



RenJet

Establishing a European renewable jet fuel supply chain: the technoeconomic potential of biomass conversion technologies

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1 Introduction

Airline operations generated 705 Mt of CO₂ in 2013, representing around 2% of global anthropogenic CO₂ emissions (ATAG, 2014). This figure is forecast to rise to between 1,000 and 3,100 Mt by 2050, with projected emissions reductions from improved air traffic management and engine efficiency expected to be offset by increased demand for air travel (Lee, Lim & Owen, 2013). 99% of airline emissions are caused by the combustion of kerosene (CAAFI, 2013; Faaij & van Dijk, 2012). The potential to reduce these emissions depends on the development of low carbon liquid fuels. Renewable fuels, specifically biofuels, are therefore considered essential for the decarbonisation of the aviation industry.

Yet current demand for – and availability of – aviation biofuels is limited. Most estimates of production costs for biomass-derived kerosene-equivalent fuels (hereafter referred to as ‘biojet’) are considerably higher than the selling price of petroleum-derived kerosene. The high cost of production is commonly attributed to three factors: the relative immaturity of biojet technology, the small number of active producers, and competition between biojet and other premium (subsidised) biofuel markets - which encourages biofuel producers to focus on other end products.

The EIT Climate KIC project ‘Fuel Supply Chain Development and Flight Operations’ (RENJET) aims to facilitate the decarbonisation of the aviation industry by accelerating the development of renewable jet fuel supply chains in the EU, simultaneously increasing availability and stimulating demand. This paper contributes to Work Package 1 of the project, which seeks to identify how and under what preconditions substantial volumes of sustainable, next generation biofuels can be made available in the short and medium term (respectively to 2020 and 2035), as well as key opportunities to establish sustainable supply chains in the shorter term. This paper reviews the commercial and technological maturity of various technologies for converting biomass to synthetic jet fuel, drawing on an extensive review of academic and grey literature published in the field. In particular, it evaluates technologies with regards to their ‘fuel readiness level’, progress towards international certification, compatibility with existing infrastructure, economic viability and the opportunity costs of producing biofuels for aviation.

The remainder of this paper proceeds as follows. Chapter 2 details the methodology for the study. Chapter 3 outlines the performance requirements of jet fuel and processes by which new jet fuels are certified. Chapters 4 and 5 respectively review the technological and commercial status of different biojet fuel conversion pathways, and the economic viability of these. Chapter 6 presents the review’s overall conclusions.

2 Methodology

2.1 Rapid Evidence Assessment

The methodology employed for this study is an adaptation of Rapid Evidence Assessment (REA). REA is a shortened version of full systematic review, originally developed as a rapid but rigorous means of evaluating the best available evidence for policy-making (GSR, 2013; Khangura et al., 2012). The REA approach is considered most viable for research questions which are constrained or focussed and well-aligned with existing research, and for subject areas where methods for the evaluation and synthesis of reviewed evidence have already been established (Thomas, 2013; Thomas, Newman & Oliver, 2013; Watt et al., 2008). In comparison to full systematic reviews REAs involve less developed search strings, less comprehensive searching, simpler extraction of data and simpler quality appraisal. Since they are less comprehensive there is however a risk of introducing bias to the results (GSR, 2013).

2.1.1 Search strategy

This study reviews published, peer-reviewed studies and grey literature examining the technological and economic feasibility of technologies to produce biojet fuel in the short to medium term (respectively to 2020 and 2035). Due to the relative broadness of this remit, the review was constrained to just three search terms: alternative fuels OR biofuels AND aviation. These were used to search the Primo Central Index and Google Scholar for English language reports published between 2009 and 2014. In addition to the systematic elements of the REA, core industry reports recommended by project partners were included in the study, and the bibliographies of relevant articles were reviewed for related citations. Non-systematic Google searches were conducted to verify the current status of the biofuel developers and facilities (both proposed and constructed) identified by the REA.

2.1.2 Technology screening

A large number of technologies are being developed which have the capability to produce biojet fuel. However many of these are unlikely to be suitable for EU-based production in the short term, for example those which are in the very early stages of R&D or which use feedstocks not available in the region. In order to develop the inclusion/exclusion criteria for the REA assessment, it was therefore necessary to first identify which families of technologies ('conversion pathways') could be suitable for EU applications in the short term. A shortlist of promising conversion pathways was drawn-up from the titles, abstracts and executive summaries of the REA search results and in conjunction with expert input from the project partners. Pathways were selected if they met the following screening criteria¹: 1) evidence of active efforts to progress international certification; 2) evidence of intention to develop a 'drop-in' jet fuel (suitable for blending with petroleum kerosene); 3) capability to process lignocellulosic feedstocks.

¹ The criteria were identified in collaboration with the project's partners. They are considered to signpost technologies which have reached a baseline level of technological maturity, have potential for commercial use in the near-term, are compatible with existing aviation infrastructure, and which will have the potential to utilise competitively priced feedstocks.

2.1.3 Inclusion/exclusion criteria

Publications were included in the review if they met both of the following criteria: 1) analysis of one or more of the pathways identified by the screening exercise, used for the production of jet fuel; 2) examination of the technological/commercial maturity of these technologies, and/or economic or policy issues related to deployment.

Publications were excluded if: 1) they did not examine the pathways identified by the screening exercise; or 2) they did not analyse the potential of these technologies to produce jet fuel (as opposed to biofuels in the round); or 3) they were concerned only with the development of technical processes to produce biojet fuels and/or the analysis of the performance characteristics of these fuels.

The search strategy identified 18,396 titles. 175 were identified that fit the inclusion criteria and were included in the review. The remainder of this report synthesises and critiques the evidence provided by these publications.

3 Jet fuel: performance requirements and international standards

Conventional jet fuel is produced by refining petroleum crude. Its composition depends on the raw crude oil, but is typically around 20% paraffins, 40% isoparaffins, 20% naphthenes and 20% aromatics (Blakey, Rye & Wilson, 2011). Each of these components plays a critical role in providing specific fuel characteristics. For example, the high hydrogen-to-carbon ratio of paraffins and isoparaffins enhances the heat density per unit mass of fuel; naphthenes help to reduce the freeze point, which is critical at high altitudes; and aromatics contribute to material compatibility and prevent leaks in the seals of some aircraft (Liu, Yan & Chen, 2013; Blakey, Rye & Wilson, 2011; Bauen et al., 2009).

Jet fuel specifications are defined in the US and Europe by two alternative standards: ASTM D1655 of the American Society for Testing and Materials (ASTM) and Def Stan 91-91 of the UK Ministry of Defence. These are broadly equivalent and focus primarily on performance properties rather than chemical composition, due to the complexity and variability of the latter (Bauen et al., 2009). Bauen et al. (2009) have identified several fuel requirements as being particularly key to the development of aviation biofuels, namely: energy content, freeze point, thermal stability, viscosity, combustion characteristics, lubricity, material compatibility and safety properties. Table 3-1 provides an overview of these in terms of their operational purpose and associated specification.

Table 3-1 Key jet fuel properties, criteria for evaluation and impact (Bauen et al., 2009)

Requirement	Purpose	Specification
Energy content	Affects aircraft range	Minimum energy density by mass
Freeze point	Impacts upon ability to pump fuel at low temperature	Maximum allowable freeze point temperature
Thermal stability	Coke and gum deposits can clog or foul fuel system and nozzles	Maximum allowable deposits in standardized heating test
Viscosity	Viscosity impacts ability of fuel nozzles to spray fuel and of engine to relight at altitude	Maximum allowable viscosity
Combustion characteristics	Creation of particulates in combustor and in exhaust	Maximum allowable sulphur and aromatics content
Lubricity	Impacts upon ability of fuel to lubricate fuel system and engine controls	Maximum allowable amount of wear in standardized test
Material compatibility	Fuel comes in to contact with large range of metals, polymers and elastomers	Maximum acidity, maximum mercaptan concentration, minimum aromatics concentration
Safety	To avoid explosions in fuel handling and tanks	Minimum fuel electrical conductivity and minimum allowable flash point.

Synthetic jet fuels (including biofuels) and synthetic/petroleum fuel blends are specified by standards ASTM D7566, established 2009². Specific fuel blends certified for commercial use are added to the standard as an annex. These ‘drop in’ fuels are considered to be equivalent to conventional jet fuel (ASTM D1655) and can be mixed in aircraft and supply infrastructure without the need for separate tracking or approval (Rumizen, 2013). Some organisations are investigating the potential for non-drop-in fuels that could be used instead of (but not mixed with) petroleum-based fuels, for example butanol (Novelli, 2011; Hileman et al., 2009). Interest in these is however limited by need to develop a secondary, parallel fuel infrastructure, which would be both extremely expensive and logistically complex (Blakey, Rye & Wilson, 2011; Bauen et al., 2009).

A further standard, ASTM D4054, provides guidance on the testing and property targets necessary to evaluate a candidate alternative fuel. Biofuel producers wishing to certify their product must collate the data required by D4054 in a research report and submit this to engine and airframe manufacturers (original equipment manufacturers, OEMs) for review. If the fuel is approved by the OEMs it is balloted to the ASTM’s membership for approval to develop an annex to D7566 (Rumizen, 2013). Figure 3-1 illustrates this process.

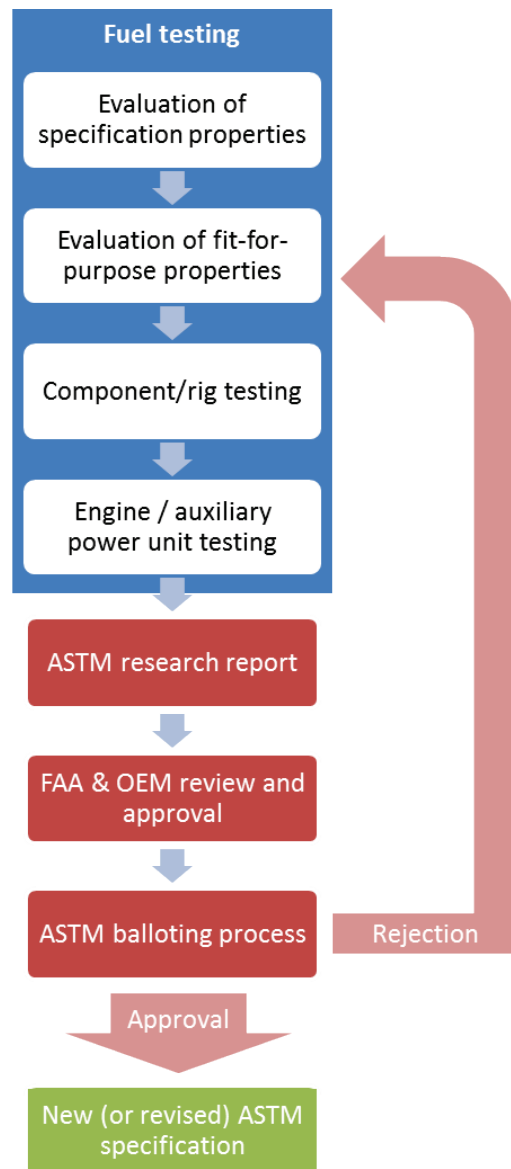


Figure 3-1 ASTM D4054 process for aviation biofuel certification. Adapted from Rumizen (2014).

² Fuels meeting the standard ASTM D7566 are considered to conform to the requirements of both ASTM D1655 and Def Stan 91-91 (IATA, 2012b).

4 Technological and commercial status of biojet conversion pathways

This chapter compares the technical suitability of different conversion pathways for production of aviation biofuels, with a focus on potential to advance supply chains within the EU over the period to 2020. For each of the pathways, the following are presented:

- Pathway characterisation – summarising the key elements of each pathway, including suitable feedstocks, processes by which these are converted to aviation fuel, alternative names used to identify the technology;
- Commercialisation status – summarising the pathway’s stage of technological development, commercial activity, progress towards certification, and corresponding Fuel Readiness Level (see 1);
- Opportunities and challenges for use in aviation – summarising the compatibility with existing infrastructure (aircraft engines and fuel supply systems), opportunity costs of producing jet fuel rather than other products.

Six pathways are analysed, of which five were identified by the technology screening activity described in Chapter 2: biomass to liquids (BTL) (which uses a Fischer-Tropsch process), hydrotreated depolymerised cellulosic jet (HDCJ), alcohol to jet (ATJ), fermentation to jet (FTJ) and aqueous phase reforming (APR). The lignin to jet (LTJ) pathway is also included as it is of specific interest to project partners. The most technologically advanced conversion pathway – hydroprocessed esters and fatty acids (HEFA) – was excluded because it requires vegetable oil feedstocks³. Figure 2 provides an overview of the processes entailed by each of these pathways.

It should be noted that the breadth and depth of literature identified varies considerably across the pathways. The greatest quantity and most detailed data are available for those pathways which are closest to commercialisation and/or which are being pursued by numerous organisations. Publically-available information is very limited for pathways in the earlier stages of development, particularly those which are dominated by just one or two proprietary processes. These differences in coverage are reflected in the level of detail afforded to each of the pathways within this report.

³ The production costs of HEFA/HRJ are understood to be dominated by the cost of the feedstock, which is typically greater than the price of kerosene. As such the pathway is considered to be economically unattractive for short to medium term deployment.

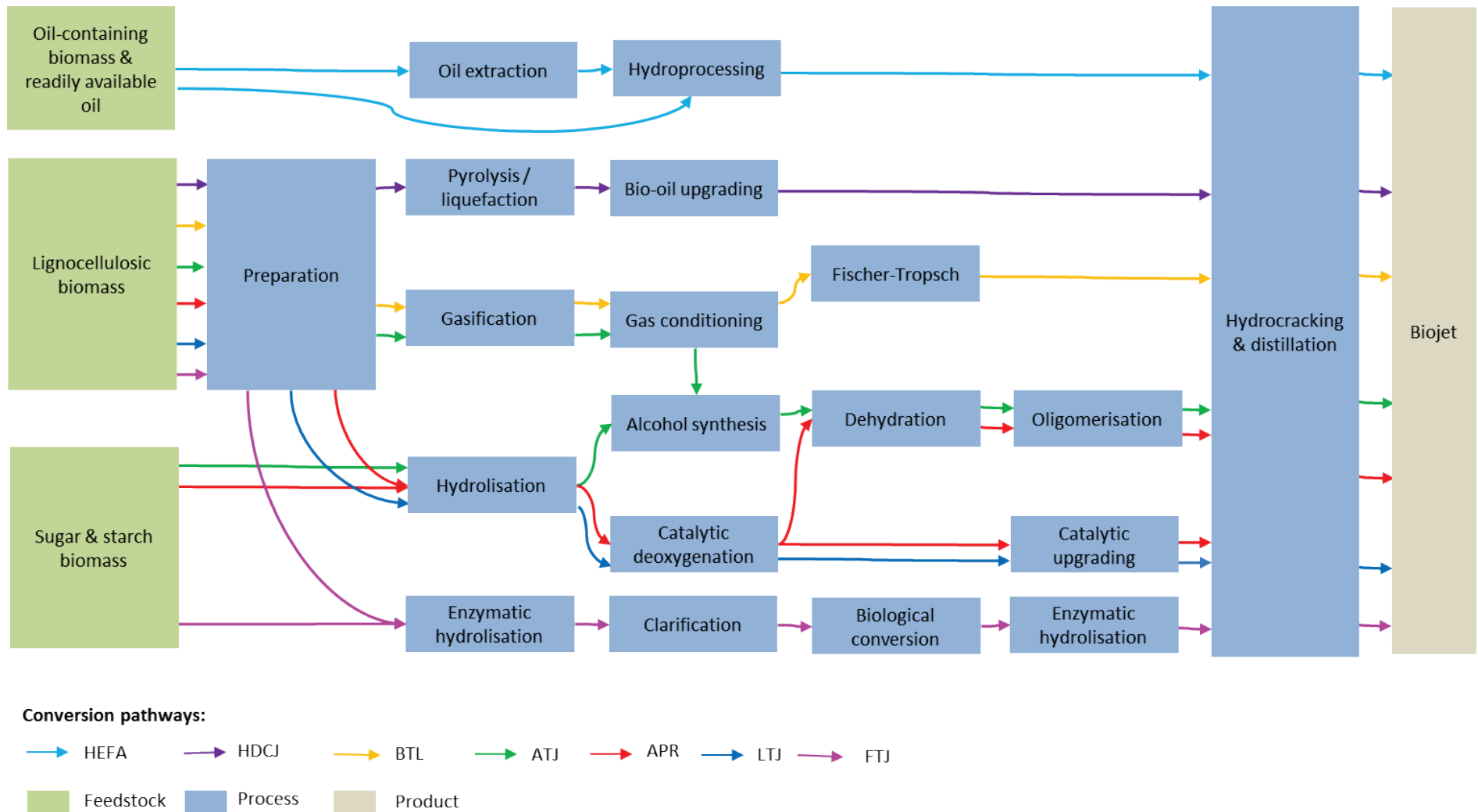


Figure 2 Biojet conversion pathways: feedstocks and processes

Box 4-1 Fuel Readiness Levels

The Fuel Readiness Level (FRL) scale has been developed by the Commercial Aviation Alternative Fuels Initiative (CAAFI) to assess the maturity of alternative jet fuels. It was endorsed by the International Civil Aviation Organization (ICAO) in 2009 (CAAFI, 2014b). The scale details nine levels of technological and commercial maturity, as follows: levels 1-4 correspond to lab-based research and development, 5 to pilot stage, 6-7 to larger-scale demonstration and certification process, 8 to the development of viable business opportunities and GHG assessment, and 9 to the operation of the first commercial plant (CAAFI, 2014a; Arup URS & E4tech, 2013). Table 4-1 provides a summary of the ‘toll gate’ achievements required to progress along the scale.

Table 4-1 FRL levels and key milestones. Source: CAAFI (2014a)

Level	FRL Description	FRL ‘Toll Gate’
1	Basic principles	<ul style="list-style-type: none"> • Feedstock & process basic principles identified
2	Technology concept formulated	<ul style="list-style-type: none"> • Feedstock & complete process identified
3	Proof of concept	<ul style="list-style-type: none"> • Lab scale fuel sample produced from realistic feedstock. • Energy balance analysis conducted for initial environmental assessment. • Basic fuel properties validated
4	Preliminary technical evaluation	<ul style="list-style-type: none"> • System performance and integration studies • Specification properties evaluated
5	Process validation	<ul style="list-style-type: none"> • Scaling from laboratory to pilot plant
6	Full-scale technical evaluation	<ul style="list-style-type: none"> • ASTM certification tests conducted: fit-for-purpose properties evaluated, turbine hot section testing, components and testing
7	Certification / fuel approval	<ul style="list-style-type: none"> • Fuel listed in international standards
8	Commercialisation	<ul style="list-style-type: none"> • Business model validated for production • Airline purchase agreements secured • Plant-specific independent GHG assessment conducted in line with internationally-accepted methodology.
9	Production capability established	<ul style="list-style-type: none"> • Full scale plant operational

The FRL scale is broadly aligned with nine-step Technology Readiness Level (TRL) scales which are commonly used to assess the maturity of innovative technologies, and which were first developed by NASA in the 1990s (Mankins, 1995). Arup URS and E4Tech (2013) observe that biofuels in general have taken between three and five years to progress by one TRL. Data specific to the progression rates of aviation biofuels is limited, but overlap with this observation. The first three fuels to achieve ASTM certification took between one and three years to complete the process (corresponding to FRL 6), whilst some others yet to complete have been working towards it for five years at the time of writing (Rumizen, 2014; CAAFI, 2013). Assuming a progression rate of 3-5 years per FRL, aviation biofuels technologies can be expected to progress by up to two levels between 2014 and 2020.

4.1 Biomass to liquids

4.1.1 Characterisation

The biomass to liquids (BTL) process involves the gasification of biomass feedstocks, followed by Fischer-Tropsch synthesis of the resulting syngas. It is also known as gasification/Fischer-Tropsch synthesis (GFT). The ASTM-certified fuel produced by this pathway is called Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK)⁴. Efforts are underway to develop a second fuel, Fischer-Tropsch synthetic kerosene with aromatics (FT-SKA).

Process description

Prior to gasification the feedstock is pretreated to reduce its particle size and moisture content (thereby densifying the biomass). This is crucial to facilitate transportation and handling, and to ensure a continuous and reliable feed of biomass through industrial facilities (Güell et al., 2012). Pretreatment may be conducted remotely (to ease the logistics of feedstock transportation) or at the gasification site itself.

The pretreated feedstock is gasified at high temperatures and pressures with a controlled volume of oxygen to generate synthesis gas (syngas), a mixture mostly composed of carbon monoxide and hydrogen. The syngas is then conditioned to remove CO₂ and impurities such as tar, H₂S, COS, HCN, NH₃ and HCl. This can involve a combination of physical and chemical process such as thermal or catalytic cracking, scrubbing, filters and cyclones (Liu, Yan & Chen, 2013; Güell et al., 2012). A variety of gasification technologies can be employed, depending on the characteristics of the feedstock. Further detail on different gasification technologies is provided in Table 4-2.

The clean syngas is subjected to Fischer-Tropsch synthesis, during which it reacts with hydrogen in the presence of a metallic catalyst (commonly iron, cobalt or nickel). The reactions are usually conducted at temperatures of 150°C to 300°C and pressures of 10 to 40 bars (Maniatis, Weitz & Zschocke, 2013; ALFA-BIRD, 2012; Bauen et al., 2009; Hileman et al., 2009; IATA, 2009). The resulting product is a mix of saturated hydrocarbons, ranging from gases to waxes. The mixture is upgraded to liquid fuels using methods common in conventional petroleum refineries, for example hydrocracking and distillation, or oligomerisation (Qantas, 2013; Blakey, Rye & Wilson, 2011; CSIRO, 2011).

Feedstocks

Most lignocellulosic feedstocks are suitable for BTL, including woody biomass, agricultural residues, manure and industrial wastes, and the drier portions of municipal solid waste (MSW). The composition of the feedstock does however affect the quality of syngas generated and the efficiency of the overall BTL process, as well as the suitability of different gasification technologies (detailed in Table 4-2). Biomass can also be gasified alongside fossil fuels such as crude oil and coal to improve process economics, but this increases the GHG emissions of the fuel produced (ALFA-BIRD, 2012; Hileman et al., 2009). Ideal BTL feedstocks contain high levels of volatile matter and low levels of ash and moisture (Arup URS & E4tech, 2013; Bauen et al., 2009).

Gasification technologies

Gasification technologies vary significantly in terms of cost, feedstock requirements and the quality of syngas produced, with associated knock-on effects for the technical and financial viability of BTL

⁴ GFT and FT-SPK are widely used to describe fuels produced from both biomass and non-biomass feedstocks.

processes as a whole. Those that produce a suitable syngas for conversion to liquid biofuels usually operate at high temperatures (reducing impurities in the syngas) and pressures, and without nitrogen dilution (i.e. they are steam or oxygen blown) (Arup URS & E4tech, 2013). The approaches most commonly employed for biofuels are fluidised bed and entrained flow gasification, although interest in plasma and hydrothermal gasification is growing (Güell et al., 2012). The relative merits of these four technologies are outlined in Table 4-2.

Table 4-2 Gasification technologies for the production of liquid biofuels.

Source data: (Arup URS & E4tech, 2013; Maniatis, Weitz & Zschocke, 2013; Güell et al., 2012; Mountouris, Voutsas & Tassios, 2008).

	Fluidised bed gasification (FBG)	Entrained flow gasification	Plasma gasification	Hydrothermal gasification
Process conditions	<ul style="list-style-type: none"> • Temperatures below the melting point of biomass ash (to avoid reactor damage) 	<ul style="list-style-type: none"> • Temperatures above the melting point of biomass ash • High pressures 	<ul style="list-style-type: none"> • Anaerobic decomposition of waste materials (non-incineration process) • Very high temperatures 	<ul style="list-style-type: none"> • Very high pressures • High temperatures
Strengths	<ul style="list-style-type: none"> • Easy to use • Relatively inexpensive 	<ul style="list-style-type: none"> • Energy efficient • High quality syngas - requires little additional purification 	<ul style="list-style-type: none"> • Very clean syngas 	<ul style="list-style-type: none"> • Suitable for wet feedstocks • No need for (expensive) drying pretreatment
Weaknesses	<ul style="list-style-type: none"> • Poor quality syngas - requires extensive conditioning 	<ul style="list-style-type: none"> • Feeding biomass into the reactor can be problematic – requires very small particle size or liquid feedstock. • Agricultural residues may clog reactor feed. • Higher capital and operational costs than FBG 	<ul style="list-style-type: none"> • High capital and operational costs 	<ul style="list-style-type: none"> • Harsh process conditions - operation and commercialisation difficult
Suitable for	<ul style="list-style-type: none"> • Small-scale operations only 	<ul style="list-style-type: none"> • Larger-scale facilities only • Woody biomass 	<ul style="list-style-type: none"> • Solid wastes of low economic value only (due to high process costs) 	<ul style="list-style-type: none"> • Wet feedstocks, e.g. macroalgae, lignin-based residues from fermentation of lignocellulosic materials
Fuel developers		<ul style="list-style-type: none"> • BioTFuel 	<ul style="list-style-type: none"> • Solena (GreenSky) 	

4.1.2 Commercialisation status

Technological development and commercial activity

Gasification and Fischer-Tropsch synthesis of coal and natural gas feedstocks are mature technologies which have been deployed industrially for several decades. Coal-derived FT-SPK has been used in blends of up to 50% with conventional jet fuel for commercial flights since 1999, and as a neat fuel (pure/unblended fuel) since 2010, with no significant technical problems reported (Maniatis, Weitz & Zschocke, 2013; Morgan, 2011). Application of the process to biomass is however relatively novel, and has yet to be fully optimised. Gasification technologies in particular are considered to require significant development, especially with regards to feedstock handling (Maniatis, Weitz & Zschocke, 2013; Güell et al., 2012). Fischer-Tropsch processes require less extensive adaptation, due to the compositional similarity of syngas produced from biomass and fossil fuels.

BTL was expected to develop rapidly in the 2000s, but progress has been slower than anticipated. Several major developers have become insolvent or cancelled projects (Arup URS & E4tech, 2013). In Europe operations have ceased at pilot plants previously operated by CHOREN and NSE Biofuels. Forest BtL has also frozen the development of a planned demonstration plant (ForestBtL, 2014; Balan, Chiaramonti & Kumar, 2013; Maniatis, Weitz & Zschocke, 2013). Several demonstration and pilot scale projects are nonetheless underway, with projected completion dates ranging from 2015 to 2018. The largest of these aim to produce 100,000-200,000 tonnes of fuel per annum and projected kerosene fractions range from 40-70% (Maniatis, Weitz & Zschocke, 2013; Güell et al., 2012). Players targeting commercial-scale plants in Europe include BioTFuels, UPM and Solena (Solena Fuels, 2014; Maniatis, Weitz & Zschocke, 2013). Regarding collaboration with the aviation industry, Solena's GreenSky London project has a fuel off-take agreement with British Airways, and CEA/Air Liquide are developing a pilot plant in partnership with Air France. Natural gas-derived FT-SPK has been commercially produced since 2012 and is routinely used in blends of up to 25% by Shell (Maniatis, Weitz & Zschocke, 2013).

Certification status

FT-SPK has been certified for blends of up to 50% with petroleum jet fuel since September 2009 (Annex A1 of ASTM D7566) (IATA, 2013).

Fuel readiness level

BTL is considered to have a FRL of 7 moving towards 8. This corresponds to a fuel already certified and listed in international standards, for which demonstration plants are operational and the first commercial-scale facilities are being developed, and for which some commercial purchase agreements have been secured.

4.1.3 Opportunities and challenges for use in aviation

Compatibility with existing systems

The composition of FT-SPK offers certain advantages over conventional jet fuel. The specific energy (per unit mass) of neat FT-SPK is 2% greater than petroleum jet due to its paraffinic structure and

low aromatic content. This reduces the weight of fuel required to fly a specific distance, thus increasing the potential payload of the aircraft – and reducing energy consumption per unit of payload (Hileman, Stratton & Donohoo, 2010; Hileman et al., 2009). The fuel also generates fewer particular matter emissions due to its structure and carbon content, benefitting airport air quality, and produces lower volumes of soot and carbonaceous deposits, decreasing maintenance needs and may potentially extend the lifetime of components such as the combustor and turbine (Hileman et al., 2009; Edwards, 2005). Further, the thermal stability of FT-SPK is higher than that of petroleum jet fuel. This could allow for improvements to the design of engines and fuel systems, and so has potential to increase the operational efficiency of aircraft (Hileman et al., 2009; Edwards, 2005). However several incompatibilities within existing aircraft infrastructure prevent the use of FT-SPK as a neat jet fuel. Its energy density (per unit volume) is 3% lower than petroleum jet due to its low aromatic content and paraffinic composition. This reduces the maximum range of the aircraft – a problem for long-distance flights requiring full fuel tanks (Hileman, Stratton & Donohoo, 2010; Bauen et al., 2009; Hileman et al., 2009). The low aromatic content also creates the risk of fuel leaks in aircraft with nitrile-rubber seals, because the elastomers in these seals expand in the presence of aromatics (Bauen et al., 2009; Hileman et al., 2009). Further, the fuel has lower lubricity, which may worsen wear on engine components (Maniatis, Weitz & Zschocke, 2013; Hileman et al., 2009). These incompatibilities are currently mitigated by limiting the concentration of FT-SPK to 50%⁵ in blends with conventional jet fuel (Hileman et al., 2009). It may be possible to resolve these problems for higher blends through the use of additives such as naphthenic compounds and aromatics. The risk of fuel leaks could be alternatively addressed by limiting the use of neat FT-SPK to aircraft without nitrile-rubber seals (Bauen et al., 2009; Hileman et al., 2009).

Opportunity costs

Fischer-Tropsch synthesis generates a range of products, the distribution of which can be controlled by varying the process conditions. The primary co-products associated with jet fuel production are diesel and gasoline, but chemicals such as hydrogen, methanol, naphtha, paraffins and lubricants can also be manufactured, and heat and power generated (Güell et al., 2012). Maximising production of diesel (rather than kerosene) is particularly attractive in jurisdictions with strict quality standards for road transport fuels such as the EU and the USA, since BTL fuels have both a high cetane number and very low sulphur content (Hileman et al., 2009).

4.2 Hydrotreated depolymerised cellulosic jet

4.2.1 Characterisation

The hydrotreated depolymerised cellulosic jet (HDCJ) pathway encompasses conversion routes based on pyrolysis, hydrothermal liquefaction, or hybrid processes. These generate bio-oils that can be thermochemically upgraded to produce drop-in fuels. The term pyrolysis to jet (PTJ) is also used to describe processes producing jet fuel via pyrolysis.

Pyrolysis

Pyrolysis is the thermal decomposition of organic materials in the absence of oxygen. It produces oils, gases, char and water, with the distribution of each being dependent on the process conditions.

⁵ In practice the blend often has to be lower, due to the variable levels of aromatics in conventional kerosene which may prevent the overall fuel mix from meeting jet fuel specifications (Maniatis, Weitz & Zschocke, 2013).

Low final temperatures (<450°C) and slow heating rates predominantly yield chars, whilst high temperatures (>800°C) and rapid heating rates mainly produce gases.

Fast pyrolysis is a variant which maximises the production of oils, with oil yields of up to 80 wt% of dry feedstock being achievable. The process involves heating finely ground feedstock to a final temperature of 400-600°C for a residence time of a few seconds, then rapidly cooling (quenching) the vapours produced to generate a bio-oil (Radlein & Quignard, 2013; Güell et al., 2012; CSIRO, 2011; Pandey et al.).

Catalysts such as zeolite can be used during pyrolysis to improve the quality of the oil product, for example by increasing aromatic content and/or lowering oxygen content. The resulting oil requires less intensive upgrading than the oil produced by non-catalytic pyrolysis, with the upgrading process crucially consuming less hydrogen, a costly input (SkyNRG, 2014; Brown et al., 2013).

Hydrothermal liquefaction

Hydrothermal liquefaction is similar to pyrolysis, but reacts organic materials in the presence of water and (commonly) catalysts. The process conditions for biomass involve low final temperatures (typically 300-400°C), high pressures (50-200 bar), and residence times of up to 30 minutes (Balan, Chiaramonti & Kumar, 2013; Güell et al., 2012; NABC, 2012; Pandey et al., 2011).

Upgrading processes

Oils produced by pyrolysis typically require more extensive upgrading than those produced by hydrothermal liquefaction. Pyrolysis oil has a high oxygen and water content, low heating value, and poor thermal stability and is highly acidic, chemically unstable, corrosive and immiscible with petroleum (Radlein & Quignard, 2013; Güell et al., 2012; Jones & Male, 2012; Pandey et al.). In comparison hydrothermal liquefaction oil tends to be higher quality, with lower oxygen and water content. However it is not clear from the literature which pathway is the more economical overall. Whilst hydrothermal liquefaction requires less extensive upgrading than pyrolysis, the initial process itself is more expensive (Balan, Chiaramonti & Kumar, 2013; Radlein & Quignard, 2013).

The most commonly employed techniques to upgrade fast pyrolysis oils are two-step hydroprocessing (hydrotreating followed by hydrocracking), and hydrotreating followed by fluid catalytic cracking (Brown et al., 2013; Radlein & Quignard, 2013; Zhang et al., 2013; Jones & Male, 2012). These processes are explained below.

Two-step hydroprocessing

The majority of hydroprocessing approaches being developed to upgrade bio-oils involve two stages of hydrodeoxygenation (Radlein & Quignard, 2013). Typically the whole pyrolysis oil is hydrotreated at low temperatures (around 250°C) and high pressures (<2500 bars) in the presence of a catalyst, before being hydrocracked at higher temperatures (350-400°C) and similar pressures (Brown et al., 2013; Radlein & Quignard, 2013). The resulting product is composed largely of hydrogen with around 20 wt% liquid hydrocarbons, mostly gasoline and jet fuel fractions suitable for drop-in use.

Fluid catalytic cracking

Bio-oils can also be upgraded by a single stage hydrotreatment followed by fluid catalytic cracking, typically using zeolite as a catalyst. This mainly produces commodity chemicals and hence is less commonly applied to the production of transportation fuels (Zhang et al., 2013).

Combined hydrothermal liquefaction and upgrading

Licella's catalytic hydrothermal reactor (CAT-HTR) technology combines hydrothermal liquefaction with upgrading in a single process, converting lignite or biomass feedstocks to fuels and chemicals. Pulverised feedstock is mixed with water to form a slurry, then injected into a continuous-flow reactor. Here the slurry is subjected to near-supercritical water conditions (approximately 300°C temperatures and 250 bar pressures) in the presence of a proprietary catalyst. The process takes around 30 minutes to produce a high energy density bio-crude (34-36 MJ/kg – twice that typical of pyrolysis oil) (ARENA, 2013). The oil produced by CAT-HTR is claimed to be much more stable than oils produced by pyrolysis and thus suitable for co-processing with petroleum crude in a conventional refinery. The process is also claimed to be more energy efficient than conventional pyrolysis, because carbon bonds are not broken during deoxygenation, and to have higher yields, because it can convert lignin as well as cellulosic sugars (Ahlqvist et al., 2013; Baskov & Pantskhava, 2013; BiofuelsDigest, 2013; Biomass Producer, 2013).

Feedstocks

Biomass feedstocks suitable for HDCJ are similar to those for BTL. Most lignocellulosic materials can be used, but the feedstock characteristics affect the composition of the bio-oil: ideal feedstocks contain high levels of volatile matter and low levels of moisture and ash content (Arup URS & E4tech, 2013; Bauen et al., 2009). It is important that it can be readily chipped or reduced to small particles to improve the reaction dynamics (Arup URS & E4tech, 2013).

Integration with other conversion technologies

Bio-oils may be used as a densified feedstock for other fuel conversion pathways. For example Bioliq uses pyrolysis oil in its Fischer-Tropsch process, whilst Metso gasifies pyrolysis oil for fermentation (Bioliq, 2014b; Balan, Chiaramonti & Kumar, 2013).

4.2.2 Commercialisation status

Technological development and commercial activity

Fast pyrolysis of biomass followed by two-step hydrothermal processing or fluid catalytic cracking is in the demonstration stages of development. Conventional pyrolysis of biomass has been deployed at pilot scale since the 1970s and at demonstration scale since the 1990s. However interest in upgrading bio-oils for transport fuel has only developed since the late 1990s (Jones & Male, 2012; Venderbosch & Prins, 2010; Bauen et al., 2009). Today considerable research efforts focus on lowering the cost of upgrading processes, both through improvements to hydrodeoxygenation methods and the development of novel upgrading techniques (Venderbosch & Prins, 2010). Key areas of investigation including the suitability and life cycle of different catalysts, minimisation of hydrogen consumption, and identification of the minimum deoxygenation required to co-process bio-oil in conventional refineries (Arbogast et al., 2013; Radlein & Quignard, 2013; NABC, 2012; BIOCOUP, 2011; Bauen et al., 2009). These new approaches are mostly in the laboratory or pilot stages of development (VTT, 2014; Venderbosch & Prins, 2010).

The slow commercialisation of fast pyrolysis technologies is blamed in part on the lack of market demand for unrefined bio-oil (Radlein & Quignard, 2013). Recent years have seen the closure of several pilot plants across Europe and the cancellation of proposed projects due to weak market conditions (BillerudKorsnäs, 2013; Venderbosch & Prins, 2010). Organisations in Europe which do

have operational fast pyrolysis pilot plants include Bioliq, Metso and the Biomass Technology Group (BTG), which is also developing a commercial-scale plant. Both the Bioliq and Metso plants are producing bio-oil for use as a gasification feedstock. The BTG plants are not aiming to produce upgraded products at present (Bioliq, 2014a; BTG, 2014b; EMPYRO, 2014).

With regards to jet fuel, major players globally include Envergent (a collaboration between Ensyn and Honeywell UOP, using fast pyrolysis/hydroprocessing), Dynamotive/Renewable Oils Corporation (ROC) (fast pyrolysis /hydroprocessing), KiOR (catalytic fast pyrolysis/fluid catalytic cracking) and Licella (CAT-HTR technology) (Radlein & Quignard, 2013)(Zhang et al., 2013; Green Car Congress, 2011). Apart from Envergent all of these operate or have operated demonstration-scale plants capable of producing jet fuel, and have plans to develop larger-scale facilities (Biomass Producer, 2013; Radlein & Quignard, 2013; Green Car Congress, 2011). Licella has memoranda of understanding to develop aviation fuels with Virgin Australia and Air New Zealand, and ROC has a memorandum with Virgin Australia (Virgin Australia, 2014; Biomass Producer, 2013).

Certification status

HDCJ is not ASTM certified at present. Test data on KiOR's process have been compiled in a research report and submitted for review by the OEMs. The fuel is expected to be approved for blends with petroleum kerosene in 2015 (SkyNRG, 2014; IATA, 2013; Lamoureux, Lew & Biddle, 2013).

Licella's CAT-HTR process is not expected to receive ASTM jet fuel certification in the short to medium term (Qantas, 2013).

Fuel readiness level

Based on the current status of the industry, fast pyrolysis followed by either two-step hydroprocessing or FCC and Licella's CAT-HTR technology are considered to be at FRL level 6. These technologies have already been scaled from laboratory to pilot stages and demonstration/early commercial scale plants are being developed. Some developers are collating data for ASTM D4054 tests.

Pyrolysis of biomass to produce oils or chars without upgrading is a more mature technology. The FRL of fuels produced using these products as feedstock depends on the maturity of the secondary conversion process (Güell et al., 2012).

4.2.3 Opportunities and challenges for use in aviation

Fuels produced from hydroprocessed pyrolysis oils route have high aromatic content, low oxygen content and few impurities – all desirable characteristics for jet fuel applications (BTG, 2014a; Radlein & Quignard, 2013; Zhang et al., 2013; Blakey, Rye & Wilson, 2011; CSIRO, 2011; Wright et al., 2010). However, upgrading bio-oil to jet fuel requires extensive hydrodeoxygenation, entailing the consumption of large quantities of hydrogen (around 4wt%) at considerable expense. Further catalyst lifetimes tend to be short and hydrocarbon yields modest (around 20wt%) (Radlein & Quignard, 2013). Some authors consider these costs to prohibit the production of fractions that are predominantly in the jet fuel range (Güell et al., 2012).

There is however interest in producing smaller volumes of jet fractions from bio-oils, and using these to create renewable additives for BTL and HEFA jet fuels (Maniatis, Weitz & Zschocke, 2013; Güell et al., 2012). These fuels contain insufficient aromatics in neat form to meet ASTM specifications, a

problem that is currently overcome through the addition of aromatics derived from fossil fuels or by lowering the concentration of BTL/HEFA in blends with conventional jet fuel (Maniatis, Weitz & Zschocke, 2013; Hileman et al., 2009). Initial assessments indicate that the addition of synthetic aromatics to neat HEFA and BTL increases the similarity of their performance to conventional jet (ALFA-BIRD, 2012; Novelli, 2011).

Pyrolysis can also be used to improve the logistics and economics of feedstock transportation, through densification of bulky biomass. This can increase the economically accessible volumes of feedstock supply for centralised plants, benefitting conversion pathways such as BTL for which economies of scale are significant. Both chars and bio-oil may be of interest for such applications (Maniatis, Weitz & Zschocke, 2013; Bauen et al., 2009).

4.3 Alcohol to jet

4.3.1 Characterisation

Alcohol to jet (ATJ) refers to the family of conversion pathways that produce jet fuel from biomass via an alcohol intermediate. Both drop-in and neat jet fuels are being targeted by ATJ developers, with some attention being paid to the potential of butanol as a jet fuel end-product, rather than an intermediate. Drop-in fuels under development include synthetic paraffinic kerosene (ATJ-SPK) and synthetic kerosene with aromatics (ATJ-SKA).

Process description

A wide range of processes can be used to synthesise alcohols, depending on the characteristics of the feedstock. Sugars can be directly converted to alcohols through fermentation with yeasts or microbe, whilst starches are converted via acidic or enzymatic hydrolysis (to release sugars), followed by fermentation. Conversion of lignocellulosic feedstocks is more complex, involving either aggressive hydrolysis followed by fermentation, or thermochemical conversion (e.g. gasification to produce a syngas) followed by fermentation or catalytic hydrogenation to synthesise alcohols (Teelucksingh, 2013; Güell et al., 2012; Rosillo-Calle et al., 2012).

The alcohols produced undergo a four-step upgrading process to create hydrocarbons in the jet fuel range. First they are catalytically dehydrated to generate olefins, then oligomerised, typically in the presence of catalysts, to produce a middle distillate containing diesel and kerosene fractions. Finally the middle distillates are hydrogenated and distilled (Teelucksingh, 2013; Güell et al., 2012; Rosillo-Calle et al., 2012).

Feedstocks

A wide range of biomass feedstocks are suitable for ATJ, including forestry and agricultural residues, starches and sugars, as well as municipal solid waste (Arup URS & E4tech, 2013; Güell et al., 2012). Ideal biomass feedstocks are highly porous, contain low levels of highly soluble lignin and have low ash and acetyl content (as this can inhibit fermentation). The cellulose and hemicellulose should be highly reactive, have a low degree of crystallinity, and preferably contain a greater balance of hexose than pentose sugars, since these are cheaper and easier to ferment (Arup URS & E4tech, 2013).

Alcohols can also be synthesised from industrial waste gases containing CO and CO₂, for example flue gases from the steel industry. This avoids the need to develop a separate feedstock supply chain and allows the CO₂ emissions to be reused before entering the environment (Güell et al., 2012).

4.3.2 Commercialisation status

Technological development and commercial activity

Technologies in the ATJ pathway bridge the pilot and demonstration stages of development. The individual technical processes employed are themselves considered to be mature, being widely used in commercial petrochemical applications (Güell et al., 2012). However, there is significant variation in the maturity of complete feedstock-to-fuel process chains, depending on the feedstock utilised and alcohol intermediate targeted. In general technologies to synthesise alcohol intermediates are better developed than those to convert the intermediates to jet fuel (Güell et al., 2012).

Synthesis of alcohols

A wide range of alcohols are in principle suitable for conversion to biojet, however currently most efforts target the ethanol and butanol produced from biomass⁶ (Güell et al., 2012; IATA, 2012a; IATA, 2011). Research into the synthesis of other alcohols remains at the laboratory scale (ALFA-BIRD, 2012). The cost of alcohol production is considered to be the greatest barrier to commercialisation of ATJ fuels at present (Güell et al., 2012). Particular challenges relate to the inherent difficulties of managing microorganisms in an industrial fermentation process, such as the rate of conversion of feedstocks to alcohols (which is low compared to chemical refineries), and the sensitivity of microorganisms to impurities (including by-products generated in situ) (Güell et al., 2012).

Bioethanol derived from 'first generation' sugar and starch feedstocks has been produced commercially for several decades. It is a mature technology that serves a large commodity market: some 108 billion litres of bioethanol were produced globally in 2012, the vast majority from sugar and starch feedstocks (Renewable Fuels Association, 2014; Güell et al., 2012). Conversion of lignocellulosic biomass to ethanol is much more novel. In 2013 BioChemtex and Ineos-Bio opened the world's first two commercial-scale plants in Italy and the USA respectively (European Biofuels Technology Platform, 2014; Beta Renewables, 2013).

Commercial production of biobutanol by the 'acetone-butanol-ethanol' (ABE) fermentation process was widespread until the 1950s, when it was replaced by a cheaper process using petroleum feedstocks (Hileman et al., 2009). Interest in the product has re-emerged in recent years, in part due to the superiority of its fuel characteristics compared to ethanol (Güell et al., 2012). Some ABE facilities are operational in China and several companies are developing alternative production methods, including retrofit solutions for existing ethanol facilities (Arup URS & E4tech, 2013). Butamax and Gevo have operational demonstration plants producing butanol and isobutanol from sugar and starch feedstocks, whilst Cobalt plans to retrofit lignocellulosic butanol demonstration facilities at an ethanol refinery in Michigan and a sugar mill in Brazil (BiofuelsDigest, 2014b; Butamax, 2014; Cobalt Technologies, 2012b). In general efforts to scale-up biobutanol over the last five years have been considerably slower than industry expectations (Arup URS & E4tech, 2013). Lignocellulosic butanol is expected to progress slowly until technologies for first-generation butanol and lignocellulosic ethanol become more advanced (Arup URS & E4tech, 2013).

⁶ There is also significant interest in the production of biomethanol, but this is not being used to develop aviation fuels (Arup URS & E4tech, 2013).

Fermentation of syngas (from lignocellulosic biomass or industrial gases) is at the demonstration stage of development (Arup URS & E4tech, 2013; Güell et al., 2012). Lanzatech, Enerkem and INEOS Bio have operational demonstration plants respectively producing alcohols from steel mill waste gases, MSW and mixed organic materials (Enerkem, 2014; INEOS Bio, 2014; Lanzatech, 2014). Lanzatech and Enerkem are developing plans for commercial-scale facilities.

Conversion of alcohols to jet fuels

Technologies to convert alcohols to jet fuels are at the laboratory and pilot stages of implementation. No details of operational dedicated pilot plants were identified in the literature. However a number of organisations are working in this area, several in collaboration with alcohol producers in order to create a complete biomass-to-fuel ATJ process. Of these, partnerships specifically interested in jet fuel include BioChemtex/Gevo, Cobalt/Albemarle Corporation/NREL and Lanzatech/Swedish Biofuels (Chiaramonti, 2013; Cobalt Technologies, 2012a; Swedish Biofuels, 2011). ZeaChem has also received funding from the US government for laboratory-scale development of an integrated ATJ process (ZeaChem, 2012).

There are also several active partnerships between fuel developers and aviation operators. Cobalt has an agreement to develop jet fuels with the US Navy, including plans to establish a pilot plant in partnership with NREL, which will process lignocellulosic biomass via n-butanol intermediates (BiofuelsDigest, 2014a). Lanzatech/Swedish Biofuels have fuel development agreements with Virgin Atlantic, the US Ministry of Defence and the Swedish Defence Material Administration (Swedish Biofuels, 2011). The partnership is evaluating possible locations for a demonstration plant capable of producing 57 million litres of biojet per annum from industrial waste gases - enough to fuel Virgin's Shanghai-London route (Downing, 2014; Teelucksingh, 2013). Gevo is being supported by Lufthansa and the US Air Force to test its fuel samples (Gevo, 2014a; Gevo, 2014b).

Certification status

Test data for ATJ-SPK route have been compiled in a research report and submitted for review by the OEMs for preliminary review (Rumizen, 2014; IATA, 2013). Industry stakeholders expect that ATJ-SPK will be ASTM certified by the end of 2014, however opinion is divided as to whether the fuel will be certified for use as a blended (< 50%) or neat drop-in fuel (SkyNRG, 2014; Qantas, 2013; Güell et al., 2012)

Certification of ATJ-SKA is not expected before 2015, but may be suitable for use in blends of up to 100% as it contains aromatics (SkyNRG, 2014).

Cobalt and American Progress are developing a method to produce jet fuel from butanol in partnership with the US Navy. This has passed the early stages of the Navy's fuel certification scheme (Qantas, 2013).

Fuel readiness level

Overall the alcohol-to-jet pathways identified are considered to have FRLs ranging from 4 to 6. The lower end of this represents fuels which are still undergoing laboratory-scale research and development (e.g. ZeaChem), whilst the upper end corresponds to technologies which are being scaled-up to demonstration stage and which are being tested for certification purposes (e.g. Cobalt).

4.3.3 Opportunities and challenges for use in aviation

Compatibility with existing systems and technical barriers

Neither ethanol nor butanol are currently considered suitable for direct blending with conventional jet fuel (Hileman & Stratton, in press; ALFA-BIRD, 2012; Hileman et al., 2009). The high volatility and low flash point of both are considered to present a safety hazard on board aircraft. Ethanol in particular may corrode effects on fuel handling systems and has a tendency to attract water (which would freeze at altitude). Further, the specific energy and energy density of ethanol and butanol are significantly lower than for conventional Jet A (approximately 40% and 23% for the two alcohols respectively) (Hileman et al., 2009). This would reduce the maximum payload and range of flights, with estimates impacting up to 55% and 36% of operations (in the case of ethanol and butanol) (ibid.). Nonetheless, some authors suggest that higher alcohols (including butanol) may be suitable for use in jet fuel blends in the longer term (Qantas, 2013; ALFA-BIRD, 2012).

Despite their unsuitability for direct use in blends with Jet A, the fuels produced by upgrading ethanol and butanol are thought to be highly compatible with existing aviation infrastructure. Unlike BTL and HEFA fuels they contain aromatics, negating the need for additives (Güell et al., 2012). Proponents of the ATJ pathway are hopeful that ATJ fuels may be suitable for use as neat jet fuels (IATA, 2013; Maniatis, Weitz & Zschocke, 2013).

Opportunity costs

Non-upgraded ethanol and butanol are considered to be suitable for use in ground transportation (Hileman & Stratton, in press; Hileman et al., 2009). The safety concerns and operational limitations highlighted for non-upgraded use in aviation do not apply to road vehicles, and both have a high octane rating which is a desirable characteristic for automotive fuels. Butanol is particularly well-suited as a blend stock for gasoline, having sufficiently similar physical and chemical properties to allow high concentration blends to be used in unmodified engines and the existing fuel supply infrastructure. Unlike ethanol, it can also be blended with petroleum fuels at conventional refineries (Hileman et al., 2009). The potential to use these alcohols in ground applications without the need for expensive upgrading processes suggests that their commercial value may be higher as an automotive fuel than an aviation fuel, particularly in the case of butanol.

4.4 Fermentation to jet

4.4.1 Characterisation

The fermentation to jet (FTJ) pathway produces alkane-type fuels from sugars via anaerobic fermentation. This is different to the ATJ pathway, which involves the production of an alcohol intermediate. FTJ is also known as direct sugar to hydrocarbons (DSHC) or direct fermentation of sugar to jet (DFSTJ), and the ASTM-certified jet fuel is called synthesised iso-paraffinic fuel from fermented hydroprocessed sugar (SIP).

Process description

FTJ approaches under development involve the conversion of sugars to isoprenoids by genetically modified organisms or yeasts. The isoprenoids are then polymerised to produce a range of hydrocarbons, which are in turn hydroprocessed to create fuel blend stocks (SkyNRG, 2014; Davis et al., 2013; Serrano-Ruiz, Ramos-Fernandez & Seplveda-Escribano, 2012).

The specific process conditions employed by different companies are not widely available in the literature. Davis et al. (2013) describe a FTJ process involving the following six major steps: pre-treatment, enzymatic hydrolysis, hydrolysate clarification, biological conversion, product purification and hydroprocessing.

Feedstocks

FTJ approaches can most easily process sugary feedstocks such as sugarcane, sweet sorghum, and maize. Crude glycerine from biodiesel production is also being investigated as a feedstock. There is potential to use lignocellulosic sugars, however the increased complexity of fermenting these feedstocks means they are not the focus of current research efforts (REG, 2014b; SkyNRG, 2014; Milbrandt, Kinchin & McCormick, 2013; CSIRO, 2011).

4.4.2 Commercialisation status

Technological maturity

The FTJ pathway is considered to be at the pilot stage of development, with a single producer, Amyris, identified as advancing towards demonstration and early commercialisation of a jet fuel product. Some companies are focussing on the extraction of high-value chemicals instead of biofuels (Arup URS & E4tech, 2013).

Amyris and Total's joint Biofene technology is the most advanced in this pathway. The process uses sugarcane-derived glucose to produce the isoprenoid farnesene, which is used as the basis for a range of petroleum replacement products. Amyris' first commercial plant in Brotá, Brazil, has been operational since December 2012, with the capacity to produce up to 50 million litres of farnesene per annum, and by June 2013 the company had produced 90,000 litres of jet fuel (Maniatis, Weitz & Zschocke, 2013; Total, 2013). Amyris has a memorandum of understanding to develop jet fuel with GOL Linhas Aéreas Inteligentes, which plans to use at least 1% biojet blends in its fleet from 2016 (Amyris, 2014; Amyris, 2013).

Another proprietary technology at an advanced stage of development is that of REG Life Sciences (formerly LS9). A pilot plant has been operational since 2008, and the process can use a range of feedstocks including lignocellulosic sugars. It is not clear whether REG is actively pursuing jet fuel production at present, although this has been considered in the past (REG, 2014a; Wesoff, 2010).

Certification status

Amyris and Total's SIP fuel was certified for blends of up to 10% with petroleum-derived jet in June 2014 (Annex A3 of ASTM D7566) (A4A, 2014a). At the time of writing no other FTJ approaches to producing biojet are being considered for ASTM certification.

Fuel readiness level

The Amyris/Total FTJ fuel is considered to have a FRL of 7 moving towards 8. This corresponds to a fuel already certified and listed in international standards, for which demonstration plants are operational and the first commercial-scale facilities are being developed, and which has good potential to secure a fuel purchase agreement. Publically available literature is insufficient to assess the FRL of FTJ fuel produced by other companies, but since none are pursuing ASTM certification FRL 5 can be assumed as a maximum.

4.4.3 Opportunities and challenges for use in aviation

The concentration of SIP which can be used in blends with petroleum jet is limited because it is not a mixture of hydrocarbons, and therefore does not meet some of the ASTM performance standards (for example, density and boiling range) (SkyNRG, 2014).

4.5 Aqueous phase reforming

4.5.1 Characterisation

Aqueous phase reforming (APR) is a catalytic process that converts soluble plant sugars into a mixture of water, hydrogen and chemical intermediates (such as alcohols, ketones, acids, furans, paraffins and other oxygenated hydrocarbons). These can in turn be converted to fuels and high value chemicals (Virent, 2014a; Tompsett, Li & Huber, 2011; Bauen et al., 2009).

Alternative names for the process include sugar to hydrocarbons via catalysis, catalysis of lignocellulosic sugars and aqueous phase processing (APP). The fuels produced by APR are called hydrodeoxygenated synthetic kerosene with/without aromatics (HDO-SAK/HDO-SK).

Process description

The first step of the APR process is pretreatment of the biomass feedstock, to extract carbohydrate fractions which are subsequently dissolved in water. The solution is reacted with a mixture of catalysts at moderate temperatures (around 230°C) and pressures to reduce its oxygen content. This involves several reactions including: reforming to generate hydrogen, dehydrogenation of alcohols and hydrogenation of carbonyls, deoxygenation, hydrogenolysis, and cyclisation. Hydrogen consumed during the process can be generated in-situ from the feedstock (Virent, 2014a; Güell et al., 2012; Tompsett, Li & Huber, 2011; Bauen et al., 2009).

Three alternative secondary steps have been identified to convert the products of APR into biofuels, as follows:

- The intermediates can be subjected to additional catalytic processing to produce a gasoline with high levels of aromatics and a high octane rating. Virent has developed this approach as a proprietary technology ('Bioforming') using a modified catalyst, ZSM-5 (Virent, 2014a).
- The chemical intermediates can alternatively be converted to hydrocarbons (predominantly alkanes) by condensation followed by hydro-deoxygenation (Virent, 2014a; Tompsett, Li & Huber, 2011).
- The APR intermediates can also be subjected to dehydration, oligomerisation and saturation to produce the hydrocarbon fractions for diesel, gasoline or kerosene (Tompsett, Li & Huber, 2011).

Feedstocks

APR uses soluble plant sugars, which may be derived from sugar, starch or lignocellulosic feedstocks for example: maize, sugarcane, sugar beet, sweet sorghum; bagasse, corn stover, grasses, wood, high performance sorghum (Virent, 2014c; Novelli, 2011).

4.5.2 Commercialisation status

Technological maturity

APR technologies to produce biofuels in general are considered to be at the R&D and pilot stages of development (Arup URS & E4tech, 2013; Güell et al., 2012). Virent is the sole organisation identified that has reached an advanced stage of jet fuel development. The company has two demonstration facilities with a combined annual production capacity of almost 60,000 litres of fuels and chemicals (Qantas, 2013; Virent, 2013).

Certification status

ASTM test data for Virent's biojet product are being compiled for a research report (Virent, 2014d). No other APR fuels were identified as currently being considered for ASTM certification.

Fuel readiness level

Jet fuel produced by Virent's 'Bioforming' technology is considered to be at FRL level 6. This corresponds to a technology which has already been scaled from laboratory to pilot stage, and which is undergoing assessment for ASTM certification.

4.5.3 Opportunities and challenges for use in aviation

Virent is developing two drop-in products: Renewable Paraffins and Naphthenes (RPN), which consists of C9-C16 paraffins and naphthenes, and an Aromatic Renewable Jet Blendstock (ARJB) which consists of C9—C11 aromatics (Virent, 2014b). ARJB is considered suitable for blends of 8-20% with synthetic paraffinic fuels (including RPN) and conventional petroleum jet. RPN is considered to have the potential to be blended at concentrations greater than 50% with conventional petroleum jet (Imrie, 2011). Virent claims that a fully renewable jet fuel could be created by blending ARJB and RPN, since in combination the two products contain sufficient normal and iso-paraffins, naphthenes and aromatics to meet key jet fuel specifications without the need for additives (Virent, 2014b). Test results published at the time of writing have not identified any incompatibilities with jet fuel specifications (Virent, 2014d).

4.6 Lignin to jet

4.6.1 Characterisation

Data on the lignin to jet pathway is very limited. The only technology that has been identified is Biochemtex's proprietary MOGHI process.

Process description

MOGHI has been designed to integrate with Beta Renewables' PROESA technology (invented by BioChemtex), which produces bioethanol from lignocellulosic biomass. The pretreatment stage of PROESA separates lignin from cellulose and hemicellulose using steam. During the MOGHI process the lignin is catalytically deoxygenated and depolymerised, then purified, before the desired end-products are separated. MOGHI uses a common industrial catalyst and hydrogen (generated and recovered as part of the process itself) (BioChemtex, 2014).

MOGHI's main target outputs are BTX aromatics (benzene, toluene and xylene) but it also produces bio-naphtha. These products can be converted into high value chemicals and fuels (including jet fuel) by standard industrial processes (BioChemtex, 2014).

Feedstocks

Beta Renewables' pilot and demonstration MOGHI plants use lignin residues from the PROESA process, but there may also be potential to use lignin collected from raw materials (Maniatis, Weitz & Zschocke, 2013).

4.6.2 Commercialisation status

Technological maturity

A MOGHI pilot plant has been operational since 2012 at the Sharon Center, Ohio and construction of a demonstration plant is underway. This is being retrofitted to Beta Renewables' existing bioethanol plant in Crescentino, Italy, and is expected to become operational during 2014. The demonstration plant aims to produce 2,000 tonnes/year of jet fuel by 2017 (BioChemtex, 2014; IATA, 2013; Maniatis, Weitz & Zschocke, 2013).

Certification status

This pathway is not being considered for ASTM certification at present.

Fuel readiness level

As a technology with an operational pilot plant and construction of a demonstration plant ongoing, MOGHI is considered to have a FRL of 5. It is beginning to move towards FRL 6 but this may take some time to achieve, as it has not yet made significant progress towards the certification of jet fuel.

4.6.3 Opportunities and challenges for use in aviation

MOGHI has been designed to integrate with PROESA. The potential to retrofit plant to other industrial processes has not been investigated in depth.

4.7 Summary

A large number of technologies to produce 'drop in' jet fuel from biomass are under development. This chapter reviewed the technical suitability of six conversion pathways considered to have potential to process lignocellulosic feedstocks. Of these five are pursuing ASTM certification and the sixth is designed specifically to process lignin. Figure 4-3 compares the fuel readiness level (FRL) of the pathways. Table 4-3 summarises of the technological and commercial factors which have informed this judgement.

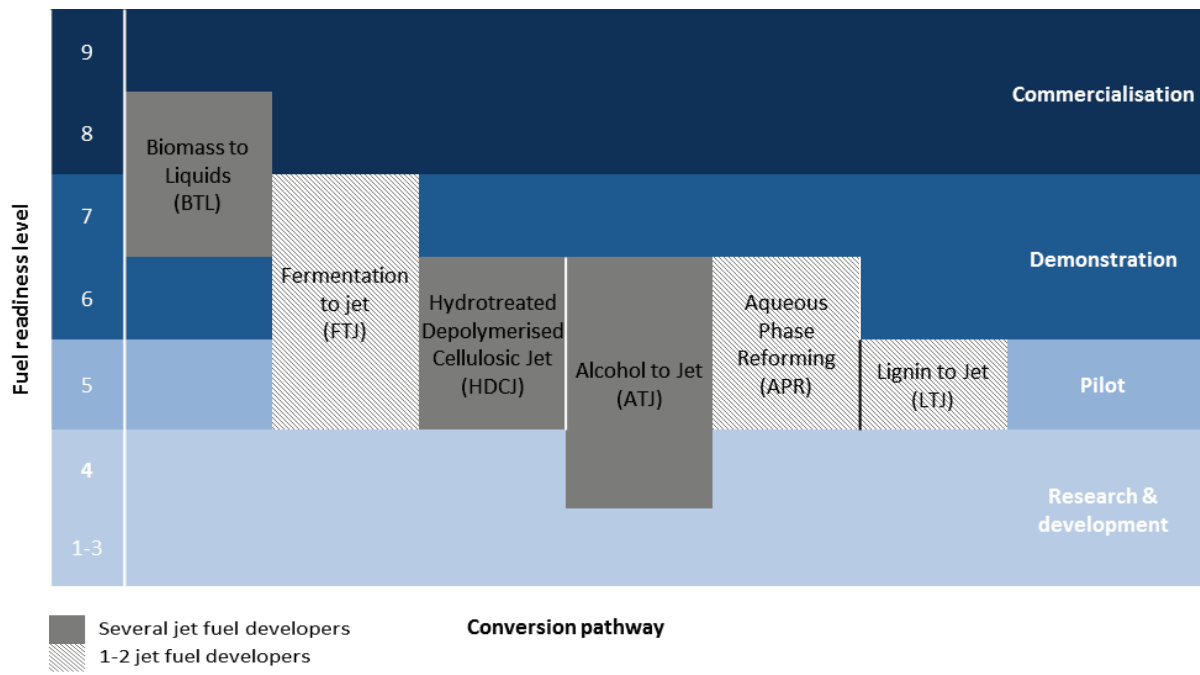


Figure 4-3 Current fuel readiness levels of biojet conversion technologies

Table 4-3 Summary of factors contributing to assessment of FRL status.

Conversion pathway	BTL	ATJ	HDCJ	FTJ	APR	LTJ
Certification status	ASTM certified for blends <50%.	Not certified. Expected 2014 for SPK, 2015 onwards for SKA.	Not certified. Expected 2015 for KiOR's process.	ASTM certified for blends <10%.	Not certified.	Not certified
Industry status	<ul style="list-style-type: none"> • Several pilot plants in operation • Commercial plants to produce jet under development in Europe, projected start-up 2015-2018. • Operational commercial plants mainly focus on diesel. • Some fuel purchase agreements with airlines. • Evidence of use in commercial flights not identified. • Several developers have suffered insolvency in recent years and/or cancelled planned plant. 	<ul style="list-style-type: none"> • Production of bio-alcohols: sugar/starch ethanol - commercially mature; lignocellulosic ethanol - early commercialisation; butanol (all feedstocks) – demonstration. • Technologies to convert alcohols to fuel less well developed. • Several partnerships between companies producing alcohols and those converting alcohols to fuels. Demonstration plants for complete ATJ process are being developed with operations expected to commence before 2020. • Collaborations with airlines and military organisations to develop fuels, with some fuel purchase agreements. 	<ul style="list-style-type: none"> • Several demonstration plants in operation (or previously operational). • Plans to further scale-up technology under development. • Some collaborations with airlines to develop fuels. 	<ul style="list-style-type: none"> • Development driven largely by single consortium (Amyris/Total) • Some pilot plants in operation. Amyris has an operational commercial plant. • Collaboration between Amyris and the airline GOL Linhas Aéreas Inteligentes to develop jet fuel. • Evidence of use in commercial flights not identified. 	<ul style="list-style-type: none"> • Development driven largely by single organisation (Virent). • Some demonstration facilities in operation. • No plans for commercial facilities identified. • No collaborations with airlines identified. 	<ul style="list-style-type: none"> • Beta Renewables has an operational pilot plant. • Demonstration plant expected to start-up in 2014, producing jet from 2017.
Technological strengths	<ul style="list-style-type: none"> • Indirect gasification technologies avoid need for external hydrogen. • Range of viable gasification technologies increases flexibility to 	<ul style="list-style-type: none"> • Well understood and developed technology to synthesise alcohols for the production of road transport fuels. • Potential to use low-cost feedstocks (lignocellulose, MSW, 	<ul style="list-style-type: none"> • Considered suitable for small-scale refineries. • Fuel contains aromatics – pathway may be suitable to produce bio-based additives for 		<ul style="list-style-type: none"> • No incompatibilities with ASTM specifications identified by preliminary tests. 	<ul style="list-style-type: none"> • Uses lignin residues from BioChemtex's PROESA process as feedstock.

	<p>use feedstock from a range of sources. Composition of syngas produced varies little according to feedstock.</p> <ul style="list-style-type: none"> • Wide range of potential co-products could bolster profitability. 	<p>industrial waste gases).</p> <ul style="list-style-type: none"> • Potential for use in high blend concentrations – no need for aromatic additives. • Wide range of revenue-generating by-products. • Low hydrogen consumption. 	<p>BTL and HEFA fuels.</p> <ul style="list-style-type: none"> • Pyrolysis suitable as a pretreatment for other conversion pathways. 			
Technological challenges	<ul style="list-style-type: none"> • Catalyst very susceptible to deactivation in the presence of impurities • Potential competition between production of jet fuel and by-products. • Gasification processes require optimisation, especially to minimise production of tars. • Attractiveness of FT fuels for road transport may disincentivise production of jet fuels. 	<ul style="list-style-type: none"> • Technologies to convert alcohols to fuels less well developed. • Cost of alcohol production is high, particularly for lignocellulosic feedstocks. • Microorganisms difficult to manage at industrial scale. • Potential competition with production of road transport fuels. 	<ul style="list-style-type: none"> • More sophisticated equipment requirements for the clean-up stage when compared with FT route • High costs associated with hydroprocessing. 	<ul style="list-style-type: none"> • Very limited data on production processes. • Small number of developers. • Process yields and costs influenced by enzyme load. • Leading process uses sugar-based feedstocks. Technologies using lignocellulosic feedstocks at an earlier stage of development. 	<ul style="list-style-type: none"> • Single major developer. • Very limited data on production processes. 	<ul style="list-style-type: none"> • Single major developer. • Application at scale and integration with industrial processes other than PROESA yet to be demonstrated.
Examples of industry players	<p>Air Liquide, Axens, CEA, ForestBtL, KIT Bioliq, NSE Biofuels, Rentech, Solena, ThyssenKrupp Industrial Solutions, TRI, UPM.</p>	<p>Jet fuel: BiocChemtex, Cobalt, Gevo, Lanzatech, Swedish Biofuels, ZeaChem</p> <p>Other transport fuels:</p> <p>Butamax, Enerkem, Ineos.</p>	<p>Jet fuel: Envergent (Ensyn/Honeywell UOP), Dynamotive Energy Systems, Renewable Oils Corporation, Licella, KiOR.</p> <p>Other bio-oil producers: Bioliq, Metso, Biomass</p>	<p>Jet fuel: Amyris</p> <p>Other fuels: REG Life Sciences, University of Wisconsin, USA (links with REG).</p>	<p>Virent</p>	<p>Beta Renewables</p>

Technology Group.

5 Economic assessment

This chapter examines available data on the economics of biojet conversion technologies. In particular it reviews contemporary estimates of production costs, projections for future costs and potential opportunities for cost reductions, and the competition between biojet and other biofuels and biochemical for producers.

The analysis focuses on data specific to biojet and not biofuels in general. Estimates have been included only if underlying methods and assumptions are publically available for examination; estimates without such an explanation (including quotes from producers cited in media reports) have been excluded. Only a small number of cost estimates meeting these criteria were identified. As for the technological and commercial assessment of the biojet pathways, the breadth and depth of available economic data varies between the pathways, with the greatest level of information being available for the most developed pathways (specifically BTL, and to a lesser extent ATJ).

5.1 Contemporary cost estimates

5.1.1 Levelised costs and minimum selling prices

6 estimates of the levelised cost of production (LCOP) and 14 estimates of the minimum selling prices (MSP) of biojet fuel were identified by the review, as outputs of 11 studies⁷. These are illustrated in Figure 5-1, normalised to 2013 USD for comparison. Prices paid by the US Department of Defence (DoD) for biojet fuel over 2011-2012 and the average price of conventional jet fuel in 2013 are also shown.

Figure 5-1 clearly demonstrates the current high cost of biojet fuel relative to conventional kerosene; the majority of estimates are at least double the average price of kerosene in 2013, \$0.77/litre (A4A, 2014b). It also shows that estimates for the BTL, ATJ and FTJ pathways overlap considerably, with mid-range values lying between \$1.20-\$2.20/litre. However the small number and uneven distribution of estimates make it imprudent to draw firm conclusions about the relative levelised cost/MSPs of the pathways⁸.

Interestingly, the average prices paid by the US DoD for ATJ and FTJ fuels are several times higher than the modelled estimates for these pathways, at 14.75 US\$/litre and 6.43 US\$/litre respectively (Blakeley, 2012). These figures may include costs for research and development as well as fuel production, making comparison with the modelled estimates difficult. Nonetheless, the scale of disparity between the figures raises questions about 'appraisal optimism' (under-estimation of costs), a phenomenon that has been widely observed of early-stage levelised cost estimates for other technologies (Gross et al., 2013). The biojet estimates identified are drawn from theoretical studies rather than project budgets, so are likely to be based on simplified systems and may not fully

⁷ The LCOP of biojet fuel represents the lifetime average (levelised) selling price that would be needed for an investment in biojet fuel production to break even. The MSP represents the lifetime average selling price that would be required for the investment to achieve a desired internal rate of return (IRR). The MSPs identified have IRRs ranging from 10-25%. Only estimates which are contemporary or projected for the very near term have been included in this study.

⁸ Over half of the estimates are for the BTL pathway. For each of the other pathways a maximum of two studies were identified that provided levelised cost/price data - with none identified for HDCJ or LTJ.

account for risks. In the absence of data from existing plants several make significant assumptions about the similarity of different technologies - for example, the only MSP estimate for APR is based on system costs for HEFA, an alternative conversion pathway (Novelli, 2011). Others anticipate learning curve effects which may or may not be realised, such as the ATJ MSP estimates by Staples et al. (2014).

Variation in the scope and underlying assumptions of the individual estimates similarly makes them difficult to compare on an equal basis. Inclusion or exclusion of particular factors can significantly affect the costs calculated, and thus conclusions about which technologies and processes are the most cost-effective. One conspicuous example is the level of IRR, which ranges from 0% (for levelised costs) to between 10% and 25% (for MSPs), and has an equivalent impact on the overall price estimated.

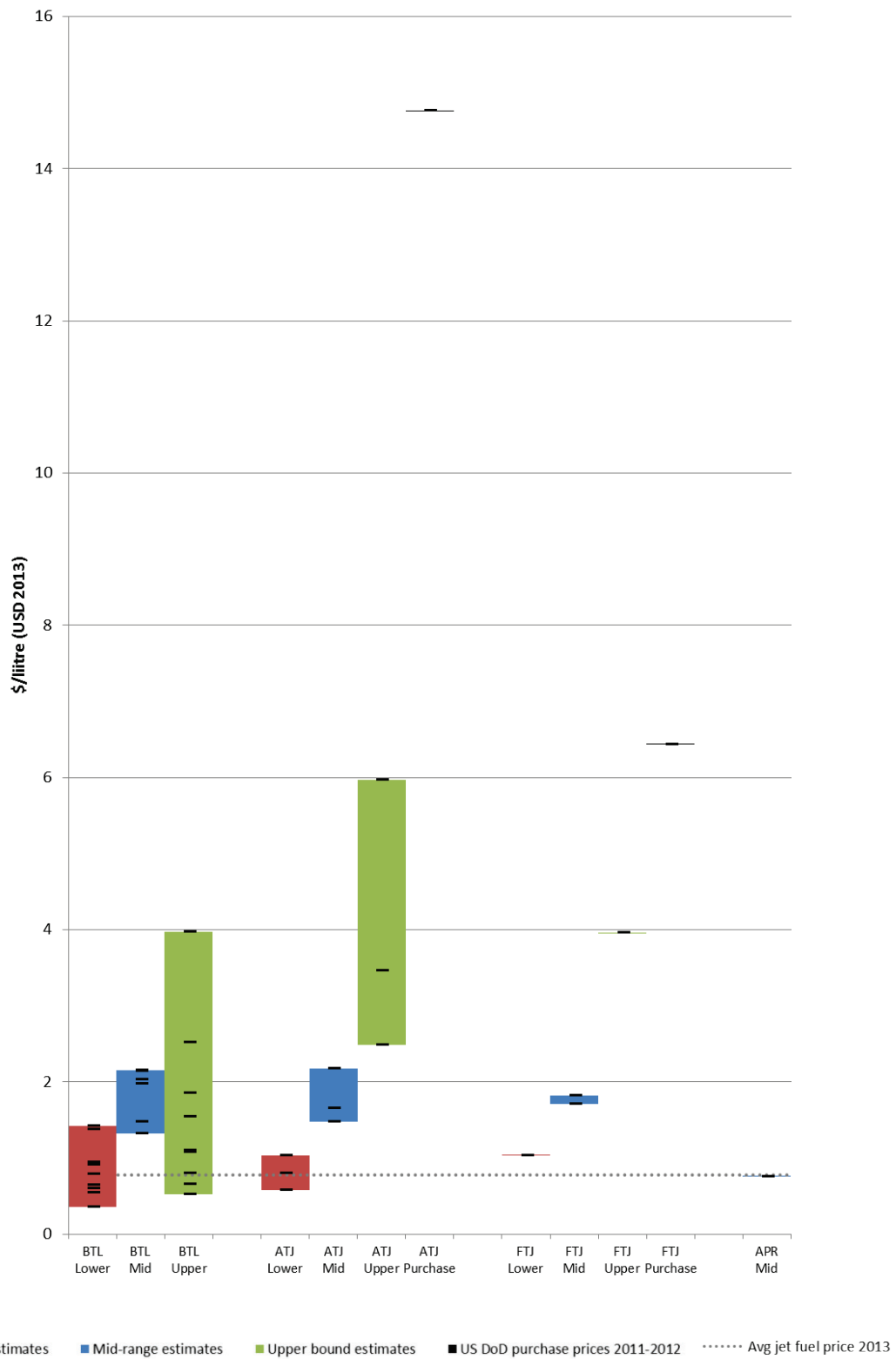


Figure 5-1 Levelised cost of production and minimum selling price estimates for alternative aviation biofuel pathways (Biomass to Liquids - BTL; Alcohol to jet - ATJ; Fermentation to Jet – FTJ; Aqueous phase reforming – APR)⁹. Source data:

⁹ Cost and production data have been collated from a mixture of sources in various formats. The following assumptions have been used to convert the data to common units.

- Currency conversion rates: 1 GBP = 1.67255 USD; 1 EUR = 1.388105 USD; 1 AUS = 0.90318 (XE, 2014).

Staples et al. (2014); IATA (2013); Klein-Marcuschamer and Blanch (2013); ALFA-BIRD (2012); Blakeley (2012); IATA (2012b); Agusdinata et al. (2011); Novelli (2011); Bauen et al. (2009); Hileman et al. (2009); IATA (2009).

5.1.2 Capital costs

10 capital cost estimates for biojet production facilities were identified, ranging from US\$ 36 million to US\$ 815 million. Figure 5-2 illustrates that, whilst the absolute level of capital investment for biojet facilities is expected to be large (particularly for BTL), the data are insufficient compare the relative capital cost of different technologies.

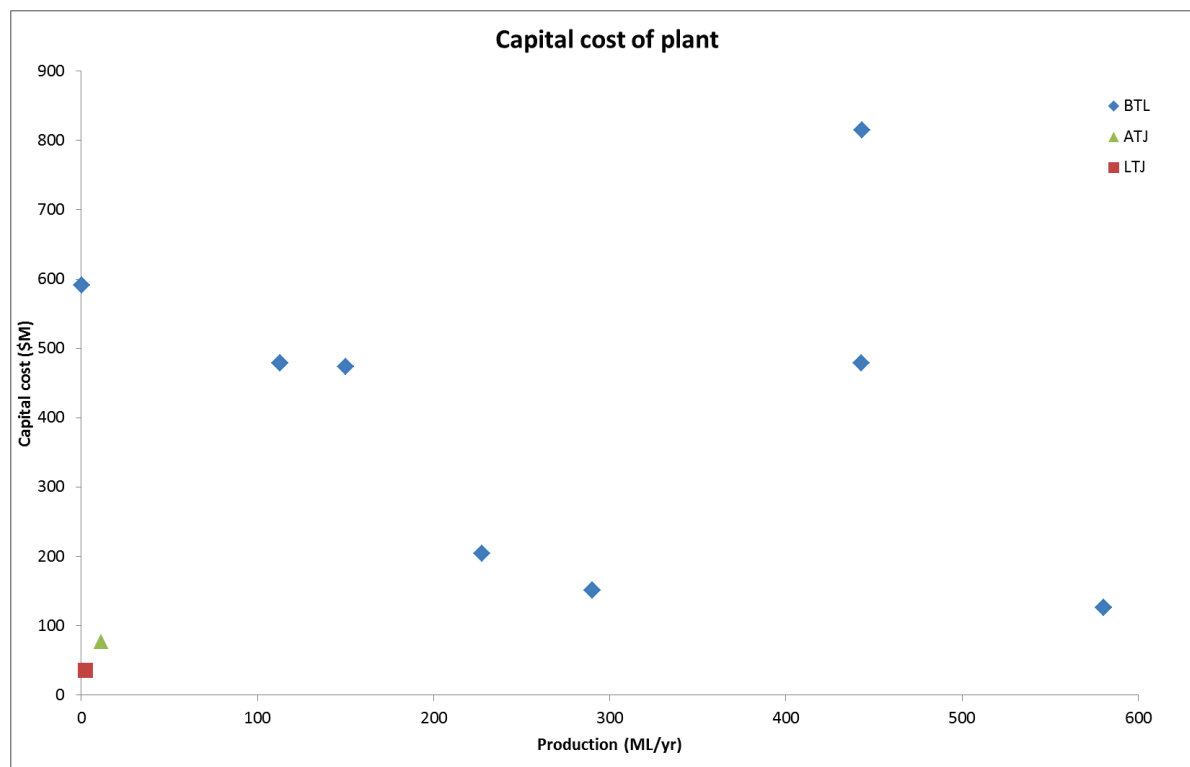


Figure 5-2 Capital cost of and capacity of proposed and modelled biojet conversion facilities. Source data: Balan, Chiramonti and Kumar (2013); IATA (2013); Maniatis, Weitz and Zschocke (2013); Güell et al. (2012); Agusdinata et al. (2011); Carter et al. (2011); Hileman et al. (2009).

5.1.3 Balance of costs in contemporary estimates

Discussion of the balance of estimates between capital, feedstock and other costs is limited to the BTL and ATJ pathways, for which the estimates identified are the most detailed. BTL in particular is understood to be capital intensive, with capital expenditure representing account for 50-75% of total production costs¹⁰ and feedstock representing 10-35%. Feedstock costs are more important for the ATJ pathway, accounting for 15%-60% of total production costs whilst capital accounts for 20-50%. For both pathways operations make up the remaining balance of costs (Staples et al., 2014;

- Costs have been normalised to 2013 USD using the US Bureau of Labor Statistics Producer Price Index for jet fuel (DoL, 2014).
- Daily production rates have been converted to annual rates assuming 365 days operation.
- Production volumes have been converted to mass using the biodiesel conversion rate of 1 litre = 0.88 kg (Iowa State University, 2008).

Rounding errors may have arisen where data has been taken from graphical sources.

¹⁰ Agusdinata (2011) estimates lower figures (in the order of 20-30%), but these are for very large-scale hypothetical plants.

IATA, 2013; Maniatis, Weitz & Zschocke, 2013; Rosillo-Calle et al., 2012; Agusdinata et al., 2011; CSIRO, 2011; Novelli, 2011).

Variation in the relative proportion of capital, feedstock and operational costs depends on specific technology employed (e.g. the gasification system and upgrading techniques for BTL), as well as the characteristics and location of feedstock resources. Under certain circumstances the flexibility of BTL to accept a wide range of feedstocks can enable an income stream to be generated from feedstock, for example if MSW is processed in jurisdictions with a landfill tax¹¹.

5.2 Outlook for future costs

5.2.1 Cost projections for the BTL pathway

Three studies were identified that model future levelised cost/MSP scenarios for the BTL pathway: Agusdinata et al. (2011), Novelli (2011) and Bauen et al. (2009). These studies investigate the conditions under which BTL jet fuels might reach price equivalence with conventional kerosene, based on key variables including the price of conventional jet fuel, feedstock type and cost, and carbon price. No studies investigating future costs were found for the other conversion pathways.

¹¹ Solena's Greensky London project will benefit from the UK's standard rate landfill tax (£72.50/tonne at the time of writing (HMRC, 2014)), which is likely to act as a reference point for the price at which Solena can charge companies to 'dispose' of their waste.

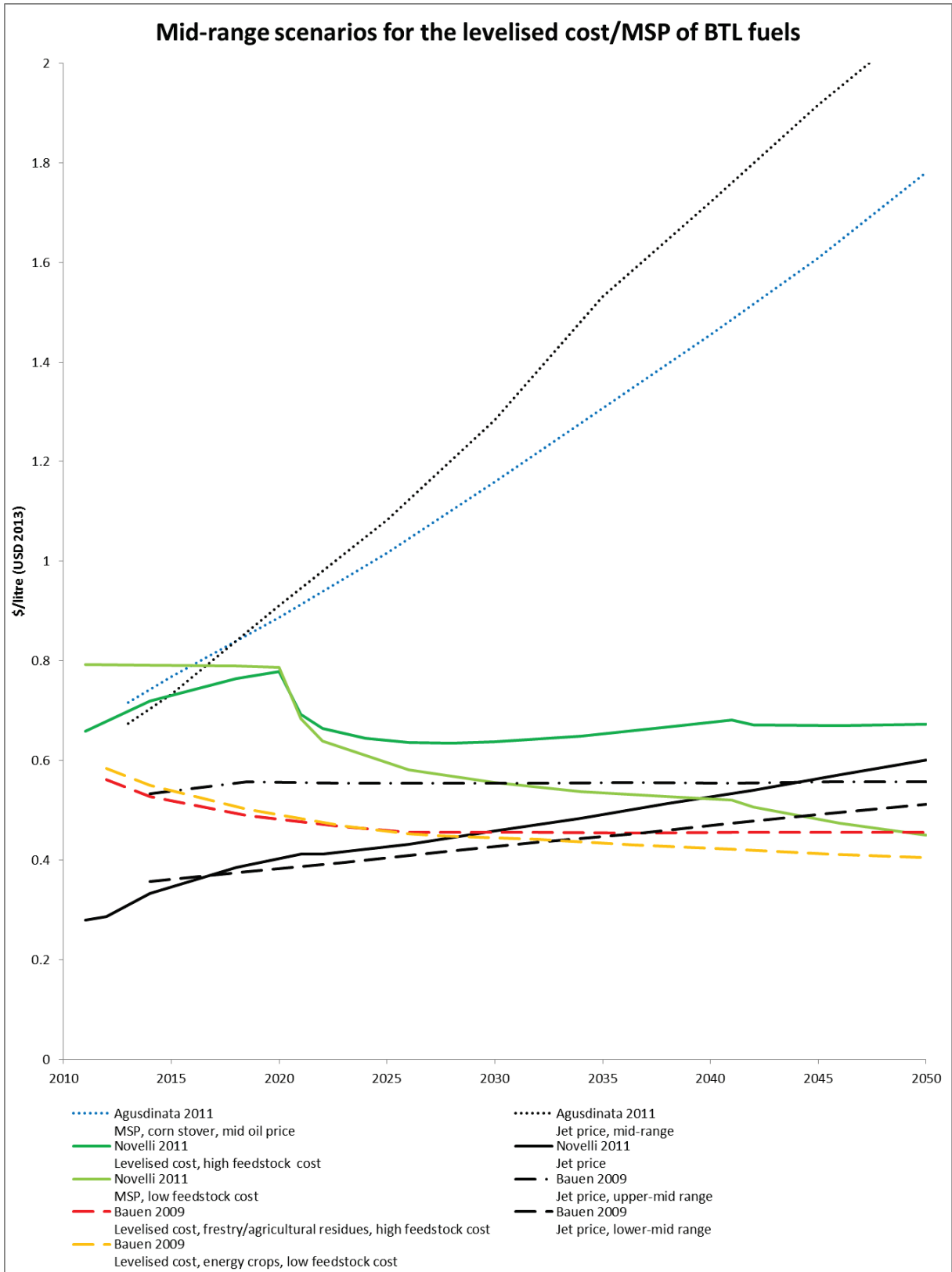


Figure 5-3 illustrates mid-range scenarios without a carbon price for each of the three BTL studies. These suggest that BTL jet fuels could reach price parity with conventional kerosene (shown in black) over the coming decades. Bauen (red/orange projections) estimates that the cost of biojet fuel could reach parity with lower-to-mid-range kerosene prices during the 2030s under mid-range assumptions for feedstock cost (high cost forestry/agricultural residues or low-cost energy crops).

Novelli (green) projects that with low feedstock costs and mid-range kerosene prices, parity could be reached around 2040. Agusdinata (blue) anticipates that with central kerosene prices (considerably higher than those projected by Novelli and Bauen) and low-cost feedstocks (agricultural residues) price parity could be reached in the 2020s.

The scenarios offer limited insight regarding absolute costs/price, as they are predicated on conventional kerosene price projections that have so far proven to be considerably lower than the market rate. Comparison of the full range of scenarios developed by the three studies does however highlight the importance of feedstock costs, particularly with regards to the cost/price of biojet fuel, the likelihood of deployment in the short-to-medium term, and the potential for price equivalence with conventional jet fuel to be reached over the coming decades.

Both Bauen and Novelli anticipate considerable learning-curve effects, with associated reductions in production costs (Novelli, 2011; Bauen et al., 2009). This view is shared by other authors, with the gasification stage of BTL thought to offer the greatest potential for technological advances, particularly with regards to feedstock handling (Güell et al., 2012). Improvements to the Fischer-Tropsch stage are expected to be smaller, due to the chemical similarity of syngas produced from biomass and fossil fuel feedstocks (Güell et al., 2012).

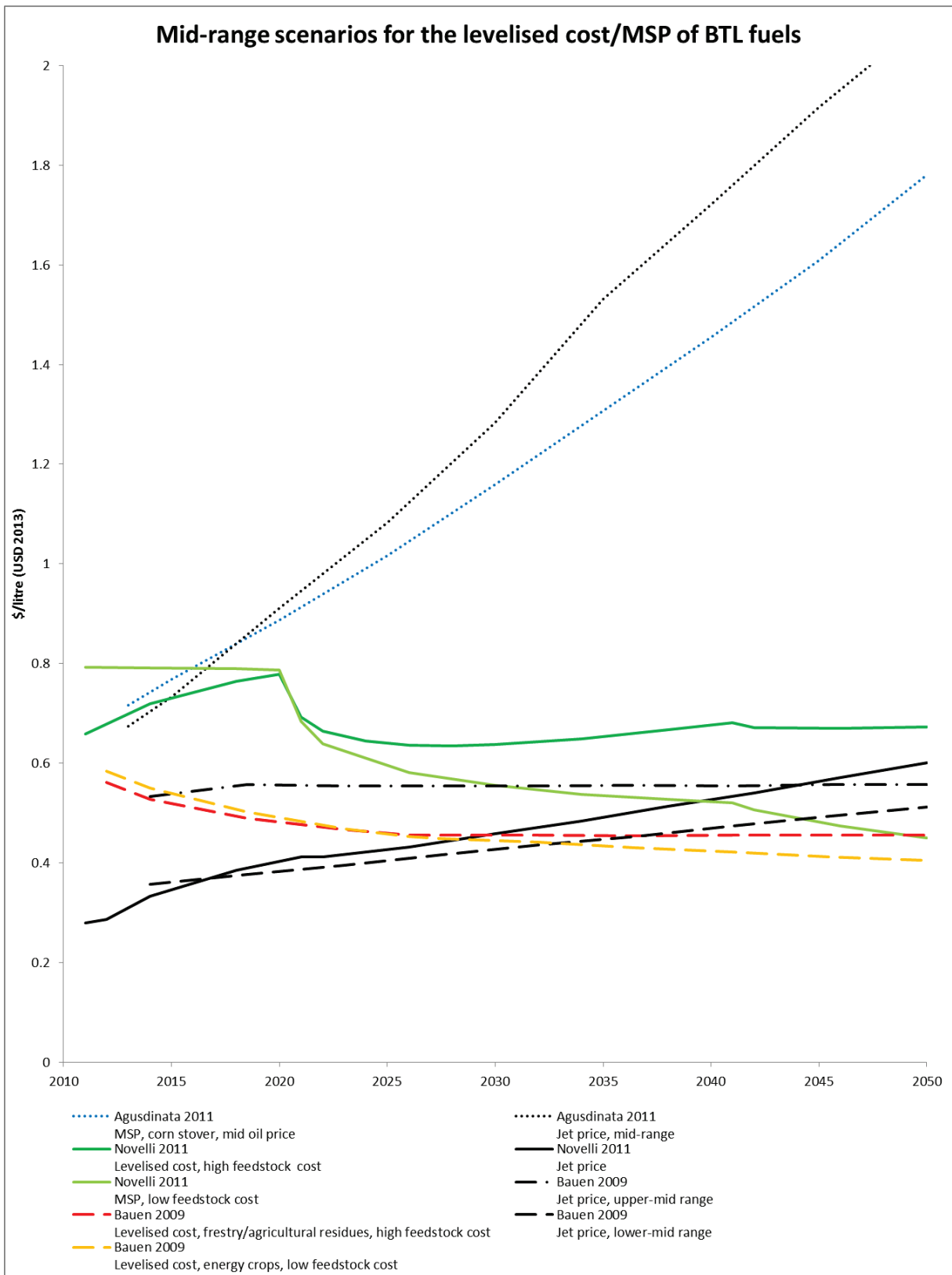


Figure 5-3 Mid-range scenarios for the LCOP/MSP of BTL fuels and corresponding jet price scenarios¹². Source data: Agusdinata et al. (2011), Novelli (2011) and Bauen et al. (2009).

¹² See footnote 9.

5.2.2 Potential for technical improvements in the ATJ pathway

The currently high cost of synthesising alcohols from biomass is considered to be the greatest barrier to the commercialisation of ATJ fuels (Güell et al., 2012). In particular the cost of feedstock pretreatment (especially for lignocellulosic biomass) and the cost of enzymes are noted to be expensive (Mohammadi et al., 2011). The cost of alcohol synthesis varies according to the intermediate being targeted, with butanol being more expensive than ethanol (Qantas, 2013). It is unclear whether the greater cost to generate butanol is offset by less intensive upgrading requirements.

Upgrading costs are perceived to be less problematic. In comparison to some of the other pathways the hydrogenation process requires only small quantities of hydrogen (approximately 0.001 wt% on dry biomass) (Güell et al., 2012).

An important characteristic of the ATJ pathway is the flexibility to use alcohols generated from a wide range of processes. As fuel conversion technologies mature, it may be possible to integrate these with a wide range of industrial processes that produce alcohol by-products or have the potential to do so (IATA, 2012a). Lanzatech's retrofit solution for steel mills is one such example. Capital costs can be reduced by if fuel conversion equipment is retrofitted to existing ethanol facilities rather than built at greenfield sites (Staples et al., 2014).

5.2.3 Scale economies

Fischer-Tropsch processes including BTL are widely recognised to benefit from significant economies of scale (Maniatis, Weitz & Zschocke, 2013; Carter et al., 2011; IATA, 2010; Bauen et al., 2009; Tarka et al., 2009). Figure 5-4 illustrates this with respect to capital costs for completed, proposed and cancelled Fischer-Tropsch facilities worldwide (Carter et al., 2011). Plants processing biomass are shown in green. The higher per unit capital costs of these biomass facilities (compared to coal and gas plants) is largely attributed to their much lower production capacities.

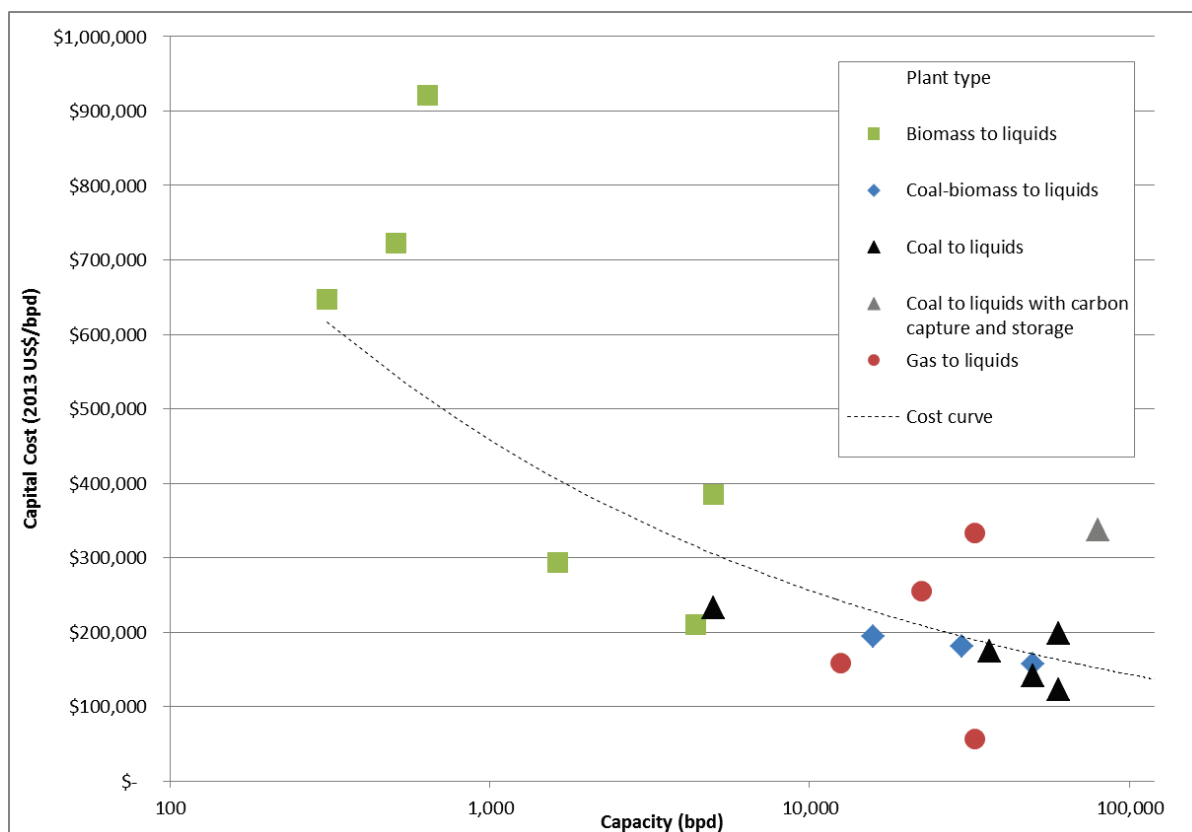


Figure 5-4 Fischer-Tropsch facility capital cost as a function of capacity for proposed, cancelled and constructed Fischer-Tropsch facilities worldwide. Solid markers denote facilities that have been built while open represents proposed, cancelled, or original estimates for facilities. Capital costs adjusted to 2013 USD and normalised to the cost per barrel of daily capacity (\$/bpd). Adapted from Carter et al. (2011).

Unfortunately the potential for biojet facilities to realise scale economies is limited by the logistical difficulties of working with biomass feedstocks. Lignocellulosic feedstocks in particular have low energy densities and tend to be bulky, making them both difficult and costly to transport. This limits the distance from which it is viable to transport the feedstock, and in turn the maximum capacity of the plant (Maniatis, Weitz & Zschocke, 2013). Carter et al. (2011) consider the technically viable capacity of BTL plants to be around 800,000 litres/day (5,000 bpd), at which capital costs are likely to be around \$1,580/litre/day capacity (\$250,000/bpd). In comparison natural gas BTL facilities can be feasible at capacities as great as 15,900,000 litres/day (100,000 bpd), with associated investment costs of around \$630/litre/day (\$100,000/bpd) capacity (Carter et al., 2011).

Nonetheless, there is considerable interest in improving the viability of larger-scale BTL plants, notably through the use of pretreated and mixed feedstocks. Pretreated, densified biomass (such as pyrolysis oil or char) should be cheaper to transport than raw materials¹³, and therefore could be gathered from a greater area for a centralised Fischer-Tropsch plant. Use of pretreated feedstock does however lower the total conversion efficiency of the BTL process, and the overall economic impacts of using a pretreated feedstock are not well understood (Maniatis, Weitz & Zschocke, 2013;

¹³ Although pyrolysis oil is denser and has better flow properties than raw biomass, it presents certain challenges, e.g. high acidic content, corrosivity, chemical instability. These will affect the ease of transportation and so the viability of this option (Radlein & Quignard, 2013; Güell et al., 2012; Jones & Male, 2012; Pandey et al.).

Bauen et al., 2009). Alternatively a larger BTL plant could process non-renewable, energy-dense feedstock (such as coal) alongside biomass, but this would increase the greenhouse gas emissions of the fuel produced (ALFA-BIRD, 2012; Hileman et al., 2009). Examples of European initiatives in this area include the Karlsruhe Institute of Technology's pilot 'Bioliq' plant, which combines decentralised pyrolysis with centralised Fischer-Tropsch synthesis. The BioTFuel collaboration aims to have an operational commercial-scale BTL plant producing diesel and kerosene from fossil fuels and torrefied biomass by 2017 (Balan, Chiaramonti & Kumar, 2013; Güell et al., 2012).

No analysis of the potential for scale economies for other the other biojet pathways was identified, however CSIRO (2011) suggests that pyrolysis-based processes would be well-suited to small-scale production (CSIRO, 2011).

5.3 Competition with co-products, the need for policy support

As noted above, most LCOP and MSP estimates for biojet are at least double the average price of conventional jet fuel. Whilst some air operators will for strategic reasons invest in small quantities of fuel at above-market rates, the volume of total sales will be limited until biojet fuel becomes cost competitive with conventional kerosene.

At the same time, biojet must compete with higher value road fuels and chemicals for production capacity. The pathways discussed in this report generate biojet as one of many products, and have the capability to control the distribution of outputs through adjustments to the process conditions (Novelli, 2011; Hileman et al., 2009). The BTL and ATJ pathways produce fuels whose composition is particularly attractive for road transportation, and thus likely to attract a price premium in jurisdictions with strict quality standards such as the EU and the USA (Hileman et al., 2009). Further the production costs of road fuels are cheaper than jet fuel for the ATJ pathway, since upgrading requirements are less demanding (Hileman et al., 2009). Some of the HDCJ and APR technologies are similarly highly suited to the production of valuable chemicals (Brown et al., 2013; IATA, 2013; Qantas, 2013; Güell et al., 2012). These are strong disincentives against the production of biojet fuel.

Given the variation in different product values, it has been suggested that the economics of biojet fuel could be improved if it is produced as a secondary - rather than primary - product, cross-subsidised by revenues from other outputs. Novelli (2011) and estimate the economically optimum proportion of jet fuel for the BTL pathway to lie between 0% and 30% of total liquid output. Research by MIT indicates that maximising the chemical outputs of APR plants could reduce the MSP of coproduced jet fuel by 77% (IATA, 2013). The potential to cross-subsidise aviation fuels is not however a driver for their production, as biojet is not always a necessary co-product of biofuels and biochemicals. For example, BTL can generate higher-value biodiesel profitably without producing any jet fuel (Novelli, 2011). A further deterrent to investment in facilities *capable* of producing biojet is their expense relative to those which target road fuels only. At present most biofuels for road transport are produced from vegetable oils as fatty acid esters (FAE) (Novelli, 2011). FAE technology is both less capital intensive and technologically more advanced than the pathways discussed in this report – making it easier to finance - however it is not suitable for the production of biojet¹⁴. In light

¹⁴ Demand for biojet-capable technologies could rise if higher policy mandates for road biofuels are increased, since high concentrations of FAE fuels are not suitable for diesel engines). This could in turn promote the coproduction of biojet fuel.

of these arguments economically rational producers may prefer to avoid capital intensive, low value biojet altogether.

Existing policy support for biofuels in the EU and USA (blending mandates and tax breaks) favours least cost options – and therefore benefits biofuels for road transportation rather than aviation (Maniatis, Weitz & Zschocke, 2013). As such it is likely that current policies will be insufficient to overcome the issues described above. Realisation of learning curve effects and associated cost reductions for biojet will require a substantial increase in the deployment of production facilities, which in turn will necessitate targeted policy interventions to bridge the price gap between conventional kerosene and aviation biofuels. The international character of aviation and the need to maintain competitiveness amongst regional suppliers present particular challenges for the design and implementation of such interventions.

5.4 Summary

A summary of the economic status of each of the biojet pathways is provided in Table 5-1.

Table 5-1 Summary of the economic status of biojet pathways.

Conversion pathway	BTL	ATJ	HDCJ	FTJ	APR	L TJ
Capital cost	<ul style="list-style-type: none"> Estimates range from \$126M to \$815M for facilities with capacities <580ML/yr. ~50% of capex from gasification and Fischer-Tropsch units 	<ul style="list-style-type: none"> \$77M for proposed 11ML/yr Swedish Biofuels plant (Balan, Chiaramonti & Kumar, 2013) ~50% of CAPEX from gasification and gas clean-up units 				\$36M for proposed 2ML/yr BioChemtex plant (Maniatis, Weitz & Zschocke, 2013)
Production cost or min selling price (USD/L)	<ul style="list-style-type: none"> Estimates range from \$0.36 to \$3.97/litre, mid-range estimates \$1.22-\$2.15/litre. 	<ul style="list-style-type: none"> Limited data. Estimates by Staples et al. (2014) range from \$0.58 to \$5.96/litre, mid-range estimates \$1.48-\$2.18/litre US MoD purchased ATJ biojet during 2011-2012 for \$14.75/litre 		<ul style="list-style-type: none"> Estimates range from \$1.03 to \$3.95/litre, mid-range estimates from \$1.71-\$1.82/litre. US MoD purchased FTJ biojet in 2012 for \$6.43/litre. 	<ul style="list-style-type: none"> Very limited data. Novelli (2011) estimates price of \$0.75/litre assuming similar capex to HEFA pathway. 	
Balance of costs	<ul style="list-style-type: none"> High capex due to complexity of conversion process and large scale of plant required to make plant economical. Logistical difficulties prevent BTL from achieving the economies of scale realised by plant processing fossil fuels. Capex in the region of \$250,000/bpd of capacity for larger BTL plant, but higher for the majority of (smaller) plant. Capex accounts for 50-75% of production costs. Feedstock accounts for 10-35% of production costs. Potential for MSW feedstock to generate revenue in certain circumstances. 	<ul style="list-style-type: none"> Capex accounts for 20-50% of production costs, feedstock for 15-60%. High costs associated with the generation of alcohols. 	<ul style="list-style-type: none"> Both capex and opex high. High costs associated with hydroprocessing. 			
Economic strengths	<ul style="list-style-type: none"> Low feedstock price Low operating costs. Indirect gasification 	<ul style="list-style-type: none"> Potential to use low-cost feedstocks (lignocellulose, 			<ul style="list-style-type: none"> Potential to reduce MSP of 	

	<p>technologies avoid need for external hydrogen.</p> <ul style="list-style-type: none"> • Significant potential for cost reductions through learning curve effects. Use of densified feedstock in large-scale centralised facilities. • Wide range of potential co-products could bolster profitability. 	<p>MSW, industrial waste gases).</p> <ul style="list-style-type: none"> • Wide range of revenue-generating by-products. • Low hydrogen consumption. 			<p>jet fuel by through co-production of chemicals.</p>
Economic challenges	<ul style="list-style-type: none"> • High capex dominates production costs. • Potential competition between production of jet fuel and by-products. • Attractiveness of FT fuels for road transport may disincentivise production of jet fuels. 	<ul style="list-style-type: none"> • Cost of alcohol production is high, particularly for lignocellulosic feedstocks. • Potential competition with production of road transport fuels. 	<ul style="list-style-type: none"> • Very limited data on production costs. • High costs associated with hydroprocessing. 	<ul style="list-style-type: none"> • Very limited data on production costs. • Process yields and costs influenced by enzyme load. 	<ul style="list-style-type: none"> • Very limited data on production costs and processes.

6 Conclusions

This paper sought to evaluate the technological and commercial viability of technologies capable of converting biomass to synthetic jet fuel, in the context of potential deployment in Europe over the period to 2020. A screening exercise and discussions with project partners resulted in a short list of six promising ‘conversion pathways’, namely: biomass to liquids (BTL), hydrotreated depolymerised cellulosic jet (HDCJ), alcohol to jet (ATJ), fermentation to jet (FTJ), aqueous phase reforming (APR) and lignin to jet (LTJ). These have been analysed in detail, with particular attention paid to their technological development, the status of existing deployment, active developers, progress towards international certification, compatibility with existing systems, the opportunity costs of producing biofuels specifically for aviation, and economic factors.

6.1 Status of conversion pathways

CAAFI’s Fuel Readiness Scale was used to compare the maturity of the short-listed pathways. Figure 4-3 summarises the results of this exercise, alongside an indication of the number of developers actively involved with the technology¹⁵.

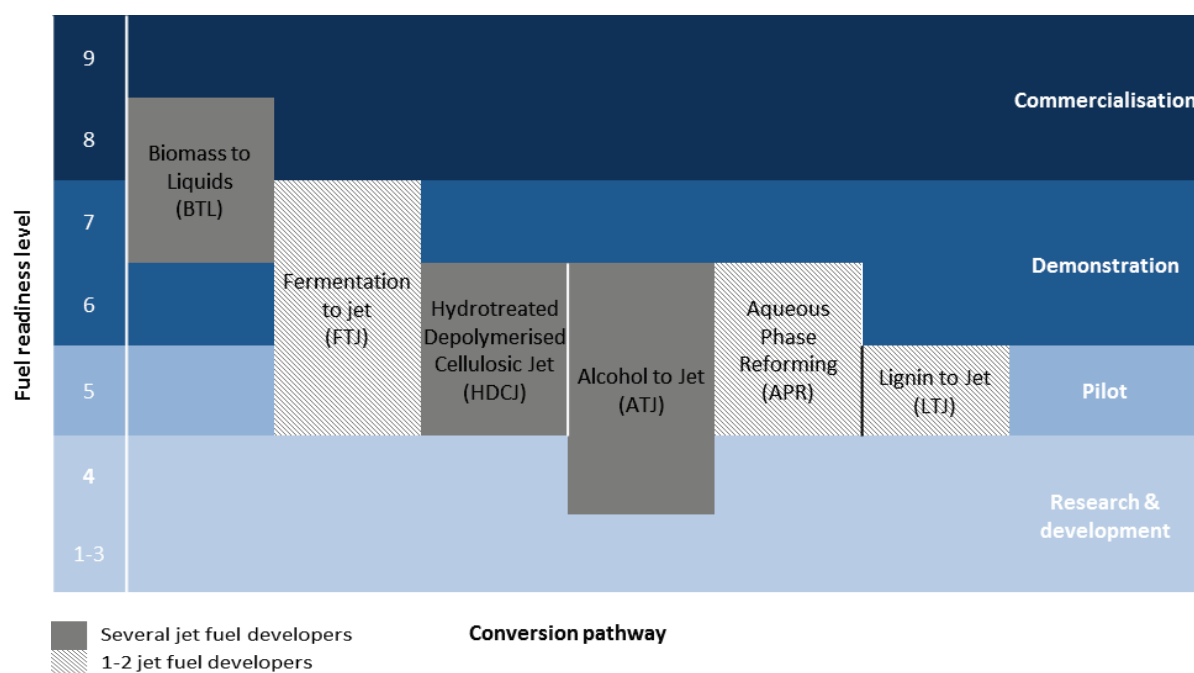


Figure 6-1 Current fuel readiness levels of biojet conversion technologies

Based on the FRL analysis, BTL is the most advanced of the pathways reviewed (FRL 7-8). Several fuel developers are involved with this pathway and BTL jet fuel is certified for use by the ASTM. The first commercial-scale BTL plant (Solena’s GreenSky London project, which will utilise a revenue-generating feedstock) is expected to become operational by 2015, with other similar projects due for

¹⁵ It should be noted that these FRL assessments compare the maturity of different biojet production pathways in isolation, ignoring potential interactions and co-dependencies. In some cases there may be potential for developments in one pathway to promote another, or for outputs from two pathways to be combined in a final biojet product. Examples include the use of pyrolysis as a pretreatment to increase the logistically viable capacity of BTL plants, the creation of aromatic additives from the HDCJ pathway, and the potential to retrofit existing first-generation ethanol facilities to produce butanol and/or to process lignocellulosic feedstocks.

completion around 2020. These developments would take BTL to FRL 9. However, the high costs, low revenues, capital intensity and technological uncertainties of BTL present a difficult investment proposition at present.

For BTL estimates of levelised costs and minimum selling prices (MSPs) range from \$0.36-\$3.97/litre, with mid-range values between \$1.33-2.15/litre, double the price of kerosene (\$0.77/litre). Capital investment represents 50-75% of total costs in contemporary production estimates. Fischer Tropsch synthesis is however subject to significant scale economies. This is driving the development of solutions to the logistical challenges of collecting bulky biomass feedstocks. Future price scenarios indicate that BTL jet fuel could become competitive with kerosene between 2020 and 2040 provided low-cost feedstocks can be accessed. Feedstock represents 10-35% of total costs in contemporary estimates.

Technologies covered by the FTJ pathway are at FRLs 5-7. A first fuel production process has been certified by the ASTM, with the producer (Amyris/Total) working alongside the airline GOL Linhas Aéreas Inteligentes to establish commercial production, and a second producer (REG Life Sciences) has an operational pilot plant. Current production routes focus on sugar as a feedstock; efforts to develop jet fuel from lignocellulosic materials are limited, although this is considered possible. Given the current status of Amyris' technology and assuming a progression rate of 3-5 years per FRL, it is realistic to project the start-up of a first commercial sugar-processing plant by 2020 (corresponding to FRL 9). Prospects for the technological development of this pathway are not however considered as robust as for BTL, due to the small number of active jet fuel developers. Regarding production costs, MSP estimates from two studies range from \$1.04-\$3.95/litre, with the mid-range values \$1.70/litre and \$1.82/litre. These are similar to estimates for the BTL and ATJ pathways, but considerably lower than the \$6.43/litre purchase price paid by the US DoD for FTJ fuel over 2011-2012.

The most advanced technologies in the ATJ pathways are at FRL 6. Commercial interest in ATJ is significant, with multiple companies and airlines actively involved in fuel development. A key strength of the pathway is its flexibility to process alcohols synthesised by a wide range of methods and from diverse feedstocks. Several partnerships targeting the production of jet fuel exist between companies that synthesise alcohols, and those that convert alcohols to fuels. Certification of ATJ fuel (corresponding to FRL 7) is expected during 2014-2015. It is reasonable to expect pre-commercialisation activities (FRL 8) for this pathway to be underway by 2020, with commercial operations (FRL 9) being foreseeable if the technology progresses well. These FRLs relate to fuels produced from sugar and starch feedstocks however; current efforts to convert lignocellulosic materials are limited. One study estimating MSPs was identified, with values ranging from \$0.58-\$5.96/litre, and mid-range values from \$1.48-\$2.18. Capital expenditure and feedstock costs represent 22-48% and 16-61% respectively. These MSP estimates are similar to those for the BTL and FTJ pathways, but much lower than the \$14.75 purchase price paid by the US DoD over 2011-2012. The high cost of alcohol synthesis is considered the greatest barrier to commercialisation of ATJ fuels, however the flexibility of the pathway to utilise alcohols generated by a wider range of processes is considered an important characteristic. Integration with industrial processes, including existing ethanol plants, could lead to cost reductions.

The HDCJ pathway represents a range of diverse fuel conversion technologies being developed by several companies in collaboration with airlines. The most advanced of these, KiOR's proprietary fuel, has completed its ASTM research report (corresponding to FRL 6). Certification of KiOR's fuel is projected for 2015, and it could reasonably reach FRL 7-8 by 2020. Other HDCJ technologies are not expected to achieve certification (FRL 7) in the near term. No cost estimates for the HDCJ pathway were identified.

APR is also at FRL 6, but only one producer, Virent, has developed jet fuel to an advanced stage and there are no partnerships with airlines. Whilst this technology could achieve ASTM certification and pre-commercialisation activities by 2020, progress depends almost entirely on the outputs of this sole developer. The MSP has been estimated at \$0.75/litre assuming capital investment is similar to that for HEFA.

LTJ is the least advanced of the pathways reviewed, being at the pilot stage of development and being promoted by only one organisation. It is unlikely that this pathway would be able to contribute meaningfully to biojet fuel production by 2020. Data on the economics of LTJ were not identified.

6.2 General observations

Biojet production pathways vary considerably in terms of their technological and commercial maturity, with the most highly developed being in the very early stages of commercialisation. The breadth and depth of available data is considerably greater for pathways which are at the higher end of the FRL scale and/or which are being pursued by multiple developers.

Economic data in particular is very limited and insufficient to allow comparison of the relative cost of different biojet technologies. Nonetheless, most estimates suggest that the current cost of producing biojet from lignocellulosic feedstocks is at least double the selling price of petroleum kerosene. Estimates further indicate that biojet technologies can be capital intensive, and that investment costs are high in absolute terms.

Reductions in biojet production costs are anticipated as experience accrues. However to realise these biojet will need to compete with other biofuels and biochemicals for dedicated production capacity. The development of biojet technology may therefore be slowed by the attractiveness of certain pathways (notably BTL and ATJ) for road fuels and/or chemicals. Further, potential economies of scale (anticipated for BTL) are likely to be constrained by logistical issues related to the transportation of feedstock. In addition sustained access to low cost feedstocks is considered necessary for biojet to become cost competitive with conventional kerosene.

Overall, biojet currently presents a risky investment proposition. Whilst some pilot and/or demonstration projects may be financed 'on balance sheet', investment in large-scale facilities is likely to be limited by the cost of and access to finance. Policy support will be necessary to promote deployment at scale in the short-to-medium term, to enable the realisation of potential cost reductions.

6.3 Next steps

This paper has reviewed the technological and commercial readiness of different biojet conversion pathways. Concurrent research by Utrecht University has investigated the European biomass

resource base and examined key sites and facilities in Europe for advanced biofuel production. A further joint activity led by SkyNRG is underway to identify specific niches with strong potential for biojet production in the EU. The combined results of these tasks will be used to identify promising biojet value chain(s) for detailed analysis and development through the remainder of Work Package 1 of the RENJET project.

This paper demonstrates that publically-available data is sufficient to evaluate the relative technological and commercial maturity of different biojet conversion pathways. However data identified on the economics of these technologies is very limited, allowing only generalised observations to be drawn. Process modelling – or a review of process model results – could be conducted to assess the comparative financial viability of the different pathways.

7 References

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