, be upgraded and fractionated into diesel and petrol blending components. The processes used to upgrade and fractionate pyrolysis oil are similar to those used in existing oil refining techniques. It is anticipated that these upgrading facilities may be located either in existing oil refineries or at standalone sites.

There are a number of properties of pyrolysis oil which affect the options for upgrading:

- High oxygen content
- High acid number (this makes re-use of existing hydrocrackers possibly problematic)
- High water content
- High metals content (particularly potassium and calcium)
- Immiscibility of pyrolysis oils with petroleum oils
- The fact that pyrolysis oils do not fractionate in the same way as petroleum oils.

In addition, the upgrading process is likely to have a significant hydrogen demand. Overcoming these properties represents a significant technical challenge, and it is not yet clear how bio-oil based products will be traced through the range of refinery products if bio-oil were to be co-processed with crude oil.

Biofuel	Capacity (tonnes/year)	Total capital cost (Euro)	Relative capital cost (Euro/GJ/year)	Relative product usability	Relative technical difficulty	Expected date of global commercialisation
FAME	250 000	50 – 100 Million	5 000 – 10 000	Medium	Low	Established
HVO	170 000 - 800 000	100 - 550 Million	14 000 - 16 000	Very high	Low – Medium	2007
Upgraded Pyrolysis Oil	100 000	100 – 150 Million	23 000 – 35 000	High	Very High	~ 2013
Hydrogen	50 000 - 200 000	275 - 400 Million	11 000 – 67 000	Low	High	beyond 2015
Methanol	260 000	450 Million	87 000	Low – Medium	Medium	2009
Ethanol (from sugars)	75 000 - 325 000	82 - 280 Million	32 000 – 40 000	Medium	Very Low	Established
Ethanol (from lignocellulose)	150 000 - 200 000	150 - 560 Million	28 000 – 137 000	Medium	High	~ 2011
Synthetic Diesel	105 000 - 200 000	400 – 650 Million	45 000 – 137 000	Very high	High	~ 2014

Table 1. Comparison of typical commercial scale production of existing and emerging biofuel technologies[9, 10, 11]

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[9] NNFCC 08/017, International Biofuel Strategy Project, November 2007 http://www.nnfcc.co.uk/metadot/index.pl?id=6597;isa=DBRow;op=show;dbview_id=2457

[10] NNFCC 08/007, Lignocellulosic Ethanol Plant in the UK - Feasibility Study (Black & Veatch), September 2008 http://www.nnfcc.co.uk/metadot/index.pl?id=7607;isa=DBRow;op=show;dbview_id=2457

[11] Wright & Brown, Biofuels, Bioproducts & Biorefining: Comparative economics of biorefineries based on the biochemical and thermochemical platforms, Vol. 1, September 2007

Ethanol

In conventional ethanol production processes that are widely practiced across the world, glucose derived from sugars or starches is fermented by yeast. Fermentation produces a dilute aqueous ethanol solution (approximately 10-13%), which is dried by a distillation process followed by a polishing step, typically using a molecular sieve. The final product must be completely dry to be suitable for blending with petrol.

Ethanol may be produced from other feedstocks including lignocellulosic biomass. Lignocellulosic biomass refers to any plant or animal matter, including straw, wood, biological wastes, and grasses. These materials are called lignocellulosic, because they contain a large proportion of lignin and cellulose. The hydrolysis of lignocellulose produces both hexose and pentose sugars. The yeasts typically employed for ethanol production do not efficiently ferment hexose sugars produced from lignocellulosic biomass and cannot ferment pentose sugars. Therefore, lignocellulosic feedstocks are fermented by microbial organisms which may ferment both of hexose and pentose sugars. Typically these are proprietary recombinant organisms whose metabolisms have been tailored to the sugars in the process. There are several demonstration plants in the EU and US, but as yet no fully commercial plants. The US has announced a target of producing ethanol from lignocellulosic biomass to the same price as that from corn by 2012.

Alternatively, ethanol may be produced from syngas. An advantage of syngas routes to ethanol is their ability to process a wider range of biomass resources. Syngas is converted to ethanol by microorganisms in a fermentation process, or by chemical catalysis. The fermentation process operates at low temperatures and low pressures. A wide variety of microorganisms can produce ethanol from syngas; careful selection of fermentation organism can allow the selective production of ethanol with no side products. This process may be economically feasible at a smaller scale than other syngas to biofuel processes because of lower capital costs. The minimum economic scale is estimated at about 20,000-30,000 tpa of ethanol. The technology is proven at pilot scale, and is expected to be demonstrated by 2012.

The chemical catalytic process is known as mixed alcohol synthesis, or higher alcohol synthesis. Mixed alcohol synthesis is similar to FT and methanol synthesis and uses catalysts modified from these processes. As the name suggests, a mixture of alcohols is produced including methanol, ethanol, propanol and butanol, from which ethanol, typically the largest component, may be isolated. The capital cost of such processes is high, and therefore the minimum economic scale is estimated to be around 100,000 tpa of alcohol products. A commercial plant is under construction in the US, with support from the US Government.

Butanol

Butanol may be derived from sugars by a fermentation process. The ABE process employs microbial organisms which ferment sugars to butanol, acetone and ethanol. Butanol is toxic to the fermentation organisms at relatively low concentrations, and the fermentation therefore produces a very dilute aqueous solution (approximately 2%). The product is isolated from this solution by distillation. Currently the distillation process is relatively complicated and expensive, due to the low concentration of butanol and the presence of ethanol and acetone.

The ABE process is currently employed for the commercial production of butanol for the chemicals industry, but not for biofuels. The commercialisation of butanol as a biofuel depends on reducing production costs, primarily through improved yields and utilization of lower cost lignocellulosic feedstocks. Recent developments in microbial and enzymatic technology are anticipated to release alternative fermentation pathways which allow butanol to be produced from sugars without the production of co-products. Once proven at commercial scale, this technology could potentially enter the market relatively quickly, through the modification of existing ethanol plants.

Methanol

Methanol is produced from syngas by a catalytic process similar to FT synthesis. The hydrogen and carbon monoxide in the syngas are reacted with a small amount of carbon dioxide over a copper-zinc oxide catalyst at a temperature of 220-300$^{\circ C}$ and a pressure of 50-100 bar (atmospheric pressure is 1.01 bar/14.7 psi).

Methanol plants are expected to be built at a capacity of about 260,000 tpa with medium capital costs in comparison to other biofuel technologies. Commercial production of biomethanol from glycerol, a co-product of the FAME manufacturing process, started in 2009 by BIoMCN in the Netherlands. The plant was constructed to make use of an existing methanol reformer thereby minimising project capital costs.

Synthetic Diesel

The most commonly considered pathway to produce synthetic diesel is the Fischer-Tropsch (FT) reaction of syngas. In the FT process, the hydrogen and carbon monoxide in syngas are reacted over a catalyst to form a wide range of hydrocarbon chains of various lengths. The molar ratio of hydrogen and carbon monoxide needs to be controlled to about 2:1, and this may be achieved by inserting a water gas shift reaction prior to the FT process. Cobalt based catalysts are most commonly used for the FT process; the alternative is to use an iron based catalyst. The reaction, which takes place at 200-350$^{\circ C}$ and 20-40 bar, produces a waxy hydrocarbon product. The crude product is hydrocracked, a standard oil refining process, to produce typically synthetic diesel and naphtha.

Whilst the FT process is not commercially operational for the production of biofuels, it is currently practiced in South Africa, Qatar, and Malaysia for the manufacture of high quality liquid fuels from coal and natural gas. Experience may be gleaned from these operations, although the level of contamination of biomass derived syngas is different compared to syngas derived from natural gas and poses a number of yet to be fully resolved challenges. Capital costs, essentially because of the high temperatures and pressures used, are higher than for established biofuels and cost reductions represent a significant challenge to the commercialisation of the technology, as illustrated in Table 1. Demonstration plants are soon to start operations in the US and Europe and commercial plants are planned to be built during this decade.

Synthetic diesel may also be produced from vegetable oils, the product of this process is also known as HVO. The conversion process involves reacting vegetable oils with hydrogen in the presence of a catalyst. This process builds on existing refinery techniques which are well understood by refiners, both economically and technologically. The technology has been in commercial operation since 2007 in Finland, and proprietary processes are being developed by a number of companies. It is possible to minimise capital costs by co-processing vegetable oil within an existing refinery making use of existing processing capacity, although this would reduce the fossil diesel capacity. It is not yet clear how biomass based products will be traced through the range of refinery products if vegetable oil were to be co-processed with crude oil derived products.

The prospects for HVO technology in the UK are dependent upon vegetable oil availability, hydrogen availability, product value, and the availability of suitable refinery capacity. The first commercial plants started operations in 2007 and can produce about 170,000 tonnes of biofuel products per year. This is equivalent to 4,250 barrels per day (bpd) which is small in comparison to existing oil refineries which each process in the region of 250,000 bpd of crude oil.

Synthetic Petrol

Synthetic petrol may be produced from vegetable oil in a very similar way to synthetic diesel outlined above, and the barriers to commercialisation are also as outlined above. The synthetic petrol and diesel products are isolated by distillation, in the same way that crude oil products are currently isolated.

Synthetic petrol may also be manufactured from methanol by the MTG or MOGD process. In the MTG process, methanol is first converted to DME over an alumina catalyst, and subsequently combined with a zeolite catalyst. The product of this process is cooled and distilled into three factions, and the heavier fraction subject to further hydro-treatment. The process is proven at commercial scale, but is not currently operational due to unfavourable economics.

The MOGD process is designed to produce petrol in combination with distillate, an intermediate which may be further processed to synthetic diesel and/or jet fuel. It also employs zeolite catalysts and typically operates at 375-450$^{\circ C}$ and 30-60 bar. The crude product undergoes upgrading to produce the finished fuel. MOGD processes are available to licence although they have not been proven at commercial scale.

Synthetic Jet Fuel

The processes to manufacture synthetic jet fuels are very similar to those of synthetic diesel and petrol. The operating conditions of the FT and MOGD processes may be adjusted to maximise production of different hydrocarbon products. For a heavier product, for example, this typically involves a lower reaction temperature and higher pressure. The product goes through stages of hydro-treatment and distillation to produce a suitable synthetic jet fuel.

DME

DME may be produced from methanol or directly from syngas, using existing single or multi step catalytic processes. The technologies are established for the conversion of syngas derived from natural gas or coal. However, the conversion of biomass derived syngas to DME is not yet commercially operational. A European consortium, which includes Volvo, is developing the production of DME from biomass. It aims to complete the construction of a DME pilot plant this year.

Methane

Methane may be produced from biogas or syngas. Biogas is mixture of about 60% methane, 40% carbon dioxide and traces of other contaminate gases, produced by AD. Methane may be separated and cleaned using existing technologies, such as pressure swing adsorption, or using membrane filters. Methane is produced from syngas by a process called methanation. In the methanation process, syngas is combined with steam and a catalyst, at around 400^{oC} and 5–60 bar. Under these conditions the majority of syngas is converted to carbon dioxide and methane, and the gas mixture is cooled to allow any residual water to condense from the gases. The carbon dioxide may be separated, as with biogas, by one of a number of commercial technologies. The final product is also known as bioSNG, and may substitute for natural gas in a range of energy applications.

Hydrogen

Renewable hydrogen may be produced by the gasification of biomass or the reformation of renewable methane. Syngas, which is the product of the gasification process, is a mixture of carbon monoxide and hydrogen along with a number of minor contaminants. Gasifiers can be designed to optimise the production of carbon monoxide and hydrogen. The hydrogen content of the product is maximised by the application, post gasification, of the water-gas shift reaction, a commercially available process in which the carbon monoxide in the syngas is reacted with steam to yield carbon dioxide and hydrogen.

Alternatively, hydrogen may be derived from methane produced by the Anaerobic Digestion (AD) of biomass. The process for deriving hydrogen from methane is known as reforming. This is a well understood technique which is carried out within existing refineries for the production of hydrogen from natural gas.

4 Feedstock Conversion Processes

There are five key intermediates from which the majority of biofuels are manufactured (Figure 1). These are:

- Vegetable oils,
- Sugars,
- Syngas,
- Biogas, and
- Pyrolysis oil.

In this section, the near term options to producing these key intermediates are summarised (Figure 5).

Vegetable Oils

Vegetable oil is extracted from number of sources. The most common vegetable oil biofuel feedstocks used within the UK are soy oil, oilseed rape, and palm oil. Although many different parts of plants may yield oil, in commercial practice, oil is extracted primarily from seeds. Waste oils are also used for biofuel production such as tallow, a by-product of the animal rendering industry and waste cooking oils. Waste oils can vary in their quality and availability, and must be cleaned prior to further processing.

Vegetable oils are lipid materials derived from plants, which are generally liquid at room temperature (palm oil, for example, is “cake like” at UK room temperatures). The chemical composition of oils varies and can impact the performance of the final biofuel product. Vegetable oil quality attributes desirable for FAME production differ from those for vegetable oil hydrogenation. For FAME production, the degree of vegetable oil saturation must be balanced to obtain satisfactory biofuel cold temperature performance, oxidative stability and degree of polymerisation during combustion. Highly saturated oils such as palm oil will tend to solidify at higher temperatures than unsaturated oils such as rape while more unsaturated vegetable oils, such as rape oil, produce biofuels which will age more rapidly than those made from palm. For vegetable oil hydrogenation, highly saturated oils such as palm oil are beneficial as they reduce the process hydrogen demand.

Sugars

Sugars are the primary feedstock for fermentation routes to biofuels, for example ethanol, and butanol. Glucose is a hexose sugar (C6) and the most commonly occurring sugar. The production of glucose from sugar crops such as sugar cane and sugar beet is a well established process carried out by the food and beverage industries. The production of glucose from starch crops is slightly more complex, as starch contains glucose in polymer form. Glucose is released from starch by a hydrolysis reaction known as saccharification. Saccharification is normally carried out with an enzyme mixture, collectively known as amylases. This is a relatively established process with low costs and high efficiency.

Lignocellulose material contains both hexose (C6) and pentose (C5) sugars, in the complex polymer forms cellulose and hemicellulose. Cellulose and hemicellulose are enclosed by a coating of lignin, a complex polymer with no sugars that gives the plant its structural strength. To obtain simple sugar monomers suitable for fermentation, it is necessary to release the cellulose and hemicellulose from the lignin and then hydrolyse these polymers to simple sugars. Enzymes are a major expense in the process of producing fuels from lignocellulosic sugars and developing new, lower cost, enzymes is a major worldwide focus.

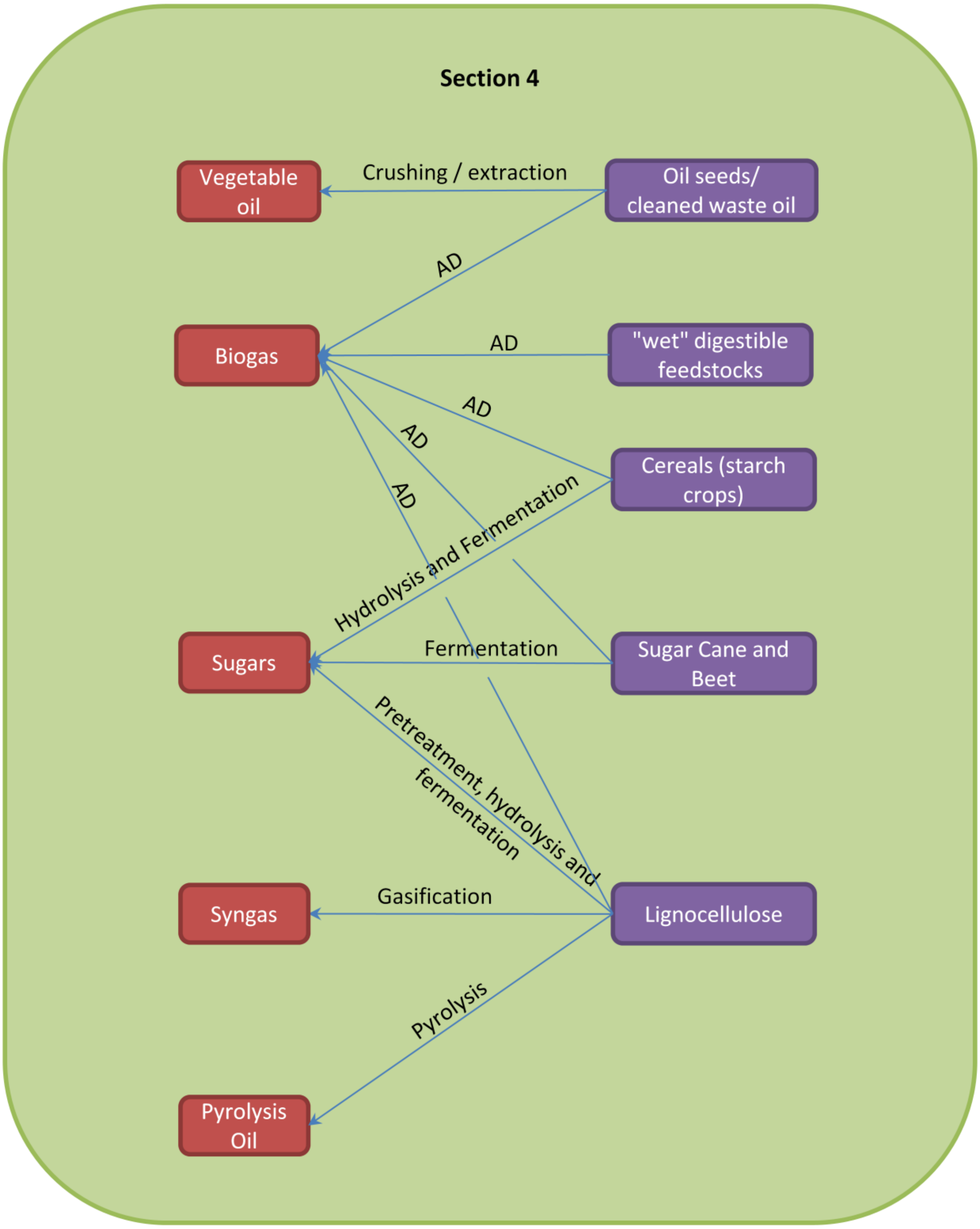

Figure 5. Feedstock conversion processes

A number of processes are in development for the efficient release of cellulose and hemicellulose from lignocellulosic material. These are typically multi-stage processes. The first stage generally involves physical treatments to reduce the particle size and increase the surface area of the lignocellulose material, thereby improving the effectiveness of subsequent stages. Dilute acid is most often employed to liberate the cellulose and hemicellulose from the lignin and at the same time hydrolyse the hemicellulose to simpler sugars. Alternative methods include steam explosion treatment, and ammonia fibre explosion. Once liberated, cellulose is hydrolysed by further acid treatment, typically at a higher temperature but lower concentration than the pre-treatment stage. Alternatively, mixtures of enzymes may be employed to carry out hydrolysis. These are known as cellulases and hemicellulases. This technology is demonstrated at pilot scale but further development is required to reach the level of efficiency and cost achieved by processes that use sugar and starch feedstocks.

The microorganisms used in fermentation are susceptible to poisoning. It is, therefore, necessary to use only clean lignocellulosic feedstocks for fermentation based pathways. A key challenge for these processes is to maximise the sugar yield whilst minimising the formation of products that inhibit the subsequent fermentation process.

Syngas

Syngas, or synthesis gas, is a mixture of carbon monoxide and hydrogen at a consistent, designed ratio. It may be used to produce a range of biofuels by separation, hydrogenation, fermentation, or more commonly by using catalysts to recombine the elements in the gas to produce, for example, methanol, ethanol, hydrogen, DME, or synthetic diesel. It can also be used to produce energy or a range of chemicals, as shown in Figure 6.

Syngas is produced by a process known as gasification. Syngas may be made from coal, natural gas, or biomass. The majority of interest in gasification for biofuels focuses on lignocellulosic feedstocks that typically have lower costs. In gasification a material containing carbon is converted into a gas in presence of insufficient oxidant for complete combustion. Typically, for syngas production, oxygen rather than air is used as the oxidant as this eliminates the costly downstream diluent effect of nitrogen. Gasification is a thermochemical process, meaning that the feedstock is heated to high temperatures, producing gases which can undergo chemical reactions to form syngas.

The crude syngas produced by gasification of biomass contains a number of undesirable contaminants. Carbon dioxide and water vapour are inert impurities which increase costs. Hydrocarbon gases, tars and inorganic compounds can potentially poison catalysts used in subsequent biofuel synthesis processes, and reduce conversion yields. Therefore, crude syngas must undergo a number of cleaning and conditioning processes. Gas cleaning technologies are commercially available. However, there has been no large scale demonstration of these technologies on biomass generated syngas. Gas cleaning comprises cracking, reforming or removal of tars and hydrocarbon gases, dust and particle filtering, and scrubbing or catalytic absorption of contaminants such as sulphur, nitrogen, fluoride compounds and carbon dioxide. In addition, it may be necessary to condition the syngas so that the ratio of hydrogen to carbon monoxide is within an acceptable range for the downstream processing. This is achieved by a water gas shift reaction, a commercially available technology.

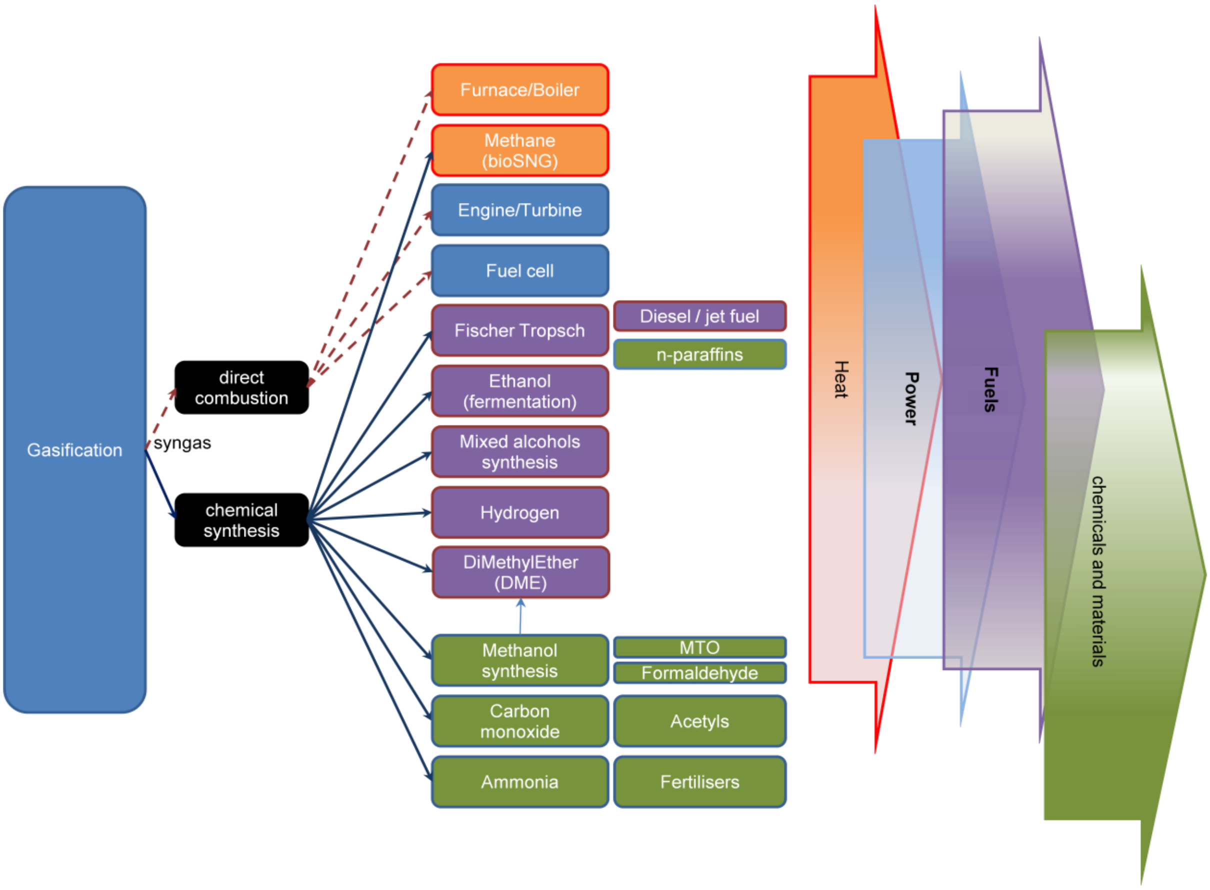

Figure 6. **Summary of variety and overlap of products available through gasification**[12]

Gasification is a mature technology, and many reactor designs are available. However, the large scale gasification of lignocellulosic biomass is less developed and gasifiers must be optimised to deal with the physical properties of lignocellulosic feedstocks and the chemical contaminants likely to be present.

A benefit of syngas routes to biofuels is that gasification is a feedstock flexible process, making it attractive for use in the UK given the variety of feedstocks available. Biomass gasification is a platform to a wide range of renewable products (Figure 6). Gasification is likely to operate on a large scale similar to waste treatment plants, though not at refinery scale.

Biogas

Biogas is a mixture of about 60% methane, 40% carbon dioxide and traces of other contaminant gases, produced by AD. AD is a biological process which relies on living organisms. There are multiple micro-organisms active in the AD process, which carry out four simultaneous biochemical processes to breakdown the AD feedstock. Hydrolysis is the first stage which breaks down the chemical bonds in fats, carbohydrates and proteins to form sugars, fatty acids and amino acids. Acidogenesis degrades the products of hydrolysis

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[12] NNFCC 07/014, Feasibility of Second Generation Biodiesel Production in the United Kingdom (Nexant), October 2007
http://www.nnfcc.co.uk/metadot/index.pl?id=4041;isa=DBRow;op=show;dbview_id=2457

into carbon dioxide, hydrogen, alcohols and organic acids. The alcohols and organic acids are degraded to acetates by acetogenesis, and in the final stage, methanogenic bacteria use acetates, hydrogen and carbon dioxide to produce methane.

AD is suitable for a very wide range of feedstocks, including agricultural wastes, manures, abattoir waste, food waste and specifically grown energy crops. Feedstocks typically have high, moisture content and low solids content of between 10-20%. The AD process has been used in the UK for several years, mostly in the sewerage industry, digesting raw sludge to a safe, inert product. Interest in AD from other sectors is growing as it has the potential to divert biodegradable waste from landfill, and generate renewable heat, power, and transport fuel.

Pyrolysis oil

Pyrolysis is the thermal decomposition of a relatively dry carbonaceous material (10% moisture content) in the absence of an oxidant. The process always yields three products: char, condensable vapours and gases (such as and including carbon monoxide and methane). Manipulating the process conditions can control the relative proportions of each. Biomass pyrolysis for the production of liquids is a medium temperature process, with short processing times typically of less than one second. It is often termed flash or fast pyrolysis. This is a destructive process, preferring dry feedstocks with low variability in composition, such as waste wood. It is most applicable to low cost lignocellulosic feedstocks.

There are no flash or fast pyrolysis demonstration plants for the production of bio-oil in the UK although these technologies are commercially available elsewhere. There is existing UK pyrolysis activity demonstrating the high temperature (around 1000^{oC}) pyrolysis of wastes. High temperature pyrolysis processes are designed to maximise the production of gases which are subsequently burnt on site to produce electricity and, if possible, heat.

The pyrolysis process needs an external source of heat and power and this is typically provided by using some of the pyrolysis products, preferably those with the lowest value. When aiming to produce liquids by flash or fast pyrolysis, the gaseous and some of the solid products typically provide the energy needed although often, such as in the Canadian Ensyn process, all of the gaseous and solid byproducts are burnt on site and the excess electricity and/or heat is sold out.

Pyrolysis oil may also be used as a feedstock for gasification. The potential advantages of pyrolysing biomass prior to gasification include improved feedstock transport logistics, ash control[13] and easier feeding into high pressure gasifiers. However, the financial benefits of pyrolysis as a pre-treatment for gasification processes are currently unconfirmed.

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[13] Biomass ash is problematic during gasification (and combustion) as it melts at a low temperature, limiting the maximum temperature at which reactions can occur. It also contains corrosive elements and can affect gasification chemistry. Liquid ash or slag can interfere with the operation of the gasifier, particularly fluidised beds, although some gasifiers such as entrained flow gasifiers, are designed to accommodate liquid slag and so can operate at higher temperatures allowing greater efficiencies.

5 Biofuel Feedstocks

There are a great number of biofuel feedstocks that may be produced indigenously or imported in to the UK. Feedstock choices are often critical to the economic feasibility of biofuel production, the sustainability, and the GHG emission saving realised. In this section feedstocks that are currently used for biofuel production, such as sugar and vegetable oil, and those in early stages of development, such as algae are discussed (Figure 7).

Vegetable Oils

There are many potential sources of vegetable oil (a sample range is shown in Table 2). A primary consideration in the selection of vegetable oil feedstocks is oil yield, and there are significant differences in oil yield between high yielding palm and rapeseed and low yielding soy. There are also wider issues surrounding the sustainability of vegetable oil cultivation for biofuel production, as reported in The Gallagher Review[14]. Concerns surround the increased demand for edible vegetable oils and the impact on food prices, and also for the impact of land use change where agricultural land is reassigned to the production of oil crops for biofuel use.

There is significant interest in research into achieving greater yields and drought tolerant crops could benefit both the fuel and food sectors. In addition, the UK is leading in developing carbon and sustainability reporting criteria with an aim to improve the sustainability of practices across the biofuel supply chain.

Crop	kg oil/ha	litres oil/ha
hemp	305	363
soybean	375	446
linseed (flax)	402	478
sunflowers	800	952
rapeseed	1000	1190
olives	1019	1212
castor beans	1188	1413
jatropha	1590	1892
coconut	2260	2689
oil palm	5000	5950

Table 2. Examples of Oil Yields (oil yields are sensitive to a wide number of variables, these figures are representative of reported typical yields)

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[14] The Gallagher Review of the Indirect Effects of Biofuels Production, July 2008. Available from: http://www.renewablefuelsagency.org/reportsandpublications.cfm

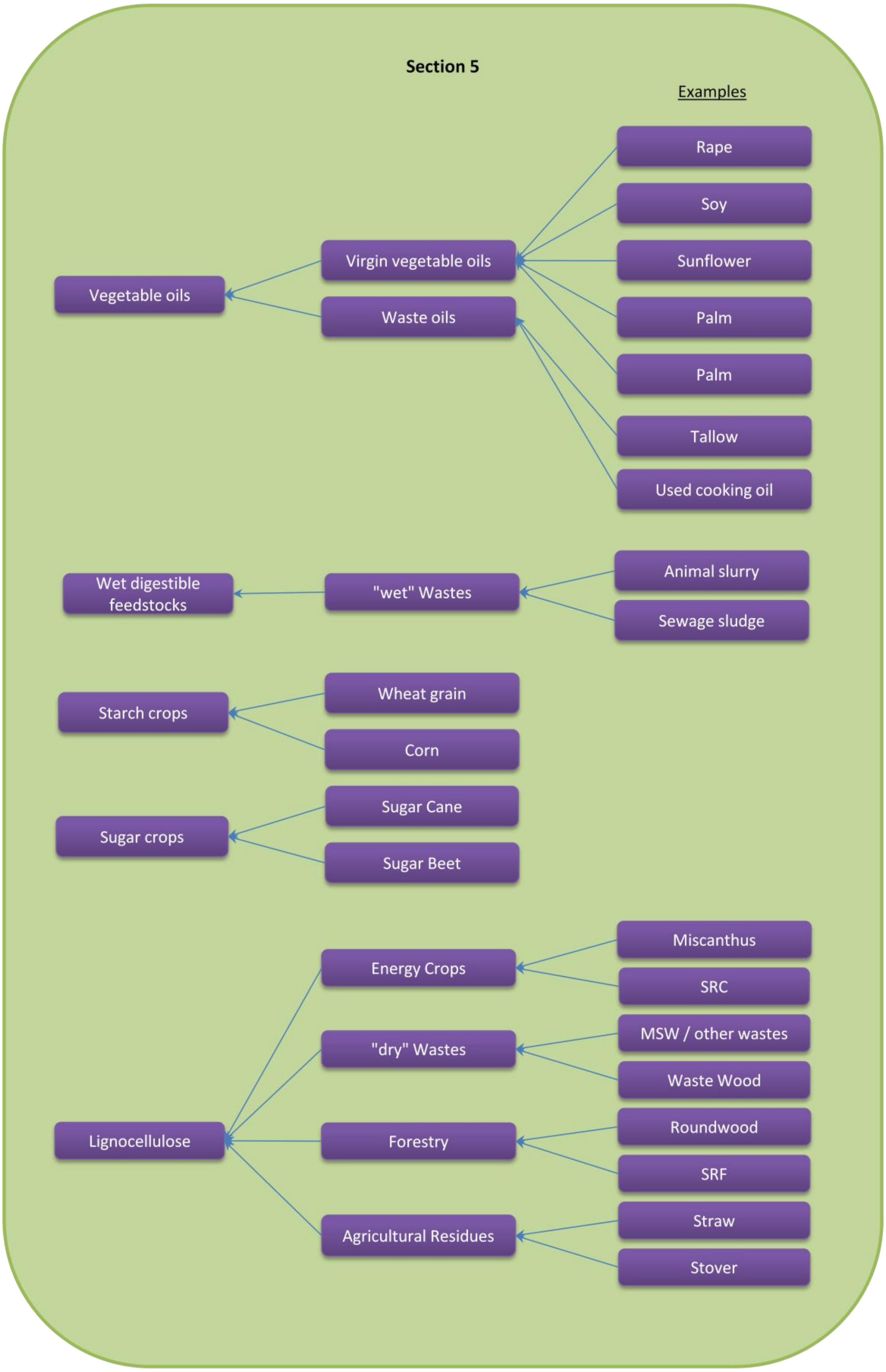

Figure 7. **Current and Future Biofuel Feedstocks**

Sugar Crops

Sugar crops include sugar cane and sugar beet. Sugar cane is the most abundant form of sugar globally. However, only sugar beet is grown in Europe. About 26 million tonnes of sugar beet were grown in Europe in 2006/07. However, 82% of ethanol used in the UK is derived from Brazilian sugar cane[1]. Ethanol derived from Brazilian sugar cane typically achieves high GHG savings due to the high productivity of the crop, high conversion yields and the use of the bagasse by-product for power generation.

Lignocellulose

Lignocellulose refers to a wide range of renewable resources including:

- Specifically grown energy crops, such as Miscanthus and short rotation coppice (SRC);
- Forestry products, including roundwood and specifically grown short rotation forestry (SRF);
- Agricultural residues, such as straw; and
- Waste materials, including waste wood and the biodegradable fraction of municipal solid waste (MSW), also known as BMW.

It is possible to convert lignocellulose material to sugars, syngas, or bio-oil. The conversion of lignocellulose to biofuels has the potential to realise very high GHG emissions savings in comparison to fossil and petrol diesel fuels and greater than conventional biofuels of up to 100% compared to petrol and diesel produced from crude oil.

For the biochemical production of alcohols from lignocellulose, there are a large number of lignocellulose pre-treatment technologies at varying stages of development. Each individual pre-treatment technology has its own strengths and weaknesses, and it is apparent that each process technology has beneficial attributes for certain feedstocks.

Algae

Algae are a varied range of organisms that can be grown in a range of aqueous environments including the sea, open ponds and purpose built photo bioreactors. Algae are typically categorised as microalgae or macroalgae.

Microalgae are a diverse group of generally single celled structure. They have rapid generation times leading to very high yields. These properties have created much interest in microalgae as a feedstock for biofuel production. Microalgae species vary in their productivity, with some species preferentially accumulating lipids while others preferentially accumulate proteins or carbohydrates. Those species with high lipid production are of most interest for the production of biodiesel. Lipid yields of greater than 54% are achievable.

Research into the use of microalgae for biofuel production is in very early stages and effort is needed to find strains of microalgae that combine both high productivity and high oil yields with an acceptable quality of lipids for fuel use. It is unlikely that large scale production of microalgae will develop in the UK, due to the lack of available land and low productivities that result from the low levels of sunlight in the UK. However, microalgae may develop in the UK for high value markets, such as speciality chemicals.

Macroalgae are a marine resource commonly referred to as seaweed. Macroalgae do not produce high quantities of oil and there is less interest in macroalgae for the production of biofuels. There is however, some interest in the using macroalgae as a feedstock for AD and this is the subject of current research.

6 Further Resources

- ADAS Improvements in land productivity and increased agricultural inputs with intensification (2008)
- BERR Renewable Energy consultation (2008)
- CONCAWE TTW/ WTW Analyses and Appendices
- DEFRA UK potential Biofuels Industry (2003)
- DEFRA Estimating the Cost-effectiveness of Biofuels (2008)
- DEFRA Estimating the Value for Money of Government Support for Biofuels (2008)
- DEFRA The Impact of Biofuels on Commodity Prices (2008)
- DEFRA UK Biomass Strategy (2007)
- DfT Liquid Biofuels and Renewable Hydrogen to 2050 (2004)
- DTI Technology Status Review and Carbon Abatement Potential of Renewable Transport Fuels in the UK (2003)
- E4tech Biofuels Review Scenario development (2008)
- E4Tech Liquid biofuels and hydrogen to 2050 - E4tech DfT (2003)
- ECN Market competitive Fischer-Tropsch Production (2005)
- EMPA Lifecycle - Environmental Assessment of Biofuels (2007)
- EU RES Directive (2008)
- EU research agenda 2008 EU Platform paper -strategy (2008)
- European Environment Agency - Maximising the environmental benefits of Europe's bioenergy potential (2008)
- House of Commons - Are Biofuel Sustainable (2008)
- House of Commons - Biofuels and Farming (2008)
- IEA Biofuels for Transport - An International Perspective (2004)
- IEA Gaps in research of 2nd generation transportation biofuels (2009)
- IEA OECD From 1st to 2nd Generation Biofuel Technologies (2008)
- NNFCC A Detailed Economic Assessment of Anaerobic Digestion Technology and its Suitability to UK Farming and Waste Systems (2008)
- NNFCC Addressing the land use issues for non-food crops (2008)
- NNFCC Lignocellulosic Ethanol Plant in the UK (2008)
- NNFCC Liquid Transport Biofuels Technology Status Report (2007)
- NNFCC National and regional supply demand balance for agricultural straw in Great Britain (2008)
- NNFCC UK biofuel production facilities (2008)
- Northeast Biofuels - UK Crops for Food and Fuel (2008)
- NREL Production of Biodiesels from Multiple Feedstocks and Properties of Biodiesels and Biodiesel Diesel Blends (2003)
- Parliamentary Office of Science and Technology Transport Biofuels (2007)
- REFUEL A European road map for biofuels (2008)
- REFUEL Biomass Resources Potential and Related Costs (2008)
- RFA Monthly Report Apr-Dec (2008)
- RFA The Gallagher Review of the indirect effects of biofuels production (2008)
- Royal Society Sustainable Biofuels prospects and challenges (2008)
- SCOPE International Biofuels Project – various studies
- UKERC Lifecycle - Can biofuels be sustainable in the UK (2008)
- UKPIA Briefing Biofuels in the UK May (2008)
- University of California part 1 A Low-Carbon Fuel Standard for California (2007)
- US RFA - Analysis of Biofuels Environmental Consequences and Interactions (2009)
- VTT Status and outlook for biofuels, other alternative fuels and new vehicles (2008)

7 Glossary

Term	Definition
BMW	Biodegradable Municipal Waste
Biomass	Any living or recently dead plant or animal material
Blending	Mixing of two compatible fuels having different properties in order to produce an intermediate fuel
Blending Component or blendstock	A blending component is a fuel that can be combined with another having different properties to produce a final fuel product that meets the specification.
Cetane Number	A relative measure of the interval between the beginning of injection and auto ignition of the fuel. The higher the number, the shorter the delay interval. Higher cetane fuels permit use in higher speed diesel engines.
CFPP	Cold Filter Plugging Point characterises the low temperature operability of fuel.
DME	Dimethyl ether
ETBE	Ethyl tertiary butyl ether
FAME	Fatty acid methyl ether
Flash pyrolysis	Also known as Fast Pyrolysis. Pyrolysis is the thermal degradation of carbonaceous materials at between $400^{\circ C}$ and $800^{\circ C}$ either in the complete absence of air or oxygen, or with such a limited supply that gasification does not occur to an appreciable extent. Also sometimes known as destructive distillation. The pyrolysis process always yields three products: a solid char, gases (such as, and including, carbon monoxide and methane) and vapours which can be condensed to form a liquid energy carrier. The yields of these products depend on the pyrolysis conditions (e.g. temperature, pressure, reaction time, catalyst).
FT	Fischer-Tropsch
Fungible	Interchangeable. Products which can be commingled for purposes of pipeline shipment
Gasification	Gasification is a process that converts carbonaceous materials such as coal, petroleum or biomass into a range of gases including carbon monoxide and hydrogen by reacting the raw material, such as wood or waste at high temperatures (800-$1300^{\circ C}$) with a

	controlled amount of oxygen and/or steam. The resulting gas is itself a fuel. Gasification is a method for extracting energy from many different types of organic materials.
GHG	Greenhouse gas
Hydrophilic	Miscible with water
Lignocellulose	A complex network of lignin, cellulose and hemicellulose found in plants
Lubricity	Lubricity describes the ability of a fluid to minimise friction between, and damage to, surfaces in relative motion under loaded conditions. Diesel fuel injection equipment relies somewhat on the lubricating properties of the fuel. Shortened life of engine components such as fuel injection pumps and unit injectors usually can be ascribed to a lack of fuel lubricity and hence is a concern to engine manufactures.
MOGD Process	A catalytic process whereby methanol is converted to a range of hydrocarbon products including diesel and petrol
MBTE	Methyl tertiary butyl ether
Octane Rating	The octane rating describes how much a fuel can be compressed in a spark ignition engine
Oxygenate	Fuel oxygenates are chemicals containing oxygen that are added to fuels, especially petrol, to make them burn more efficiently, typically reducing exhaust carbon monoxide levels. Adding oxygenates to petrol boosts the petrol's octane level and reduces atmospheric pollution associated with automobile emissions. Typical examples include MTBE, ETBE and ethanol.
Particulates	Free suspended solids
Refinery	A plant used to separate the various components present in crude oil and convert them into usable products or feedstock for other processes.
Saturated and unsaturated	Organic compounds such as vegetable oils typically contain of chains of carbon atoms joined together along with smaller numbers of other atoms such as oxygen and nitrogen. When linking carbon atoms together, each carbon atom must make four bonds to other atoms (e.g. another carbon atom, a hydrogen atom, an oxygen atom etc). Where four single bonds are made to four separate atoms, the bonds are said to be saturated. If a double (or triple) bond is made to a separate single atom, then the molecule is said to

	be unsaturated. The degree of unsaturation is a method of specifying the magnitude of double and triple bonds within a molecule. Many vegetable oils contain different fatty acid chains with one (monounsaturated) or more (polyunsaturated) double bonds in them.
Synthesis gas or syngas	A clean gas containing a mixture of carbon monoxide and hydrogen at a designed molar ratio. For the FT process, a H_2:CO ratio of 2:1 is typically required.
tpa	Metric tonnes per annum