Biofuels Review:

Advanced Technologies Overview

For the Renewable Fuels Agency

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E4tech

1. Lignocellulosic ethanol

1.1 Description

Lignocellulosic biomass (e.g. wood, straw, components of municipal solid waste etc), consists of a combination of lignin, cellulose and hemicellulose which provide the structural framework making up most plant matter. A wide variety of fuels could be derived from lignocellulosic material via the biological or chemical synthesis of products derived from the biological or chemical breakdown of cellulose, hemicellulose and lignin. To date, the focus has been on production of ethanol by these routes. However, there is also interest in producing other chemicals and fuel components via these routes.

Fermentation of sugars from sugar crops and from hydrolysis of starch crops to produce ethanol is a commercial and widely used process. Routes from lignocellulosic materials to ethanol are more complicated than those from sugar and starches, as lignocellulosic materials contain more complex sugar polymers, such as cellulose and hemicellulose, which are more difficult to break down chemically, together with lignin.

Processes being developed involve pre-treatment to separate the biomass into cellulose, hemicellulose and lignin (a process which generally also hydrolyses the hemicellulose to sugars) then hydrolysis of the cellulose to produce sugars. The cellulose hydrolysis stage can be carried out by chemical routes, such as acid hydrolysis, which is a well known process, or by biological routes, using enzymes, which are in development. The sugars derived from hemicellulose and cellulose are then fermented to ethanol using yeasts.

1.2 GHG savings from route

GHG emissions from lignocellulosic ethanol chains will vary depending on the feedstock and the particular technology used to produce the fuel. The well-to-tank GHG emissions from lignocellulosic ethanol projected for 2020 are estimated to be in the range of 15.9-19.9kgCO2e/GJ (depending on whether energy crops or residues are used), resulting in a 76-81% reduction in GHG emissions compared with gasoline[1].

1.3 Development status

The production of fuels from this type of biomass is currently under development, with a range of processes at the research, development, demonstration and pre-commercial stages.

Some aspects of the lignocellulosic ethanol production process are currently well developed. For example, steam explosion, dilute acid and alkaline hydrolysis are commonly used as a pre-treatment (separation) process, dilute acid hydrolysis is commonly used for the conversion of hemicellulose to sugars and concentrated or dilute acid hydrolysis is used for the conversion of cellulose to sugars.

However, there are a number of key areas for RD&D, including enzymatic hydrolysis, and fermentation of some of the sugar types produced. C6 fermentation to ethanol is an established and conventional process in which the yeast *Saccharomyces cerevisiae* is commonly used to facilitate the fermentation. However, fermentation of C5 sugars, such as xylose, is much more difficult and the yeast commonly used to ferment C6 sugars cannot ferment C5 sugars.

[1] Calculated from JRC/EUCAR/Concawe (2007)

There is also an R&D focus on Consolidated Bioprocessing (CBP), a process in which all the stages of conversion from cellulosic feedstock to ethanol can take place in a single vessel; the benefit of which is that the process can be made cheaper and quicker.

Although this is not yet a commercial route, large public and private RD&D efforts are being directed to lignocellulosic ethanol development, and rapid technical progress is being made. By 2015, further facilities are expected to have been built and early adopters' technology development to be complete.

1.4 Issues and challenges

The key challenge is to find more energy efficient and low cost processes to ethanol production, and possibly to producing other fuels and fuel additives.

One of the most promising technologies is considered to be enzymatic hydrolysis. This technology is currently more expensive than the other hydrolysis technologies, but is thought to have the greatest potential for cost reduction, to a level competitive with ethanol from other sources. The key to commercially viable processes is low cost cellulase production, an area which is believed to have significant potential for cost reduction.

The key areas of focus for research going forward are microbe development, scale up, process control and plant design. In terms of making the process work, a number of demonstration plants have been able to demonstrate the science. The imminent construction of the first commercial plants, will demonstrate whether these routes suitably perform at scale.

In the US there is strong political and financial support for the production of lignocellulosic ethanol from native non-food feedstocks such as corn stover and switchgrass. In other regions, including the EU, one could argue that there is a lack of a policy focus to encourage and incentivise the production of 2nd generation biofuels, in particular by rewarding their lower GHG intensity compared to other biofuels. The lack of a link between emissions savings and the level of financial support is not helping the progression of these technologies to commercialisation. There is also a high risk associated with the high capital cost of commercial scale plants which is hindering their financing, and support is needed to cover commercialisation costs.

There is also uncertainty around whether the best use of biomass resource is transport fuels or production of heat and power.

1.5 Key players and activities

There are few commercial plant developers currently. Most commercial activity is in the US, Canada, Spain and Scandinavia, (see below). However, there are also UK companies involved in this area.

- In the US, Mascoma Corporation is building the country's first cellulosic ethanol plant using switchgrass as a feedstock. Its 5m gallon/yr "biorefinery" is expected to be operational from 2009.
- Poet (previously Broin) is expect to begin construction on a lignocellulosic ethanol plant in Iowa in 2009 and begin operation in 2011.
- Canada's Iogen has plans for a commercial scale lignocellulosic ethanol plant, using enzymatic hydrolysis. They currently have a demonstration plant and are co-operating with Shell on development and commercialisation.
- Abengoa are constructing a 70ton/day lignocellulosic ethanol plant in Salamanca, Spain.
- Etek Etanolteknik AB have developed a pilot plant in Sweden

Plant developers may have their own enzymes (e.g. Arkenol) or may license these enzymes from their developers (e.g. Novozymes, Genencor, Roal). In the UK, TMO Biotech is developing a bacterium for fermentation of lignocellulose derived sugars.

1.6 Deployment prospects

The next couple of years are crucial for understanding the deployment prospects for this technology. If all goes well with the first-of-a-kind commercial plants in terms of the technology and scale up, and given the right policy support and market signals, lignocellulosic ethanol plants could potentially be being built at commercial scale (beyond first of a kind) by 2015-2018. However, it is not expected that the plants would be fully commercial by this stage; some financial support would still be likely to be needed as it is not envisaged that the costs could come down so significantly in this short period to make them cost competitive. The competitiveness of lignocellulosic ethanol plants is likely to rely on the availability of relatively low cost feedstocks.

Lignocellulosic ethanol plants are most likely to be built in North America, Europe and Australia, stimulated by policies aimed at deploying biofuels to reduce reliance on fossil fuels and reduce GHG emissions. There may also be a good case for this technology to be employed in countries like Brazil where there are large volumes of bagasse which could be used as feedstocks for lignocellulosic ethanol production. China may also be an early adopter of lignocellulosic ethanol technology.

2. Syndiesel or Biomass-to-Liquids (BTL)

2.1 Description

A range of liquid and gaseous transport fuels, such as synthetic diesel and gasoline, methanol, ethanol, dimethylether (DME), methane, and hydrogen can be produced from biomass using thermal processing routes. In these, biomass is gasified to produce a syngas, consisting mainly of carbon monoxide and hydrogen. The syngas is then reacted in a catalytic process (the Fischer-Tropsch process) under certain temperature and pressure conditions to produce one or more products. (Alternatively the syngas could be fermented to produce ethanol but the development of this alternative route is still at an early stage). The key feedstock ultimately being considered for this route is waste (agricultural wastes, waste wood residues and municipal solid waste) for economic reasons, but energy crops could also potentially be used as feedstocks for this process.

Gasification has been proven to work on a wide range of feedstocks. However, gasifiers and gasification systems are generally designed to operate with feedstocks with narrow physical and chemical property ranges. Generally, feedstocks with low ash content, low alkali metals and low levels of contaminants are preferred. Also, the quality of the syngas will be crucial to a reliable operation of a downstream equipment, which means that clean and homogeneous feedstocks will be preferred e.g. wood.

The quality of the fuels that can be obtained, the range of fuel products and co-products, and the potential for producing biofuels with low GHG intensity, make syngas-based systems particularly attractive. There is strong interest in developing this route, in Europe in particular.

2.2 GHG savings from route

GHG emissions from biofuels derived from gasification routes are likely to be very low in comparison with fossil-derived liquid fuels. For example, the well-to-tank GHG emissions for Fischer-Tropsch biodiesel projected for 2020 are estimated at around 2.9-6kgCO2e/GJ (depending on whether or not residues or energy crops are used as a feedstock), resulting in a 93-96% reduction in GHG emissions compared with diesel[2].

2.3 Development status

Biomass gasification technologies are commercially available, at different scales and with different designs. Similarly, syngas conversion technologies have been demonstrated at commercial scale for synthetic diesel and gasoline, methanol, ethanol, DME, methane and hydrogen. Synthetic fuels are produced commercially today mainly from natural gas or the gasification of coal e.g. Sasol plants in South Africa and Qatar. However, there is very limited commercial experience in integrating biomass gasification with downstream processes for the production of liquid or gaseous transport fuels. The only experience involves the gasification of mixed feedstocks, including biomass, at the Schwarze Pumpe plant in Germany for the production of methanol and in the Choren pilot plant.

Despite both biomass gasification and the Fischer-Tropsch process for fuel production from syngas being demonstrated technologies already used at scale, further R&D, and demonstration is needed to determine plant configurations that will be technically and economically viable using biomass.

A number of companies and research organisations are developing systems for the production of transport fuels from biomass-derived syngas, in Europe in particular.

2.4 Issues and challenges

Companies and research organisations are addressing a number of issues en route to the commercialisation of biomass-to-liquids systems, some key issues being: gasifier designs, syngas quality, product selectivity in chemical synthesis, process integration, and scale. Scale in particular may determine the type of gasification system used, which in turn may determine the share of different products produced (i.e. transport fuels, electricity and heat).

In particular, development will need to examine more closely:

- the choice of gasification technology (e.g. entrained flow vs fluidised bed) and its design to account for biomass feeding and syngas quality requirements
- gas cooling and cleaning technologies that meet the stringent downstream catalytic process requirements while reducing losses in thermal efficiency
- cost of oxygen plants
- design of downstream processes and optimisation of outputs based on considerations of process efficiency and product values – this will include catalyst development to produce the required products
- the ability of this route to accept mixed feedstocks or mixed waste
- the effectiveness of gas cleaning systems in reliably producing syngas of suitable quality for the FT process.

One key uncertainty is whether it will be possible to procure enough feedstock to feed a plant at the scale needed for the plant to be economically viable. With current technologies, it is expected that BTL plants will need to be very large in order to be economic. Therefore a challenge is whether this process can be made to work technically and economically at a smaller scale. This would enable

[2] Based on JRC/EUCAR/Concawe (2007) Well to tank report.

distributed production of syndiesel from waste biomass close to the location where it is produced, which is attractive in terms of reduced transport costs, etc.

As with lignocellulosic ethanol, there are no policy mechanisms in place to drive the development of this technology. Policies that would reward the low GHG intensity of this route could potentially help the technology enter the market.

2.5 Key players and activities

A number of companies have large scale gasification technologies including Conoco Phillips, Siemens, VTT, TPS, Choren, Lurgi, Shell, GE, Kellogg Brown and Root, Prenflo, Advantica BGL, Noell, Winkler and KRW. Not all of these companies are focusing on biomass feedstocks. The 5 year EU project Chrisgas is using a TPS gasifier based at Varnamo in Sweden; the focus of this project is the production of a clean hydrogen rich gas stream from biomass that would be suitable for synthetic fuel production.

Examples of companies focusing on the production of fuels from syngas are Sasol, JFE Holdings in Japan (slurry bed FT reactor producing DME), Fuel Frontiers Inc (ethanol from syngas) and Syntroleum (focus so far on CTL and GTL).

Few companies are seriously looking at the whole process of fuels from biomass. The key company working in this area is Choren. In partnership with Shell and Volkswagen, Choren is constructing a first-of-a-kind demonstration biomass-to-liquid plant in Germany at a scale of 15,000 tonnes of diesel per year. Choren has plans for five commercial scale sigma plants which will each have a capacity of 200,000 tonnes diesel per year. The first of these plants is expected to begin construction in 2011. Another key player in this area is the Canadian company Range Fuels, which is building a demonstration plant in the US that will produce ethanol from lignocellulosic material (wood, grasses, corn stover) via syngas, using a catalytic process. In addition to Choren, there are also other small projects at Gussing (Austria) and Karlsruhe (Germany).

2.6 Deployment prospects

With Choren's beta plant already under construction and its sigma plants in the planning, the first BTL plants are likely to be in Europe, and before 2020. There is also interest and technology development in the US and it would be feasible for BTL plants to be built in the US also before 2020, if the key technical barriers described above can be addressed.

As the BTL process will be tried at demonstration scale for the first time in the coming year or so, it is not yet known whether this process can be made to work economically at scale. However, many are optimistic about its prospects and significant amounts of private capital are being invested in this technology.

With the current policy environment not distinguishing between biofuels on their carbon intensity, and in the absence of other targeted support, it is not expected that there would be a large demand for second generation biodiesel in the coming years and that there would therefore only be a few of the plants built prior to 2020. If the first BTL plants are successful and policy in the US and EU is changed to significantly support the production and use of second generation biodiesel, the prospects could be more optimistic with perhaps 5 or 6 plants by 2020, and many more beyond that date if they can be made technically and economically feasible, in particular at smaller scales.

3. Hydrogenation routes

3.1 Description

Hydrogenated biodiesel routes do not easily fall into the categorisation here of either “first generation” or “second generation” biofuel. This process takes a vegetable oil feedstock and produces a higher quality product than first generation biodiesel which can be blended with fossil diesel at higher volumes.

The hydrogenation process would normally be integrated within an oil refinery to avoid having to construct a dedicated hydrogenation production unit. The process can be integrated with hydrotreaters, and make use of hydrogen, already used in a refinery to remove sulphur.

3.2 GHG savings from route

The GHG emissions savings from this route are similar to the emissions savings from conventional biodiesel production.

3.3 Development status

This process is in the early commercial stage of development and there are several companies with technologies that use this process. The company which is furthest on with this technology is probably Neste. The Neste NExBTL process has been producing 170,000t/yr at its Porvoo plant in Finland and has plans for other plants to come on stream in the near future. Other companies developing this process are still at the pilot/demonstration scale.

3.4 Issues and challenges

One of the most important issues is that like first generation biofuel, the production of this fuel is currently limited by the need for food based feedstocks (vegetable oils) which are becoming increasingly expensive with concerns about global food shortages.

To be economically viable hydrogenation needs to be closely coupled to a refinery operation. One of the components leading to high costs is the additional hydrogen stream that is needed, especially if not coupled to a refinery. If it is integrated with a refinery, the volume of conventional fuels that can be processed through the hydrotreater is also reduced.

Another challenge to hydrotreated biodiesel routes is that they do not have any greater GHG savings than conventional biofuels. Thus they would not be favoured by a policy which moved to linking biofuel support to the GHG intensity of the fuel.

3.5 Key players and activities

There are several companies either already producing or about to start producing hydrotreated biodiesel for sale commercially. The key companies are:

- Neste oil – NExBTL process is a refinery integrated process currently operating at the Porvoo refinery in Finland
- Petrobras – In the H-BIO process, the vegetable oil stream is blended with mineral diesel fractions and hydrotreated in integrated units that are usually used for sulphur content reduction.
- Conoco Phillips – Has a stand-alone system at a small refinery in Cork, Ireland, which has been producing 150,000 litres/day of biodiesel from soybean oil since 2006.

- UOP – Has developed a hydroprocessing technology (‘Ecofining process’) which will be incorporated into a plant to be built by ENI. It is expected to come online in 2009 and will produce 650 bpd biodiesel.

3.6 Deployment prospects

With demand for biodiesel set to continue, processes which produce a superior diesel product and which can be blended at higher levels and at similar cost are likely to be attractive. However, this product is still dependent on vegetable oils as feedstock and therefore is not as attractive as those second generation biofuels which can be produced from wastes and residues.

4. Pyrolysis to transport fuels

4.1 Description

Fast pyrolysis is a process in which the biomass is rapidly heated in the absence of oxygen to produce a gas, char and organic vapours. When the gas is cooled it forms a low quality but energy dense liquid called a bio- or pyrolysis-oil. However, commercial fast pyrolysis reactors can produce a stable transportable oil from biomass, provided that the char can be adequately removed from the oil. This pyrolysis oil is not suitable for use as a transport fuel as it is acidic and contains water and oxygen. Pyrolysis could potentially operate on a wide range of feedstocks, depending on the pyrolysis reactor design.

There is currently interest in upgrading this oil so that it can be integrated into a conventional oil refinery. There is also interest in the development of a catalytic pyrolysis route in which a transport fuel can be made directly from an improved pyrolysis process.

4.2 GHG savings from route

As this process is at an early stage and there is no agreed upon process by which transport fuels would be produced using a pyrolysis process, it is not possible to estimate the GHG savings from this route. However, the carbon intensity of the fuel will depend on the carbon intensity of the feedstock production and of hydrogen production and consumption, if a hydrotreating process is used.

4.3 Development status

Biomass pyrolysis itself is at the early commercial stage, with few relatively small scale plants operating. There are still some challenges for improving the pyrolysis technology, which are listed in the next section. The production of transport fuels through a pyrolysis process is still at the R&D stage.

4.4 Issues and challenges

There are several key areas for improvement of this technology:

- Reactor design – different designs are being pursued by different developers.
- Oil quality improvement – reducing suspended chars, alkali metals, water and viscosity, increasing pH and improving oil yield.
- Optimisation of process relative to feedstock used.

4.5 Key players and activities

There is interest in this route from a range of different players. The main industries involved are pyrolysis reactor developers (e.g. Dynamotive, Ensyn and BTG), catalyst developers and petrochemical companies. There is also significant interest from the academic community.

UOP, Shell, Arkema, Albermarle, Sasol and Sabic are all involved in US DoE and EU funded projects in this area. ConocoPhillips is also working with ADM and the University of Iowa on fast pyrolysis and oil upgrading.

4.6 Deployment prospects

Given that the production of transport fuels using the pyrolysis process is still at the R&D stage and that there are still significant improvements and developments required, it is not expected that this route would have significant penetration in the global biofuel mix by 2020. There could be demonstration/early commercial plants before this stage, but these would be likely to be first-of-a-kind plants.

5. Other advanced biofuel technologies

A number of other advanced biofuel technologies are also the subject of research and interest, for example biobutanol and algal biofuels. They are only discussed briefly here as they are not expected to have significant contributions to the biofuel mix by 2020.

5.1 Biobutanol

Biobutanol is an alternative to ethanol with 30% higher energy density and which can be produced via a number of routes. It can be produced biologically (i.e. using enzymes) from sugar and starch crops, (e.g. corn, wheat, sugarcane and sugarbeet) using the ABE (Acetone Butanol Ethanol) process, and other more novel routes which use different bacteria and enzymes. Some developers currently working on biobutanol also claim that the process will be able to use lignocellulosic feedstocks in the future.

There are several companies working on this route, for example, Green Biologics in the UK, Dupont and British Sugar and also Virgin Fuels. As the majority of work on biobutanol is being conducted behind closed doors it is difficult to know how close to a commercially scalable process these companies are. DuPont have said their technology will be commercially proven in the UK. This will be using first generation feedstocks such as sugarbeet and wheat. A commercially viable process for producing biobutanol is not available today. If this were found, biobutanol could be produced instead of ethanol. Similarly to ethanol its application to lignocellulosic feedstocks could significantly expand production.

5.2 Algal biofuels

Microalgae produce chemicals and substances that have a number of uses, including the production of transport fuels. The use of high oil yielding micro-algae as a feedstock for biodiesel production has the potential for efficient land and resource use, as the ponds or reactors in which they are grown can be sited on unproductive land.

The production of biofuels from algae has been looked at in some depth over the past 50 years by, in particular, the US and Japan. However, the US and Japanese programs were discontinued without researchers reaching the ultimate goal of cost effective production of algal biofuels. However, with the increasing cost of conventional fossil fuels, concern about using edible feedstocks for biofuel production and the development of more sophisticated tools for manipulating the algae, a renewed interest in this area has been observed.

This is potentially a promising area. Given the right conditions (temperature, light, sufficient space) and if robust high oil yielding microalgae can be developed, there is potential for these challenges to be overcome.

There are a large number of companies starting up in this area which quote high yields for algal oil production and who release press statements saying that they will be producing large quantities of algal biodiesel in the coming months or years. None of these companies have yet produced algal biofuels at scale and none have produced evidence of the GHG intensity of their fuel. We believe that whilst this is potentially a promising technology, there is still much to be done in terms of basic R&D and also understanding and improving the GHG intensity of the process.

6. "New crops" for first generation technologies – Jatropha, cassava, sorghum

There are crops which are not currently widely used for biofuel production or which are not commercially grown but which could potentially be attractive feedstocks for first generation fuels. These include jatropha for biodiesel and cassava and sorghum for bioethanol. They are potentially interesting as first generation biofuel feedstocks as the GHG intensity of the biofuel route in which they would be used is expected to be lower than other conventional crops. However, this is an assertion which would need to be investigated further.

Cassava and sorghum are currently grown on a significant scale worldwide; 18.5Mha cassava and 41Mha of sorghum was grown in 2006. To date cassava and sorghum have not been used as primary feedstocks for first generation ethanol production, however some countries and companies are starting to look at these crops as having significant potential as biofuel feedstocks as they can perhaps be grown on lower quality land with high yields.

The average yield for cassava globally is 12.2t/ha [3] but some countries, e.g. India, quote average yields to be as high as 31t/ha. As a tropical plant, it can be grown in warm and humid climate, typically where rainfall is relatively abundant. Significant volumes of cassava are grown in particular in Thailand, Nigeria, Indonesia, Mozambique and Brazil. The cassava root is rich in starch and its attraction for biofuels is the high yields that can be achieved. China, Nigeria, Brazil and Thailand are all interested in expanding cassava production for fuel ethanol.

Native to Africa, sorghum is drought and heat tolerant, making it a particularly important crop in arid areas. Its average yield is much lower than for cassava, at 1.4t/ha[4]. The reason why the yield of sorghum may seem so low is that in the countries in which sorghum is grown in the largest quantities, including Sudan, Nigeria and India, it is not produced in commercial operations. Yields could be improved through better management and higher rates of fertiliser application. Additionally, there has been an increasing interest into looking into the genetic transformation of sorghum. Whilst there are no transgenic crops under cultivation to date, the genetic mapping of sorghum is underway, and this should provide the sorghum science community with tools for improving sorghum yields. Additionally, some researchers in the US are interested in fast growing varieties of sorghum that produce large amounts of biomass (or stover) so that this can be harvested for lignocellulosic biofuel production and the grain can be retained for other uses.

[3] FAO Stat (2006)

[4] FAO Stat (2006)

Jatropha curcas is a non-food crop, the seeds of which can be crushed to produce a toxic, inedible vegetable oil. It can be grown on semi-arid lands in warm and humid climates. In the past, the crop has been grown for soap and candles and also as a medicine. India is particularly interested in growing jatropha for fuel production and has ambitious plans to convert more than 11Mha of wasteland to growing jatropha. India has a national policy which does not allow edible oils to be used as fuel. Other regions in which it could be grown include Southern Africa, South East Asia and Latin America.

There are also other crops which are not grown extensively at present but which are being investigated as potential new feedstocks, e.g. *Camelina sativa*. Camelina is native to Northern Europe and Central Asia and currently has an oil yield similar to rapeseed. However, it has not been grown commercially for at least 50 years and consequently there has been little focus on improving yields. It is therefore expected that yields could be improved significantly. Camelina has low requirements for tillage and weed control. However, the fact that it has not been grown commercially to date means that it is unproven so far as a reliable feedstock for biodiesel production.

Table 1: Advanced Biofuel Technologies Overview (Source: E4tech)

	Description of process	GHG savings	Development status	Issues and challenges	Deployment prospects
Lignocellulosic ethanol	Hydrolysis of lignocellulosic plant matter to fermentable sugars, followed by fermentation to ethanol	76-81% reduction compared with gasoline[5]. Will vary depending on feedstock and technology.	Component processes at different stages of development. Steam explosion, acid/alkaline hydrolysis for pre-treatment well developed. Enzymatic hydrolysis and C5 sugar fermentation at the R&D-early demo stages.	Low cost enzyme production. Development of robust microbes. Demonstration of processes at scale, process control, plant design. Potential for integration of process with production of other fuels and fuel additives.	First of a kind commercial plants currently being built. Success with these likely to lead to construction of further plants before 2020. Continued financial support likely to be needed to 2020 as cost unlikely to fall enough to make the route cost competitive in this time period.
Syndiesel (BTL)	Gasification of biomass to a syngas consisting mainly of CO and H2. The syngas is reacted in a catalytic (FT) process at specified temperature and pressure to produce a range of liquid and gaseous transport fuels.	93-96% reduction compared with diesel[5]. Savings will vary depending on feedstock used (e.g. residues or energy crops).	Gasification technologies commercially available. Syngas conversion technologies (mainly from natural gas or coal) demonstrated at commercial scale. Little commercial experience of integrating biomass gasification with FT process.	Key issues relate to gasifier design, syngas quality, product selectivity in chemical synthesis, process integration and scale. Further RD&D needed to determine plant configurations that will be technically and economically viable using biomass. Sourcing enough biomass to supply demands of plants at viable scale may be a challenge.	Demonstration plants already under construction, with significant amounts of private capital being invested. First full scale plants could be built before 2020 in Europe.
Hydrogenation	Hydrogenation of vegetable oils to produce a fuel product similar to diesel.	Savings similar to those from conventional diesel production	Early commercial – several companies use this process, e.g. Neste.	This process is currently limited by the need for food based feedstocks and the fact that the GHG emissions savings are not any greater than for conventional 1G biodiesel. For economic reasons the route will probably need to be coupled to a refinery process.	Attractive as it produces a superior product that can be blended at higher levels at similar cost. However, this process still uses vegetable oils as feedstock making it less attractive than 2G biofuels which can be produced from wastes and residues.
Pyrolysis to transport fuels	Rapid heating of biomass in the absence of oxygen to produce a char, gas and organic vapours. Cooled gas forms an oil which can be upgraded and integrated into a conventional oil refinery.	Not possible to estimate as no agreed upon process by which transport fuels would be produced. GHG intensity will depend on feedstock and whether hydrotreating is part of the chosen process.	Biomass pyrolysis at the early commercial stage with relatively few small scale commercial plants in operation. The production of transport fuels through a pyrolysis process is still at the R&D stage.	Key issues include reactor design, oil quality improvement (reducing suspended chars, alkali metals, water and viscosity, increasing pH and improving oil yield), and optimisation of process relative to feedstock used.	Given this process is still at R&D stage with significant improvements and developments still needed, it is not expected that this route would have significant penetration in the global fuel mix by 2020. There may be some demo/early commercial plants under development by this stage.
Butanol	Fermentation of sugars from biomass to butanol. 30% higher energy content than ethanol.	GHG savings likely to be similar to ethanol.	Several companies working on this route, although unclear how close to a commercial process these companies are.	Key challenges relate to optimising the butanol yield, concentration and rate of process and the separation and purification process.	Those currently developing routes from sugar and starch feedstocks used in 1G plants anticipate their processes should be ready in 2010.
Algae	Culture of oil containing micro-algae, followed by harvesting of the oil and esterification to biodiesel.	GHG are unknown as there is no single agreed upon route; process is still very much at the R&D stage.	Route still at R&D stage. Although many companies claim they are nearing commercialisation there is little evidence of this so far.	Key challenges relate to developing micro-algae with high oil yields and economically culturing algae at large scales.	Given that micro-algal biofuels are still very much at the early R&D stage, it is not anticipated that this route will be commercial before 2020.
Non food 1G feedstocks	E.g. Jatropha	Emissions from route assumed to be similar to palm oil.	In the past the crop has been used for soap, candles and medicine.	Jatropha has not been grown on a large scale and it is not known yet whether the high yields quoted can be achieved.	India plans to convert >11Mha of wasteland to grow jatropha. Other likely regions are Southern Africa, SE Asia and Latin America.

[5] Calculated using JRC/EUCAR/Concawe (2007)