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# **Advanced Biofuel Demonstration Competition Feasibility Study**

## **Annex 1: Technology status update**

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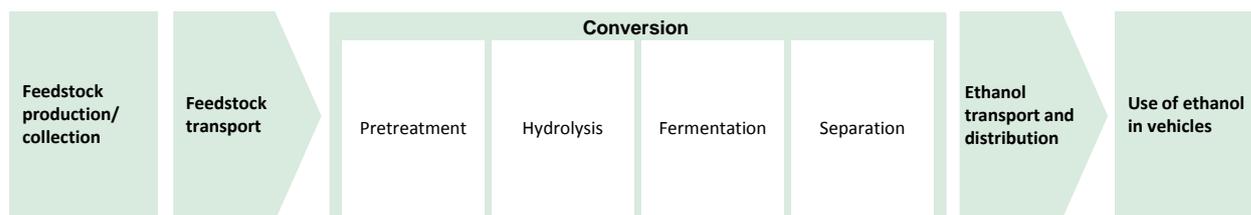
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## 1. Lignocellulosic Ethanol

### 1.1. Technology description

This route involves converting lignocellulosic feedstocks, such as energy crops, residues or wastes, into ethanol. Pre-treatment and hydrolysis are used to break down the feedstock into sugars, which are then fermented to produce ethanol, as shown in the process schematic below. Research on consolidated routes that combine pre-treatment, hydrolysis and/or fermentation in a single step is ongoing.



**Figure 1: Process schematic for lignocellulosic ethanol production**

### 1.2. Feedstocks

In principle, any lignocellulosic material can be used as an input, including dedicated energy crops, agricultural residues and wood residues, and wastes. Most of the demonstration plants are currently focusing on 'soft' feedstocks such as corn cobs, corn stover, and wheat straw, with others using wood waste, woodchips and sugarcane bagasse (Bacovsky, 2013). Operating and planned early commercial plants are also planning to use energy crops, switch grass, agricultural and forestry residues.

In addition the following feedstocks have been mentioned for testing in future plants: paper fibres, Municipal Solid Waste (MSW), vegetative waste, pulpwood, Citrus, oak, pine, and pallet wood waste, husks and recycled waste (Bacovsky, 2013; Sheridan, 2013).

The most suitable and available feedstocks in the UK are likely to be straw, waste wood, forestry residues, MSW and to a smaller extent energy crops (in the 2020 timeframe).

### 1.3. Current technology status

Lignocellulosic ethanol plants as a whole are at the large demonstration stage (TRL7), with the Beta Renewables plant becoming operational in 2013, and several others under construction (Table 1). The pre-treatment processes nearing commercialisation currently use homogeneous rather than mixed feedstocks. Enzymatic hydrolysis is being used in these demonstration scale plants. There are around 6-7 small scale demonstration plants currently operational in Europe with capacities of 1-6 million litres per year (ML/yr) and 2-3 pilot plants. The US has a similar number of demonstration plants of the same scale, but at a more advanced stage of development, with four plants under construction (US Department of Energy, 2013).

### 1.4. Outputs (fuels, current & potential)

Current focus is on ethanol production, but some players such as Zechem could produce jet fuel, diesel, gasoline and chemical products in their biorefinery.

### 1.5. Key actors and activities

The UK does not currently have any lignocellulosic ethanol demonstration or commercial plants based on biological routes under development. TMO Renewables operated a pilot plant in the UK from 2008 until recently, when the company entered receivership. The unit was designed to demonstrate the hydrolysis and fermentation of a range of feedstocks, and was developed at a cost of £7.8M. A few actors are working on specific technology aspects or as project developers (Table 2), besides these, the UK has engineering contractors with experience in ethanol plant design and construction.

In Europe, key actors are Abengoa, Beta Renewables, SEKAB, Clariant and Inbicon (Bacovsky, 2013). Abengoa is operating two small demonstration plants in Spain and a large demonstration plant with a capacity of 50 ML/yr is coming online in France by the end of 2013, partially funded by the EU. The most advanced player in Europe is Beta Renewables with a large demonstration plant of 50 ML/yr in operation in Italy since mid-2013. SEKAB is running a very small pilot plant in Sweden since 2004 and aims to open a 60 ML/yr facility in Poland in 2014 at an investment cost of £144M. Clariant is running a small demonstration plant in Germany, and plans to build 60-180 ML/yr plants from 2014 onwards. In Denmark, Inbicon have operated a demonstration plant since 2009 and are conducting a feasibility study for a biorefinery with a 73 ML/yr ethanol output to be operational in 2016 (Maabjerg Energy Concept, 2013).

The US has a similar number of key actors; among them are Abengoa, Bluefire, Beta Renewables, Zechem, Fiberight, Poet-DSM, Mascoma and Dupont (Sheridan, 2013; BlueFire Renewables, 2013; Advanced Ethanol Council, 2013). Iogen are also active in Canada. Several actors have plants under development or construction due to come online in 2014: Abengoa is constructing a 95 ML/yr plant in Kansas, Bluefire is constructing a 72 ML/yr plant in Mississippi, and POET-DSM is constructing a 75 ML/yr plant in Iowa. The largest project under development is a 113 ML/yr plant in Iowa by DuPont due to become operational in late 2014 (Sheridan, 2013). At an earlier stage are Zechem who have a 95 ML/yr biorefinery in development in Oregon, and Mascoma who was aiming to construct a 75 ML/yr consolidated-bioprocessing plant in Michigan, although Valero has recently left their joint venture. Fiberight's 23 ML/yr demonstration is operational, however, their UK fermentation technology supplier, TMO, is no longer in business.

In Brazil, one of the key actors is GranBio which plans to bring a 90 ML/yr plant into operation in 2014 based on Beta Renewables technology (Bacovsky, 2013). Collaborations between European, US and Brazilian companies include Raizen Energia S/A a JV of Shell and Cosan (Shell is contributing Iogen's fermentation technology and Codexis' enzyme knowledge) (Ethanol Producer, n.d.), and Novozymes who plan to operate a commercial scale ethanol plant by late 2014 (Novozymes, 2013). Inbicon are also partnering with ETH to build a plant by 2015 (D Glass Associates, n.d.), and Usina Maria Ltda had formed a JV with TMO Renewables to develop a pilot plant in Brazil co-located with an existing sugar cane ethanol facility, however the future of this plan is now uncertain.

**Table 1: Operational and planned full demonstration and commercial scale plants for lignocellulosic ethanol production**

Company	Scale M litres	Status	Region	Start-up date
Beta Renewables	50	Operational	Italy	2013
Fiberight	23	Operational	USA	2013
Abengoa	50	Under construction	France	2014
Abengoa	95	Under construction	USA	2014
BlueFire	72	Under construction	USA	2014
POET- DSM	75	Under construction	USA	2014
GranBio	90	Under construction	Brazil	2014
Clariant	TBC	Planned	Europe	TBC
SEKAB	60	Planned	Poland	2014
Dupont	113	Planned	USA	2014
Beta Renewables	75	Planned	USA	2014
Inbicon	38	Planned	USA	2015
Mascoma	75	Planned	USA	2014
Zechem	95	Planned	USA	2014
Raizen Energia	TBC	Planned	Brazil	2014
Usina Maria	TBC	Planned	Brazil	2014
Inbicon	73	Feasibility study	Denmark	2016
Futurol	180	Feasibility study	France	2016

Sources: (Bacovsky, 2013; BlueFire Renewables, 2013; Futurol, 2010; Maabjerg Energy Concept, 2013; US Department of Energy, 2013)

**Table 2: Key actors in the UK**

Company	
WhiteFox	Developing novel membrane technology
Scarab	Project developer in waste-to-ethanol in the UK
BP Biofuels	BP is currently operating a demonstration plant in Louisiana, US but has stopped plans to develop a commercial scale plant in Florida (Smart Planet, 2013). BP acquired Verenium's technology in 2010, and has an R&D facility in San Diego, US.

### 1.6. Further needs for commercialisation and potential in the UK

The key to achieving full commercialisation in the next few years lies in the successful commissioning and operation of the full demonstration plants currently under construction; development and demonstration of improved pre-treatment technologies to enable higher conversion efficiencies and maximise co-product revenues (or their onsite use); and optimisation of hydrolysis and fermentation techniques for C5 sugars. Further work is also required on cost reduction and successful integration of pre-treatment, hydrolysis and fermentation steps (avoiding contamination/inhibition, whilst still achieving high yields and productivity).

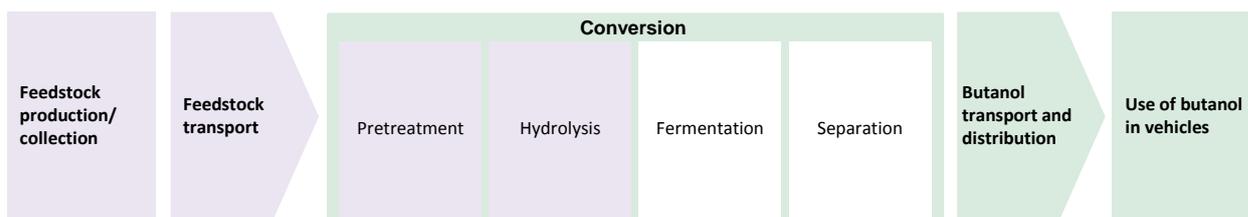
The first full demonstration plant came online in 2013 with several others expected to follow in 2014. The majority of European plants plan to use wheat straw as either the sole feedstock

or along with other agricultural residues. The opportunity to transfer the technology to the UK following successful demonstration elsewhere in Europe is therefore seen to be strong. As a consequence of demonstration activities elsewhere, lignocellulosic ethanol plants may be operational in the UK by 2020, provided the right conditions for investment are established. This is not to say that this technology should be excluded from the competition, since the UK has research strengths in fermentation technologies, and there are a number of technologies at earlier stages of development. There may be value in supporting the development of earlier technologies, in particular those based on UK IP and capable of realising efficiency improvements or reduced production costs.

## 2. Lignocellulosic Butanol

### 2.1. Technology description

This route involves converting lignocellulosic feedstocks, such as energy crops, residues or wastes, into butanol. Pre-treatment and hydrolysis are used to break down the feedstock into sugars, which are then fermented to produce butanol, as shown in the process schematic below.



**Figure 2: Process schematic for lignocellulosic butanol production**

The steps shown in purple are the same as for the process for lignocellulosic ethanol production. The remaining steps are similar to the processes for “1G” butanol production from sugars, derived from sugar or starch crops. However, there is research on consolidated routes to butanol that combine pre-treatment, hydrolysis and fermentation in a single step, as is being done for lignocellulosic ethanol.

### 2.2. Feedstocks

Current butanol research is focused on first generation sugar and starch feedstocks, in particular corn starch. However, potentially all lignocellulosic feedstocks can be used -the Alpena Biorefinery plant is demonstrating the use of wood and GreenBiologics are testing cellulosic biomass feedstocks.

Feedstocks that may be applicable to the UK include straw, wood waste, and forestry residues, MSW and to a smaller extent energy crops (in the 2020 timeframe).

### 2.3. Current technology status

As for lignocellulosic ethanol, some pre-treatment processes are still at the early R&D stage whereas others are nearing commercialisation. Enzymatic hydrolysis is being used in demonstration scale plants for ethanol production and may be used for butanol production. Fermentation of C5 and C6 sugars to butanol is commercial using the Acetone-Butanol-Ethanol (ABE) process (TRL8-9), although the process yields are typically found to be

uneconomic for fuel production. Other fermentation pathways for producing only butanol are at the demonstration stage (TRL5-6).

Most developers are currently focusing on demonstrating butanol production based on sugar and starch feedstocks, with an aim to move to lignocellulosic feedstocks in the longer term, using technologies developed and demonstrated for lignocellulosic ethanol. For example, Gevo have licensed organisms from Cargill that would allow them to use lignocellulosic feedstocks.

#### 2.4. Outputs (fuels, current & potential)

Butanol can be used blended with petrol for road transport, and may also be used in the chemical industry. There is also research into the conversion of butanol into drop-in diesel, gasoline and jet fuels. Outputs will likely be used in the highest value market.

#### 2.5. Key actors and activities

American Process Inc., Cobalt biofuels and GreenBiologics (a UK company based in Oxford), are currently the three key actors developing lignocellulosic butanol plants (Table 3). American Process Inc. in cooperation with Cobalt Biofuels started operating the 4 ML/yr Alpina bionrefinery small demonstration facility in Michigan, USA in 2013 using wood-based sugars (Alpena Biorefinery, 2013). Cobalt Biofuels and other partners plan to build a pilot plant to convert switchgrass into butanol (European Biofuels Technology Platform, 2013). GreenBiologics operate a small pilot plant in Iowa using corn mash, and have produced n-butanol in a trial run at demonstration scale (3.2 ML) from lignocellulosic feedstocks such as corn husks, cobs and stover in China in 2012 (GreenBiologics, 2013).

Gevo and Butamax, a JV between Dupont and BP, are developing butanol plants, based on sugar and cereal feedstocks. Gevo own and operate a full demonstration plant in Minnesota, US. After several months shut-down, the plant aimed to resume production and reach full capacity of 70 ML/yr by the end of 2013 (Doom, 2013). Butamax entered into an agreement with Highwater Ethanol LCC in October 2013 to retrofit their ethanol plant to butanol (European Biofuels Technology Platform, 2013).

Both Gevo and Butamax intend to build butanol plants that will use lignocellulosic feedstocks in the future. Several other actors are working on butanol as well, but do not indicate if they intend to use lignocellulosic feedstocks.

The UK has two notable industrial actors developing technologies relevant to lignocellulosic butanol production - namely GreenBiologics and BP, who partially owns Butamax.

**Table 3: Operational and planned plants for lignocellulosic butanol production**

Company	Scale M litres	Status	Region	Start-up date
American Process Inc.	4	Operational	Michigan, USA	2013
GreenBiologics	0.04	Operational	Ohio, USA	2013
Cobalt	Pilot	Planned	TBC	TBC

Sources: (Alpena Biorefinery, 2013; BiofuelsDigest, 2012; GreenBiologics, 2013; European Biofuels Technology Platform, 2013)

## 2.6. Further needs for commercialisation and potential in the UK

The development needs to reach commercialisation for lignocellulosic butanol are very similar to lignocellulosic ethanol plants. A particular focus needs to be on the optimisation of pre-treatment, hydrolysis and fermentation techniques as well as their integration into a single step.

Lignocellulosic butanol plants are currently at the pilot stage and small scale demonstration stage. If current development activities are successful and if further learning from lignocellulosic ethanol development is applied, it is possible that the commercial development of lignocellulosic butanol may follow that of ethanol with a delay of approximately 3 years, in which case commercial plants could be operating in 2020. The UK has world leading capabilities in butanol production, but it is worth noting that technology developers are not necessarily focused on demonstrating the technology in the UK.

## 3. Gasification + catalytic synthesis

This chapter groups together gasification technologies with five different downstream catalytic synthesis steps. The five different catalytic synthesis steps are:

- Fischer-Tropsch (FT) synthesis to produce FT diesel, FT jet and naphtha
- Dimethyl ether (bioDME) synthesis
- methane synthesis to produce bio-Synthetic Natural Gas (bio-SNG)
- Mixed alcohols synthesis to produce methanol, ethanol, butanol and higher alcohols
- Methanol synthesis

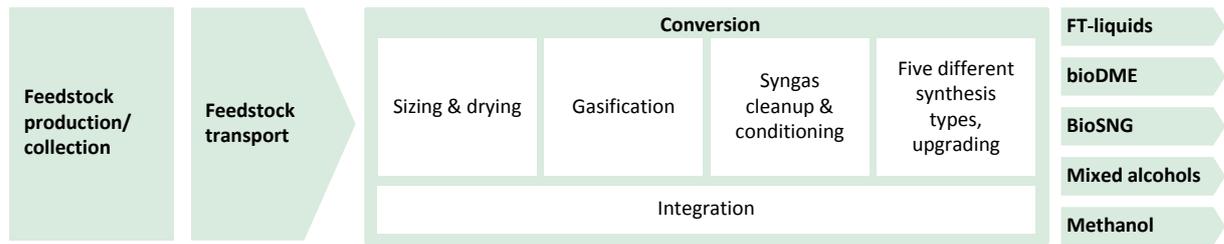
The differences in development status and various plant developments between the five synthesis routes are explained within this chapter.

### 3.1. Technology description

These five gasification routes involve thermo-chemically converting lignocellulosic feedstocks, such as energy crops, residues or wastes, into syngas. Cleaned and conditioned syngas is then catalytically converted into different liquid or gaseous fuels depending on the catalytic synthesis process as shown in **Error! Reference source not found.**:

- FT-Synthesis: FT-liquids get upgraded into petrol, diesel or jet fuel
- Dimethyl ether synthesis: bioDME
- Methane synthesis: bioSNG
- Mixed alcohol synthesis: Mixed alcohols
- Methanol synthesis: Methanol

Some catalytic syntheses have different valuable by-products such as naphtha, heat and power.



**Figure 3: Generic process schematic for gasification with five catalytic synthesis types**

Given the downstream demands for all five synthesis types, and multiple gas clean-up steps, the avoidance of nitrogen in the syngas is required, and operating at elevated system pressures is also advantageous. The gasifiers chosen are therefore most likely to be oxygen or steam blown, pressurised fluidised bed gasifiers (i.e. bubbling, circulating and dual fluidised bed gasifiers), or entrained flow gasifiers (which are all oxygen-blown at pressure). These have the ability to achieve very large scales, and meet the minimum economic scale of downstream catalytic synthesis. The suitable gasifier types, cleaning & conditioning steps and syngas requirements are very similar between the five different synthesis types, with only some differences in optimal syngas H<sub>2</sub> to CO ratios, catalyst materials used and catalysis conditions required.

### 3.2. Feedstocks

Gasification can use a wide variety of feedstocks, but the feedstock requirements in terms of size, moisture and ash content are determined by each gasifier type. The wide range of possible feedstocks is particularly attractive to the UK due to the possibility to use wastes such as MSW.

Forestry is the primary feedstock proposed for use in both of the planned commercial FT projects in Europe, possibly with a small amount of tall oil. Current pilot plants in the US are using forest residues, corn stover and bagasse (Bacovsky, 2013). The Solena project in London plans to use MSW. Woody biomass (whether imported or domestic), MSW and C&I wastes are available in large volumes and would be suitable for a UK plant.

### 3.3. Current technology status

Combined biomass gasification and catalytic synthesis routes are currently at the pilot to early demonstration stage (TRL 5-6). Many of the plant components are nearing commercial availability in other applications, e.g. biomass chipping and drying, syngas clean-up, plus FT and methanol synthesis reactors for coal syngas. However, some processes are only at pilot scale, such as pressurised oxygen-blown biomass gasification, novel hot gas clean-up, mixed alcohol synthesis, and micro-channel fuel synthesis reactors. Plant integration experience is in line with the overall route (TRL 5-6).

There are some specific differences between the five synthesis types with regards their level of technology development and level of scale-up required:

- **FT-synthesis:** In Europe, there are 2 full-scale demonstration plants planned and awarded funding under NER300 (Vapo Forest BTL and UPM Stracel), another similar project on the NER300 reserve list (UPM Rauma), a 5 ML/yr small demonstration plant planned for 2017, and a handful of pilot plants under 1 million litres (European Biofuels Technology Platform, 2013a) (ifP Energies Nouvelles, 2013). These full scale

demonstration plants (135-150 ML/yr) are approaching commercial scale, but the plants in operation today require scale up of at least 30 times to reach full commercial scale (around 130 ML/yr). In the US, around four pilot plants are currently operating, but only intermittently and at scales up to 1 ML/yr. There is another pilot under construction and another planned (Bacovsky, 2013; US Department of Energy, 2013), along with the proposed Fulcrum Bioenergy plant (Sierra Biofuels) which awaits funding.

- **bioSNG synthesis:** Both gasification and methanation involve mature technologies, already used at large scale for fossil fuel feedstocks. Methanation has been intensively investigated in the past, in particular methane production from coal. However, to date, only two designs of Dual gasifier have been developed in combination with downstream methanation: a Austro-Swiss consortium led by REPOTEC & CTU, and ECN. These developers have each been working on bioSNG for about ten years, with pilot plants operating in Austria and the Netherlands. A small demonstration plant (20MW) is under construction in Gothenburg (GoBiGas), and the Phase 2 expansion (to produce 100MW) has NER300 funding. To reach commercial scale from today's demonstration plant, a scale up by at least a factor of 5 will be required. E.ON have future plans for building 200MW commercial bioSNG plants in Scandinavia, but timelines are currently unclear – their Swedish Bio2G project is on the NER300 reserve list.
- **Methanol synthesis:** BioMCN already has a first-of-a-kind commercial plant (TRL8) in the Netherlands, cracking crude glycerine to syngas, and synthesis of methanol at 250 ML/yr – this is the largest advanced biofuel plant in the world. However, this is a significantly easier and cheaper process than the gasification of solid feedstocks, and whilst the operational experience with cleaning bio-derived syngas and methanol catalysis can be utilised, the crucial gasification step is still missing. However, BioMCN plans to build a 250 ML/yr commercial scale plant using wood feedstocks (the Woodspirit project), which was recently awarded NER300 funding. Uhde also have their 130 ML/yr Värmlandsmetanol project in planning, looking to use forestry feedstocks.
- **bioDME synthesis:** The overall TRL level of DME is only 5, since Chemrec's pilot plant in Sweden has not yet led onto any further development of their demonstration project. Significant scale-up of at least 30 times will be required to reach full commercial scale.
- **Mixed alcohol synthesis:** The synthesis step is only at the pilot stage, and the Range Fuels demonstration plant in the US only managed to produce methanol before shutting down. Only pilot plants are currently operating and a scale-up factor of around 7 is required to reach commercial scale. However, Enerkem's Edmonton plant (38 ML/yr) is under construction, and other North America developers also have proposed plants at near full commercial scale. There is no European activity in this area.

In the last few years, several leading gasification to biofuel projects such as Choren in Germany, NSE Biofuels in Finland and RangeFuels in the US have stopped operations, with closure of companies and shelving of plans. Some of the technology developed has been taken over – Choren’s gasifier was bought by Linde, and Range Fuel’s Soperton plant was bought by Lanzatech (Bacovsky, 2013).

### 3.4. Outputs (fuels, current & potential)

- FT-Diesel and Naphtha (normal ratio 80:20)
- Bio-DME
- Bio-SNG
- Mixed alcohols
- Methanol

### 3.5. Key actors and activities

Current key actors in Europe and the US depend on the synthesis type, and gasifier design. In Europe these are UPM, Vapo, Solena, Velocys, Johnson Matthey, Uhde, Solena, REPOTEC & CTU, Goeteborg Energi, E.ON, ECN, Chemrec and BioMCN. Key actors in North America are Enerkem and Haldor Topsoe. Activities in North America are almost exclusively limited to mixed alcohol and FT synthesis, with little interest in the synthesis of methanol, bio-SNG or bio-DME (Sundrop are only considering methanol as a route to gasoline).

The UK does not have any actors with large-scale gasifier technologies, but Velocys (previously Oxford Catalysts) and Johnson Matthey are considered two of the key players in catalysis, particularly FT, (see Table 5: Operational and planned plants for gasification and catalytic synthesis). In addition the UK has other existing industrial FT capability e.g. BP and UOP. Solena were aiming to have their wastes to FT jet plant in London operational by 2015 (BiofuelsDigest, 2012a), using Velocys FT technology, although this project is still in planning. Solena also have several other FT jet projects in planning, including cooperation agreements in Sweden (SAS), Italy (Alitalia) and Australia (Qantas).

The two key actors in Europe are UPM-Kymmene (a Finnish pulp, paper & timber manufacturer) and Vapo (a Finnish bioenergy, peat & sawmill company). UPM was awarded €88.5M and Vapo €170M under the NER 300 scheme in December 2012 (European Biofuels Technology Platform, 2013a). Vapo’s ForestBtL project is now aiming to use the Carbo-V gasification technology originally developed by Choren (and bought by Linde when Choren became insolvent) – however, the scheme is in doubt since Metso, a gasifier developer, recently left the consortium (Green Car Congress, 2013a).

In addition five French actors and Uhde form a consortium planning to construct a demonstration FT plant by 2017 and are currently operating two pilot plants (European Biofuels Technology Platform, 2013a). Neste Oil and Stora Enso’s JV (NSE Biofuels) built a pilot in Finland (now closed), but did not progress to demonstration after an unsuccessful application to NER300 (European Biofuels Technology Platform, 2013a).

All actors in the US are currently operating at pilot scale, with a few developers considering large demonstrations, but little action actually taking place. The most advanced actors are Haldor Topsoe operating a pilot plant at the Gas Technology Institute (GTI) in Illinois, along with Iowa State University and the Renewable Energy Institute International (Bacovsky, 2013; US Department of Energy, 2013). TRI also have an integrated FT pilot, and built a large steam reformer at the Trenton pulp mill in Canada in 2009 to convert black liquor to syngas – but

without the downstream biofuels steps. Enerkem (based in Canada) are the most active developer in North America, with an operational pilot, demonstration under construction, and several other commercial plants in planning.

### 3.6. Further needs for commercialisation and potential in the UK

The key to achieving full commercialisation is the successful commissioning and operation of integrated demonstration plants. The different component parts have been demonstrated at pilot scale, hence the integration of these technologies and demonstration of reliable operation and output is the next stage for commercialisation. In addition, improvements in catalysts and syngas clean-up will improve reliability, reduce production costs, and improve the economics of small scale plants.

The UK has the opportunity to deliver a large scale gasification and FT-synthesis project by 2020, due to the interest and activity of Solena and British Airways.

**Table 4: Key actors in the UK**

Company	Synthesis type	Activity description
Velocys	FT	Their micro-channel FT reactor system is being tested at the Güssing gasifier in Austria, in conjunction with their commercialisation partners, SGC Energia. In addition they are the selected technology partner for the British Airways Solena project in London. This technology could enable FT plants with a smaller minimum economic scale. Velocys also produce speciality catalysts, including a carbide based FT catalyst, plus other catalysts for petrochemical processes, GTL, fuel cells, biogas conversion and portable steam.
Johnson Matthey	FT, methane and methanol	One of the world's largest catalyst manufacturers. Works on a range of process technologies and catalysts for syngas generation and makes FT catalysts. Together with Davy Process Technology and Aker Kvaerner, Johnson Matthey is a member of the One Synergy Alliance, which develops a portfolio of technologies and catalysts used in the production of methanol, methanol derivatives and syngas for FT. Its focus is on processes and catalysts for the GTL process but this may find application in the conversion of biomass derived syngas.

**Table 5: Operational and planned plants for gasification and catalytic synthesis**

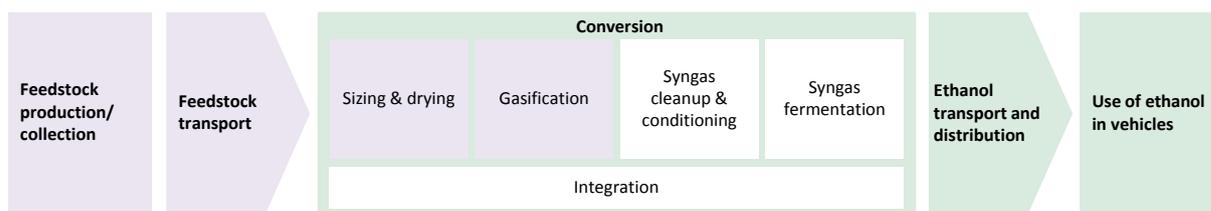
Company	Synthesis type	Scale M litres	Status	Region	Start-up date
Haldor Topsoe	FT	1.3	Operational	Illinois, US	2013
Solena	FT	65	Planned	London, UK	2015
UPM	FT	135	Planned	Stracel, France	TBC
UPM	FT	135	Planned	Rauma, Finland	TBC
Vapo	FT	150	Planned	Ajos, Finland	2016-17
Uhde/BioTFuel*	FT	TBC pilot	Planned	France	TBC
ECN	bioSNG	1 MW pilot	Operational	Netherlands	2008
REPOTEC & CTU	bioSNG	1 MW pilot	Operational	Güssing, Austria	2009
Göteborg Energi	bioSNG	20 MW	In construction	Göteborg, Sweden	2014
E.ON	bioSNG	200 MW	Planned	Southern Sweden	2015
Göteborg Energi	bioSNG	80 MW	Planned	Göteborg, Sweden	2016
ECN	bioSNG	10 MW	Planned	Netherlands	TBC
GDF Suez	bioSNG	12 MW	Planned	Lyon, France	TBC
Chemrec	DME	1.2 pilot	Operational	Pitea, Sweden	2011
Bioliq	DME	0.5 pilot	Operational	Karlsruhe, Germany	2013
Chemrec	DME	TBC	Planned	Örnsköldsvik	TBC
BioMCN	Methanol	159 commercial	Operational	Netherlands	2009
Uhde	Methanol	79	Planned	Sweden	TBC
BioMCN	Methanol	500	Planned	Delfzijl, NL	TBC
Energkem	Mixed alcohol	5	Operating	Westbury, Canada	2009
Energkem	Mixed alcohol	38	In construction	Edmonton, Canada	2013
Energkem	Mixed alcohol	38	Planned	Varenes, Canada	TBC
Energkem	Mixed alcohol	38	Planned	Pontotoc, USA	TBC
Fulcrum	FT or mixed alcohol	38	Planned	McCarran, USA	2015
Sundrop	Methanol to gasoline	189	Planned	Alexandra, USA	2016

\*This relates to the BioTFuel project a cooperation of five French partners and Uhde. The consortium aims to reach commercial scale production by 2020. Sources: (European Biofuels Technology Platform, 2013a; US Department of Energy, 2013; BiofuelsDigest, 2012a; Bacovsky, 2013; Hydrocarbon Processing, 2013; ECN, 2013; Goteborg Energi, 2013; Gaya, 2013; E.ON, 2013)

## 4. Gasification with syngas fermentation

### 4.1. Technology description

In this route, lignocellulosic feedstocks, such as energy crops, agricultural and forestry residues or wastes are converted into ethanol. Using gasification, the feedstock is thermo-chemically converted into syngas, before the syngas is anaerobically fermented by micro-organisms into ethanol (**Error! Reference source not found.**). Even though most developers are focused on producing ethanol for transport, other alcohols or organic acids can also be produced.



**Figure 4: Process schematic for gasification with syngas fermentation**

Syngas fermentation is very different to the other catalytic fuel synthesis routes, as syngas quality requirements are less strict, economies of scale are different, and the fuel production step relies on low temperature and pressure biological processes, rather than high temperature and pressure chemical reactions.

#### 4.2. Feedstocks

Lignocellulosic feedstocks such as energy crops, residues or waste can be used for this route. The INEOS Bio plant uses vegetative waste, waste wood and garden waste. Woody biomass (whether imported or domestic), MSW and C&I wastes are available in large volumes and would be suitable for a UK plant.

#### 4.3. Current technology status

The overall development status of syngas fermentation has reached the demonstration stage (TRL 6-7). Many of the plant components are getting close to commercial availability in other applications, e.g. biomass chipping and drying, gasification and syngas clean-up. Syngas fermentation reactors and plant integration experience are in line with the overall route (TRL 6-7). Development has recently advanced due to INEOS Bio's 30 ML/yr demonstration plant coming online in Florida. Other companies such as Coskata or Lanzatech are currently only working on the syngas fermentation, but are not integrating it with the gasification step yet. To reach commercial scale a scale up by approximately a factor of 2-3 would be required (Ethanol Producer, 2010; Rice, 2008).

#### 4.4. Outputs (fuels, current & potential)

Ethanol and potentially other alcohols (e.g. butanol) or organic acids (e.g. acetone).

#### 4.5. Key actors and activities

The key actor for integrated gasification with syngas fermentation is INEOS Bio in the US. They are currently operating one integrated demonstration plant at 30ML/yr and are aiming to build plants of twice or three times of the current size in the coming years (Biofuelsdigest, 2013). Other actors working on syngas fermentation are Coskata in the US, and Lanzatech (operating in New Zealand, China and the US) who are planning commercial scale syngas fermentation plants in the next few years. However, Coskata backed out of developing biomass-syngas routes recently, to concentrate on natural gas and fossil feedstocks. Lanzatech acquired the Range Fuel Soperton plant assets in 2012 (to test forest residue syngas), but are currently focused on global project opportunities that utilise steel mill and other waste carbon gases (without the need for gasification).

**Table 6: Key actors and plants for gasification with syngas fermentation**

Company	Scale M litres	Status	Region	Start-up date
INEOS Bio	Pilot	Operational	Fayetteville, US	2004
INEOS Bio	30	Operational/ramp-up	Florida, US	2013

Sources: (Bacovsky, 2013; E4tech, 2012)

INEOS Bio had planned to build a 30 million litre plant based on MSW in Seal Sands (Tees Valley), UK, and received public funding for FEED studies. However, after the indecisive December 2013 vote on ILUC within Europe (and continued lack of policy certainty), we now understand that INEOS Bio have stopped development work on this project, and are no longer pursuing opportunities in Europe.

#### 4.6. Further needs for commercialisation and potential in the UK

The current INEOS Bio plant in Vero Beach, Florida, needs to be proven in full integrated operation, and at maximum capacity – it is currently still in a ramp-up phase. Similar to the catalytic synthesis routes, improvements in gasification and syngas clean-up will improve reliability, reduce production costs, and improve the economics of small scale plants – syngas fermentation also would benefit from yield and productivity increases, plus reduced parasitic energy consumption.

There may still be an opportunity for UK deployment of this technology by 2020, however the likelihood of the Seal Sands project being resurrected is currently slim.

## 5. Fast pyrolysis and pyrolysis oil upgrading

### 5.1. Technology description

Biomass is thermally decomposed in the pyrolysis step to produce a liquid bio-oil, along with some fuel gas and solid biochar. Fast pyrolysis is carried out at around 500°C in the absence of oxygen and maximises the production of bio-oil (as opposed to slow pyrolysis which maximises bio-char production). After feedstock reception, storage and handling, drying and grinding, the feedstock is transferred to a pyrolysis reactor. The key reactor types that are currently used and demonstrated are bubbling fluidised bed, circulating fluidised bed and a rotating cone reactor. Bio-oil can be used in heat and power, however only through upgrading the bio-oil can it be used as a transport fuel. Besides gasification routes for converting pyrolysis oil into syngas, hydro-treatment and zeolite cracking are the two main upgrading processes (E4tech, 2012). They can either be carried out in a standalone upgrading process or be integrated in a conventional oil refinery.

### 5.2. Feedstocks

In principle, any dry lignocellulosic biomass feedstock can be used as an input to the fast pyrolysis process, including dedicated energy crops, agricultural residues, wood residues, and wastes. Mixed and variable feedstocks can be used, however their composition impacts the yield and bio-oil composition. In addition, most upgrading processes use hydrogen as additional input.

Kior is currently using wood and forestry residues and intends to use Southern Yellow Pine at its planned facility in Mississippi (Kior, 2013). Woody biomass (whether imported or

domestic), agricultural residues, MSW and C&I wastes are available in large volumes and would be suitable for a UK plant.

### **5.3. Current technology status**

Several companies have fast pyrolysis technologies at TRL 7-8, but the upgrading step is only currently at around TRL 5. The combined route will therefore be at TRL 5. Pyrolysis oil upgrading is likely to be carried out at large scale in order to be economically viable, and hence significant up-scaling will be required.

### **5.4. Outputs (fuels, current & potential)**

Gasoline, diesel, jet fuels and chemicals can be produced from the different fractions of the pyrolysis oil (Dynamotive, 2013). Alternatively, gasification routes as described above offer alternative outputs such as bioSNG, bioDME, methanol and mixed alcohols.

### **5.5. Key actors and activities**

Several companies are working on different processes of fast pyrolysis and bio-oil upgrading, in particular in the US. The most advanced player with an integrated technology currently is Kior, operating a demonstration scale plant in the US since early 2013 and planning a similar, but larger facility in Mississippi (Kior, 2013). UOP were awarded \$25 million to build a demonstration scale plant in Hawaii in 2010 (US DoE, 2012; UOP, 2011), with construction close to completion. For this project UOP is working with Ensyn, a pyrolysis technology provider, in a joint venture named Envergent Technologies (Ensyn, 2013). In addition Ensyn is working with Chevron Technology Ventures in a similar cooperation. Anellotech is operating a pilot plant in the US using a catalytic fast pyrolysis process with a zeolite-based catalyst to produce aromatic and olefinic hydrocarbons (Anellotech, 2013; Lane, 2013). A further project in the US on integrated pyrolysis with upgrading, supported by the US DoE, has been successfully completed in 2012 by the Gas Technology Institute (Gas Technology Institute, 2012). Other companies that are active in the integrated process chain are Mercurius Biorefining and Dynamotive Energy System Corporation (European Biofuels Technology Platform, 2014).

Johnson Matthey, BP, Rotawave, Centre for Process Innovation (CPI), Catal International, Greenergy, and Velocys could also add industrially relevant expertise, along with a number of small pyrolysis developers in the UK.

### **5.6. Further needs for commercialisation and potential in the UK**

Regarding the technology development for fast pyrolysis reactors the following improvements could be undertaken which could help to produce better quality oils and reduce upgrading requirements:

- Reactor design which addresses issues such as heat transfer and reaction rates and the removal of impurities
- Further scale-up
- Improving oil stability and quality (via reduced acidity, water and oxygen contents). This could be achieved through new pyrolysis processes (e.g. microwave pyrolysis) and through optimising the combination of feedstock composition and pyrolysis process.
- Use of catalysts (e.g. zeolites) in the pyrolysis reaction to help optimise the reaction and oil quality and potentially yield other useful products, such as aromatics.

With the pilot plant of Future Blends, and further relevant industrial experience, the UK has potential of the UK to play a role in the development of fast pyrolysis and upgrading, particularly on waste feedstocks. However, it should be recognised that the likes of KiOR and Envergent are at least 1-2 TRL levels ahead of UK developments – although we note that 2G BioPOWER is a project developer looking at bringing Envergent’s technology to the UK.

**Table 7: Key actors and commercial scale plants for fast pyrolysis with pyrolysis oil upgrading**

Company	Process step	Scale M litres	Status	Region	Start-up date
Future Blends	Both	0.03 pilot	Operational	Oxford, UK	TBC
Licella	Catalytic fast pyrolysis	0.3 pilot	Operational	Australia	2008
Gas Technology Institute	Both	Pilot	Completed (was operational)	Illinois, US	Stopped in 2012
Anellotech	Catalytic fast pyrolysis	Pilot	Operational	New York, US	2013
Kior	Both	50	Operational	Columbus, US	2013
Next Fuels	Thermochemical liquefaction	Pilot	Operational	SE Asia, using palm waste	TBC
UOP-Ensyn	Both	0.2 pilot	In construction	Hawaii, US	2014
Kior	Both	150	Planned	Natchez, US	TBC

Sources: (Future Blends, 2013; Anellotech, 2013; Lane, 2013; Gas Technology Institute, 2012; European Biofuels Technology Platform, 2014; Kior, 2013)

Besides significant capabilities in academia, Future Blends is the only UK-based company currently operating an integrated fast pyrolysis and upgrading pilot plant (Future Blends, 2013).

**Table 8: Key actors in the UK in fast pyrolysis and pyrolysis oil upgrading**

Company	Process step	Description
Future Blends	Both	Company set up for the “Pyrolysis challenge” Carbon Trust competition in 2012 and funded through the competition. Developing new pyrolysis and upgrading IP, for more stable bio-oil and cheaper fuel production.

Sources: (Future Blends, 2013)

## 6. Novel sugar based routes

### 6.1. Technology description

Affordable and sustainable sugars form the base of the ‘novel sugar routes’, which collectively describes several very different biochemical and thermochemical technologies. However, each route transforms sugars into a range of bio-products, chemicals and fuels. Bio-chemical transformations of sugars include the use of biological catalysts (e.g. LS9), heterotrophic algae/micro-organism fermentation to lipids (e.g. Solazyme, BP-DSM), or the use of genetically modified yeasts to produce farnesene (Amyris). Virent is using a thermo-chemical

transformation through aqueous phase reforming of sugars to produce a mixture of alcohols, ketones, acids, furans and other oxygenated hydrocarbons. Note that these novel routes do not include autotrophic (sunlight using) micro-algae or macro-algae technologies (e.g. Sapphire, Parabel, Cyanotech).

## **6.2. Feedstocks**

Sugars can be crushed directly from feedstocks such as sugarcane and sugar beet, hydrolysed from starch crops or extracted from lignocellulosic raw materials after pre-treatment. Current actors such as Solazyme are using sugarcane as their main feedstock, but also aim to use corn, corn stover, Miscanthus, switchgrass, forest residues and different waste streams in the future.

Sugarbeet is grown in the UK, but the main opportunity will arise from sugars extracted from lignocellulosic feedstocks such as straw, woody biomass and forestry residues.

## **6.3. Current technology status**

The current technology status varies strongly per individual actor, as it is not a common technology being used. Overall the TRL level is between 4 and 5 as most plants are at the pilot plant stage or earlier. However, the Amyris plant is at demonstration scale (TRL6) and the Solazyme plant will reach TRL 6 once the plant has been commissioned in 2014. However, this technology status and level of development has been based on using readily available sugars from sugar or starch crops – only a few developers have conducted batch tests with lignocellulosic sugars to date. Therefore, the TRL level using non-food crops will be nearer 3-4.

## **6.4. Outputs (fuels, current & potential)**

A very wide range of renewable and conventional fuels as well as diverse bio-products and chemicals, some currently actors, such as Amyris, are focusing on higher value chemical markets, but may develop transport fuels in the near future.

## **6.5. Key actors and activities**

Solazyme is a key actor based on algae fermentation of sugars, operating one pilot plant and planning to commission a large demonstration plant in early 2014, which could be expanded to 400 ML/yr by 2016 (European Biofuels Technology Platform, 2013c; Yahoo, 2013). LS9 expanded their pilot plant operation to 135,000 L/py in late 2012 and are intending to build a 38 ML/yr plant (Lane, 2013a). Amyris have been operating a large scale demonstration plant at 50 ML/yr in Brazil since late 2012 (Amyris, 2012). Other companies actively developing novel sugar based routes are Virent, Shell and BP-DSM.

**Table 9: Key actors and plants of novel based sugar routes**

Company	Scale M litres	Status	Region	Start-up date
Solazyme	Pilot	Operational	California, US	TBC
BP-DSM	Pilot	Operational	West Coast US	TBC
Virent	0.04	Operational	Madison, US	2010
Virent/Shell	0.04	Operational	Houston, US	2012
LS9	0.14	Operational	Florida, US	TBC
Amyris	50	Operational	Paraiso, Brazil	2012
Solazyme	100	Under construction	Brazil	2014
Solazyme	57	Planned	Roquette, France	TBC
LS9	38	Planned	Florida, US	TBC
Virent	76	Planned	US	TBC
Amyris	100	Planned	Sao Martinho, BR	2015

Sources: (Bloomberg, 2013; European Biofuels Technology Platform, 2013c; Yahoo, 2013; Lane, 2013a; LS9, 2012; Amyris, 2012; Lane, 2013b)

Most actors working on novel sugar based routes are active in the US and Brazil. BP is the only actor with origins in the UK; however its sugar-to-diesel operations are based in the US.

#### 6.6. Further needs for commercialisation and potential in the UK

Each individual technology needs to be proven at demonstration and then commercial scale. Technological challenges that need to be overcome are very actor specific. In most cases, developers still need to reduce plant capital costs and parasitic energy use, improve the productivity of their organisms/catalysts, demonstrate high process and extraction yields at scale in the real world (not just in the lab), plus optimise any co-products for maximal revenues. However, one common challenge that all the developers and novel sugar routes face is the switch to lignocellulosic sugars, and the additional capital costs, impurities and need to use C5 sugars that these feedstocks present.

The potential for the deployment in the UK is likely to be very limited since sugar is not abundantly available as a cheap feedstock (unlike in Brazil and the US), and the majority of actors are active in these two countries.

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