
Technological and commercial maturity of aviation biofuels:

Emerging options to produce jet from lignocellulosic biomass

Rebecca MAWHOOD¹, Evangelos GAZIS², Ric HOEFNAGELS³, Sierk DE JONG⁴, Raphael SLADE⁵

¹ Centre for Environmental Policy, Imperial College London, London SW7 1NA, UK, rebecca.mawhood@imperial.ac.uk

² Centre for Environmental Policy, Imperial College London, London SW7 1NA, UK, e.gazis@imperial.ac.uk

³ Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands, r.hoefnagels@uu.nl

⁴ Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands, S.A.deJong@uu.nl

⁵ Centre for Environmental Policy, Imperial College London, London SW7 1NA, UK, r.slade@imperial.ac.uk

Abstract: The aviation sector is responsible for an increasing share of anthropogenic CO₂ emissions. Wider adoption of aviation biofuels (biojet) is imperative for the reduction of greenhouse-gas emissions, however it represents a radical departure from the existing technological regime of petroleum-based fuels. Further market deployment will require significant techno-economic breakthroughs, as well as adaptation of the existing supply chains and infrastructure.

Although a large number of technologies which have the capability to produce such fuels are being developed, many of these are unlikely to be suitable for EU-based production in the short-term. Biojet production pathways vary considerably in terms of their techno-economic features, with the most highly developed being in the very early stages of commercialisation.

In this article, the authors map current development and manufacturing efforts within five emerging biojet technological pathways. The research draws upon a comprehensive review of the international academic and grey literature in order to characterise the pathways according to their technological and commercial maturity, as well as progress towards international certification.

By implementing the Fuel Readiness Level (FRL) methodology, the authors provide insights regarding not only the current status of the biojet sector, but also potential opportunities for the short-term development of supply chains in the EU.

Keywords: Aviation biofuels, Fuel Readiness Levels, Lignocellulosic biomass

1. INTRODUCTION

Aviation is currently responsible for 2% of global anthropogenic CO₂ (ATAG, 2014). Its emissions are set to increase rapidly in response to growing customer demand, from 705 Mt of CO₂ in 2013 to between 1,000 and 3,100 Mt by 2050 (Lee, Lim, & Owen, 2013). CO₂ per passenger mile will need to be reduced greatly if the sector is to stabilise its greenhouse gas emissions, let alone reduce these in line with wider international policy ambitions. Near-term options to decarbonise air travel, however, are limited. Modern aircraft are already highly fuel-efficient, and technological improvements tend to be incremental. Moreover, since commercial aircraft have a service lifetime of 25 years, the diffusion of improvements across the active global fleet tends to be slow (Lee et al., 2013). Advances in air traffic management and engine efficiency have the potential to reduce aviation emissions by an estimated 0.8% per annum over the period to 2050, equivalent to an aggregate reduction of around 15% from 2015 (CCC, 2009; Lee et al., 2013), but these reductions are expected to be insufficient to offset increases in passenger numbers. Consequently, the majority of emission reductions will need to come from the uptake of low carbon liquid fuels and particularly biofuels.

Within the aviation sector there is optimism that kerosene-like fuels produced from biomass (hereafter referred to as biojet) could offer a viable means to reduce emissions under the right policy circumstances. A number of commercial and military aircraft operators (e.g. KLM, Virgin, British Airways, US Air Force) are supporting biojet R&D projects, both in anticipation of future emissions reduction requirements and as a means to increase the fuel supply security and reduce exposure to fuel price volatility (Academic1, 2014; Consultant1, 2014; InterGovt1, 2015). Yet to date almost all flights fuelled by biojet have used fuels produced from vegetable oils and fats via hydroprocessed esters and fatty acids (HEFA) technology (EBTP, 2015). Although the production of biojet from these feedstocks is straightforward, the potential to scale-up production is restricted because sustainable sources are limited and expensive (raw vegetable oils are often more costly than kerosene). Current R&D efforts in the EU are therefore focussing on the development of biojet from second generation, lignocellulosic feedstocks, which are considered to have greater potential for cost-effective and large-scale production.

Lignocellulosic biojet technologies are in general at an earlier stage of development than those using first generation oil-based feedstocks or those processes targeting biofuels for road transport. They cover a broad range of distinct fuel conversion approaches, but a common terminology allowing processes to be easily differentiated has yet to be defined. There are also many competing claims by companies seeking to promote their own proprietary technology. Such issues hinder the comparison of these prospective technologies from both a policy and investment strategy perspective.

This paper provides insights into the future potential of biojet technologies by mapping the companies claiming to be able to produce second generation biojet commercially within the next five years, and evaluating the maturity of technologies being adopted using the Commercial Aviation Alternative Fuels Initiative's (CAAFI) Fuel Readiness Level (FRL) methodology. This research has been conducted as a first-stage assessment of opportunities to develop sustainable European biojet supply chains in the context of the Fuel Supply Chain Development and Flight Operations (RENJET) project, funded by the EIT Climate-KIC. The paper's overall aim to synthesise the current status of emerging biojet technologies, including known barriers and opportunities affecting their commercial outlook, in order to inform the development of new and ongoing research strategies within the biojet arena.

The remainder of this paper proceeds as follows. Section 2 outlines the methodology for both the collection and analysis of evidence. Section 3 provides an overview of the investigated technologies, as well as the factors on which the assessment is based. Finally, Section 4 provides a summary of the findings with regards to the technological and commercial maturity of different aviation biofuel technologies.

2. METHODOLOGY

2.1. Rapid Evidence Assessment

This study employed a Rapid Evidence Assessment (REA) methodology (GSR, 2013; Khangura, Konnyu, Cushman, Grimshaw, & Moher, 2012) to identify studies from both academic and grey literature examining the short-to-medium term feasibility of biojet technologies, as well as companies producing second generation biojet. The Primo Central Index and Google Scholar were interrogated for English language reports published between 2009 and 2014, using the following search terms: alternative fuels OR biofuels AND aviation. Core industry reports recommended by an advisory group were also included, and the bibliographies of relevant articles were reviewed for related citations. Non-systematic searches were conducted to verify the current status of the biofuel developers and facilities (both proposed and constructed) identified by the REA, and stakeholder interviews were held to elicit expert opinion on the potential for future deployment.

Publications were included in the REA if they met both 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 more generally); 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. This search strategy identified 18,396 titles, of which 175 were deemed to fit the inclusion criteria.

2.2. Identifying emerging conversion pathways

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. In order to identify those families of technologies ('conversion pathways') with potential for EU applications in the near term, a shortlist of promising pathways was identified. 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.

This screening exercise identified five key conversion pathways with potential for commercial-scale production of biojet in the EU within the next 5-10 years. These are: biomass to liquids (BTL), hydrotreated depolymerised cellulosic jet (HDCJ), alcohol to jet (ATJ), fermentation to jet (FTJ) and aqueous phase reforming (APR). An overview of the production processes involved for each of these pathways is illustrated in Figure 1.

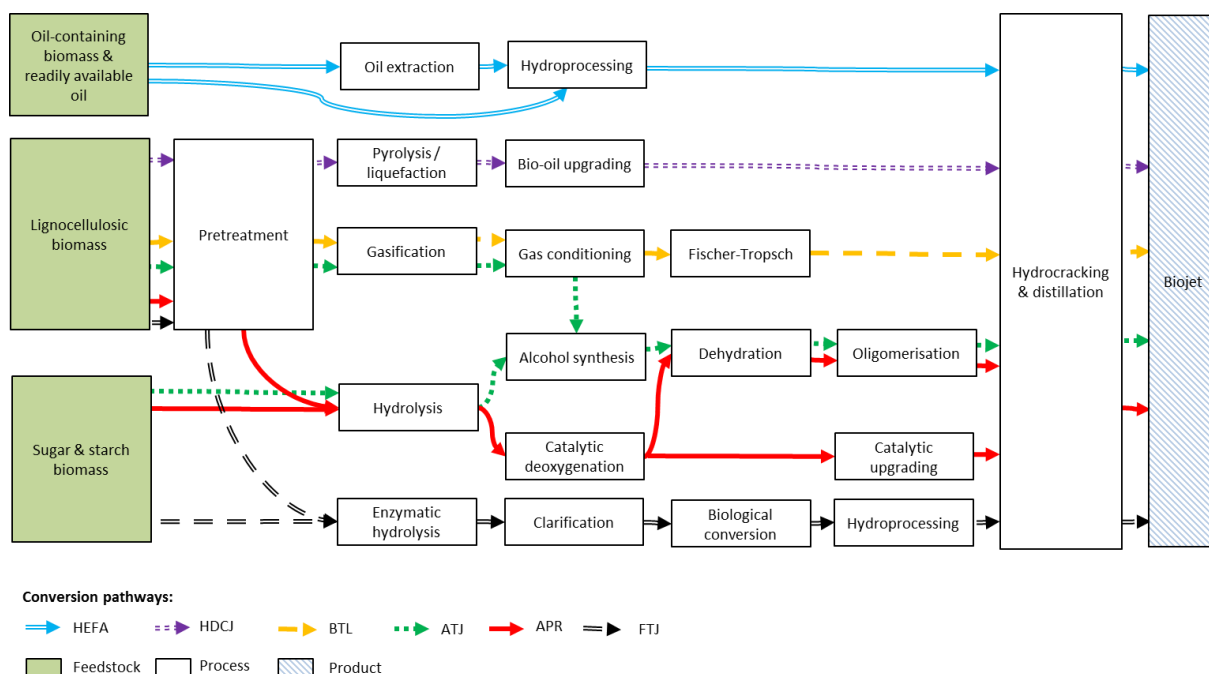


Figure 1 Biojet conversion pathways. HEFA = hydroprocessed esters and fatty acids (HEFA), HDCJ = hydrotreated depolymerised cellulosic jet, BTL = biomass to liquids, ATJ = alcohol to jet, APR = aqueous phase reforming, FTJ = fermentation to jet.

2.3. Fuel Readiness Level (FRL) appraisal

The Fuel Readiness Level (FRL) approach is based on NASA's 'Technology Readiness Level' (TRL) scale and provides a descriptive hierarchy of "toll gates" designed to enable consistent comparison of technological maturity between different types of technology (Steiner, Lewis, Baumes, & Brown, 2012). It was devised and formally adopted by the CAAFI in 2009 to reflect the specific range of risks affecting the development of fuels (as opposed to equipment), specifically the fuel's chemistry and its compatibility with fuelling infrastructure and aircraft (CAAFI, 2014). The resulting series of Fuel Readiness Levels (outlined in Table 1) provides a gated measure of technological and commercial maturity based on progress in the development, testing and certification of alternative fuels. Levels 1-4 correspond to lab-based research and development, 5 to pilot facilities, 6-7 to larger-

¹ The criteria were identified in collaboration with the paper's advisory group. 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.

scale demonstration plants and ASTM fuel certification², 8 to the development of viable business opportunities and GHG assessment, and 9 to the operation of the first commercial plant (Arup URS & E4tech, 2013; CAAFI, 2014).

Arup URS and E4Tech (2013) have observed 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 consistent 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). Based on such observations it would be reasonable to assume that emerging biojet technologies could progress by up to 2 FRLs by 2020.

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

Level	FRL Description	FRL 'Toll Gate'
1	Basic principles	• Feedstock & process basic principles identified
2	Technology concept formulated	• Feedstock & complete process identified
3	Proof of concept	• Lab scale fuel sample produced from realistic feedstock. • Energy balance analysis conducted for initial environmental assessment. • Basic fuel properties validated
4	Preliminary technical evaluation	• System performance and integration studies • Specification properties evaluated
5	Process validation	• Scaling from laboratory to pilot plant
6	Full-scale technical evaluation	• ASTM certification tests conducted: fit-for-purpose properties evaluated, turbine hot section testing, components and testing
7	Certification / fuel approval	• Fuel listed in international standards
8	Commercialisation	• 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	• Full scale plant operational

3. BIOJET CONVERSION PATHWAYS CHARACTERISTICS AND STATUS

3.1. Biomass to liquids (BTL) – FRL 7/8

Biomass to liquids (BTL) is the most advanced of the fuel conversion pathways identified. It involves the gasification of biomass feedstocks to produce syngas, which feeds a Fischer-Tropsch (FT) reactor to produce long chain alkanes. These are then cracked to produce synthetic paraffinic kerosene (SPK) which can substitute directly for conventional kerosene jet fuel.

The gasification/Fischer-Tropsch process has been applied to coal and natural gas feedstocks in industry for several decades. Coal-derived FT jet fuel has been used in blends of up to 50% with conventional jet fuel for commercial flights since 1999 and as a neat (pure/unblended) fuel since 2010, with no significant technical problems reported (Maniatis, Weitz & Zschocke, 2013; Morgan, 2011). Natural gas-derived FT jet fuel has been commercially produced since 2012 and is routinely used in blends of up to 25% by Shell (Maniatis, Weitz & Zschocke, 2013). Application of the process to biomass, however, is relatively novel and considered to require considerable further development, particularly regarding the handling of feedstocks in gasification. Fischer-Tropsch synthesis requires less extensive modification, due to the compositional similarity of syngas produced from biomass and fossil fuels (Maniatis, Weitz & Zschocke, 2013; Güell et al., 2012). Biomass-derived FT-SPK has been ASTM certified for commercial use (in blends of up to 50% with petroleum jet fuel) since September 2009 (IATA, 2013), but production volumes remain low and only a handful of demonstration flights have been completed.

BTL was expected to develop rapidly in the 2000s, but progress has been slower than anticipated (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). A small number of demonstration projects are nonetheless underway, with projected completion dates ranging from 2017 to 2020. The largest of these aim to produce 100,000-200,000 tonnes of fuel per annum and projected kerosene fractions range from 40-70%

² The ASTM International standard ASTM D7566 (established 2009) specifies technical requirements for synthetic jet fuels, including biofuels and blends with petroleum kerosene (Rumizen, 2013). Fuels meeting the standard are considered to be equivalent to conventional jet fuel and can be mixed in aircraft and supply infrastructure without the need for separate tracking or approval. A further standard, ASTM D4054, provides guidance on the testing requirements and property targets necessary for the evaluation of a candidate synthetic jet fuel.

(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, Fulcrum Bioenergy and Red Rock Biofuels have respectively signed offtake agreement with British Airways, Cathay Pacific and Southwest Airlines. GreenSky London project has a fuel off-take agreement with British Airways (Solena Fuels, 2014), Fulcrum Bioenergy has an offtake agreement with Cathay Pacific for five production plants, and Red Rock has an offtake agreement with Southwest Airlines (Fulcrum Bioenergy, 2015; Lane, 2015; Solena Fuels, 2014; Southwest Airlines, 2014). Solena and Fulcrum Bioenergy's planned facilities will process municipal solid waste, whilst Red Rock's will use forestry and sawmill residues.

BTL fuel has achieved ASTM certification (corresponding to FRL 7), and it is moving towards FRL 8. BTL demonstration plants are operational and the first commercial-scale facilities are being developed, indicating that business models have been validated for production. Further three fuel purchase agreements have been secured with airlines.

3.2. Fermentation to jet (FTJ) – FRL 7

The fermentation to jet pathway describes technologies that produce alkane-type fuels from sugars via anaerobic fermentation, without an alcohol intermediate. This technology has the potential to use lignocellulosic sugars as feedstock, however currently most research efforts are focussed on simple sugars (e.g. sugarcane, sweet sorghum, maize) since these are easier to ferment (REG, 2014b; SkyNRG, 2014; Milbrandt, Kinchin & McCormick, 2013; CSIRO, 2011).

FTJ development is being led by a joint venture between Amyris and Total. Their proprietary 'Biofene' technology uses sugarcane-derived glucose to produce the isoprenoid farnesene, which is used as the basis for a range of petroleum replacement products. The first commercial plant in Brota, Brazil, has been operational since December 2012 and has the capacity to produce up to 50 million litres of farnesene per annum (Maniatis, Weitz & Zschocke, 2013; Total, 2013). Amyris has a memorandum of understanding to pursue jet fuel development with the airline GOL Linhas Aéreas Inteligentes, which plans to use at least 1% biojet blends in its fleet from 2016 (Amyris, 2014; Amyris, 2013). Biofene jet fuel was certified for blends of up to 10% with petroleum-derived jet in June 2014 (Annex A3 of ASTM D7566) (A4A, 2014a). Air France is using a 10% blend of the fuel for a weekly scheduled flights between Paris and Toulouse (Enerzine.com, 2014).

LS9 has had an operational FTJ pilot plant since 2008 and was formerly targeting the production of biojet. However since being bought out by REG Life Sciences in 2014 the company's focus has shifted from biofuels to biochemicals (La Monica, 2014; Wesoff, 2010).

Amyris' Biofene jet fuel is considered to have a FRL of 7 moving towards 8. It has achieved ASTM certification, a fuel purchase memorandum of understanding has been signed with an airline, and a first commercial plant capable of producing jet fuel is operational. These factors suggest that the business case for jet production is promising. The publically available literature on FTJ fuels produced by other companies is insufficient to assess their FRLs, but since none are pursuing ASTM certification FRL 5 is assumed as a maximum.

3.3. Alcohol to jet (ATJ) – FRL 4-6

The alcohol to jet pathway covers a wide range of technologies producing jet fuel from biomass via alcohol intermediates. The alcohols are converted to hydrocarbon fuel via dehydration, oligomerisation and hydrogenation.

The individual technical processes employed in the ATJ pathway are considered to be mature, being widely used in commercial petrochemical applications (Güell et al., 2012). However complete feedstock-to-fuel process chains for biojet are at the pilot and demonstration stages of development. In general technologies to synthesise alcohol intermediates are better developed than those to convert the intermediates to jet fuel. The most advanced biojet research efforts are targeting ethanol and butanol as intermediates (Güell et al., 2012; IATA, 2012a; IATA, 2011).

Alcohol synthesis

Bioethanol derived from 'first generation' sugar and starch feedstocks is a fully mature technology that serves a large commodity market: some 108 billion litres of bioethanol were produced globally in 2012 (Renewable Fuels Association, 2014; Güell et al., 2012). Conversion of lignocellulosic biomass to ethanol is however much more novel. BioChemtex and Ineos-Bio opened the world's first two commercial-scale plants in 2013, 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). However, interest in biobutanol has re-emerged in recent years, due in part to the superiority of its fuel characteristics compared with 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). The companies 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). Efforts to scale-up biobutanol over the last five years have in general been 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).

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 to jet fuel

A key strength of the ATJ 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, notably BioChemtex/Gevo, Cobalt/Arlbermarle Corporation/NREL and Lanzatech/Swedish Biofuels (Chiaramonti, 2013; Cobalt Technologies, 2012; Swedish Biofuels, 2011). In most cases, the jet fuel conversion processes are at the laboratory and pilot stages of development. Lanzatech and Swedish Biofuels are 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).

There are 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 and Swedish Biofuels have fuel development agreements with Virgin Atlantic, the US Ministry of Defence and the Swedish Defence Material Administration (Swedish Biofuels, 2011). Gevo is being supported by Lufthansa and the US Air Force to test its fuel samples (Gevo, 2014a; Gevo, 2014b). Byogy Renewables and Avianca Brazil are working in partnership to accelerate ASTM approval of Byogy's ATJ fuel, which is hoped to be suitable as a 100% replacement for petroleum kerosene (PR Newswire, 2014).

ATJ-SPK fuel from starch and sugar feedstocks is currently undergoing ASTM evaluation (IATA, 2013; Rumizen, 2014). Certification is expected during 2015, although 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). ATJ-SKA (from starch and sugar feedstocks) is expected to take longer to achieve certification, but may be suitable for use in blends of up to 100% since it contains aromatics (SkyNRG, 2014). Cobalt's fuel has passed the early stages of the US Navy's fuel certification scheme (Qantas, 2013).

Overall ATJ approaches are considered to have FRLs ranging from 4 to 6. The lower end of this represents fuels which are still undergoing laboratory-scale technical evaluation (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).

3.4. Hydrotreated depolymerised cellulosic jet (HDCJ) – FRL 6

The hydrotreated depolymerised cellulosic jet (HDCJ) pathway represents a diverse range of fuel conversion technologies including conversion routes based on pyrolysis, hydrothermal liquefaction and hybrid processes. For liquefaction-based HDCJ, wet lignocellulosic biomass is converted to a bio-oil with a low oxygen content, whilst for pyrolysis-based HDCJ, dry lignocellulosic biomass is converted to a bio-oil with a high oxygen content. In both cases this conversion is achieved via hydrothermal catalysis and the bio-oil is subsequently upgraded using hydrogen.

Biomass pyrolysis has been deployed at pilot scale since the 1970s and at demonstration scale since the 1990s, but interest in upgrading the bio-oils generated for transport fuel only developed in the late 1990s (Jones & Male, 2012; Venderbosch & Prins, 2010; Bauen et al., 2009). Considerable R&D efforts are underway to lower the cost of upgrading processes, both through improvements to hydrodeoxygenation methods and the development of novel upgrading techniques (Arbogast, Bellman, Paynter, & Wykowski, 2013; Bauen, Howes, Bertuccioli, &

Chudziak, 2009; BIOCOUP, 2011; NABC, 2012; Radlein & Quignard, 2013; Venderbosch & Prins, 2010; VTT, 2014). These new approaches are mostly in the laboratory or pilot stages of development.

Recent years have seen the closure of several biomass fast pyrolysis pilot plants across Europe and the cancellation of proposed projects due to weak market conditions (BillerudKorsnäs, 2013; Venderbosch & Prins, 2010). The slow commercialisation of these technologies is blamed in part on the lack of market demand for unrefined bio-oil (Radlein & Quignard, 2013). Organisations in Europe which do have operational pilot plants include Bioliq, Metso and the Biomass Technology Group (BTG), which is also developing a commercial-scale plant (Bioliq, 2014a; BTG, 2014b; EMPYRO, 2014). However, these companies are not currently targeting jet fuel: both the Bioliq and Metso plants are producing bio-oil for use as a gasification feedstock, whilst the BTG plants are not aiming to produce upgraded products at present.

Licella is the leading the development of HDCJ biojet. It has one pilot and two demonstration-scale facilities operating its proprietary 'catalytic hydrothermal reactor' (Cat-HTR) technology, and is developing plans for a commercial scale facility (Biomass Producer, 2013; Radlein & Quignard, 2013; Green Car Congress, 2011). The fuel is undergoing testing against ASTM specifications (Nabi et al., 2015). Licella has memoranda of understanding to develop aviation fuels with Virgin Australia and Air New Zealand, and Renewable Oils Corporation has a memorandum with Virgin Australia (Virgin Australia, 2014; Biomass Producer, 2013). KiOR (catalytic fast pyrolysis/fluid catalytic cracking) was also playing an important role until recently, operating a pilot plant and having advanced its biojet to ASTM assessment, however the company was declared bankrupt in early 2015 (Chandler, n.d.).

Licella's Cat-HTR biojet is at FRL 6: it has been scaled from laboratory to pilot stages, a demonstration plant is being developed, and ASTM testing is underway. The publically available literature on HDCJ fuels being developed by other companies is insufficient to assess their FRLs.

3.5. Aqueous phase reforming (APR) FRL 6

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).

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). Its fuel is being tested against ASTM specifications (Virent, 2013).

Virent's APR fuel is considered to be at FRL level 6 since demonstration facilities have been established and the fuel is being tested against ASTM specifications.

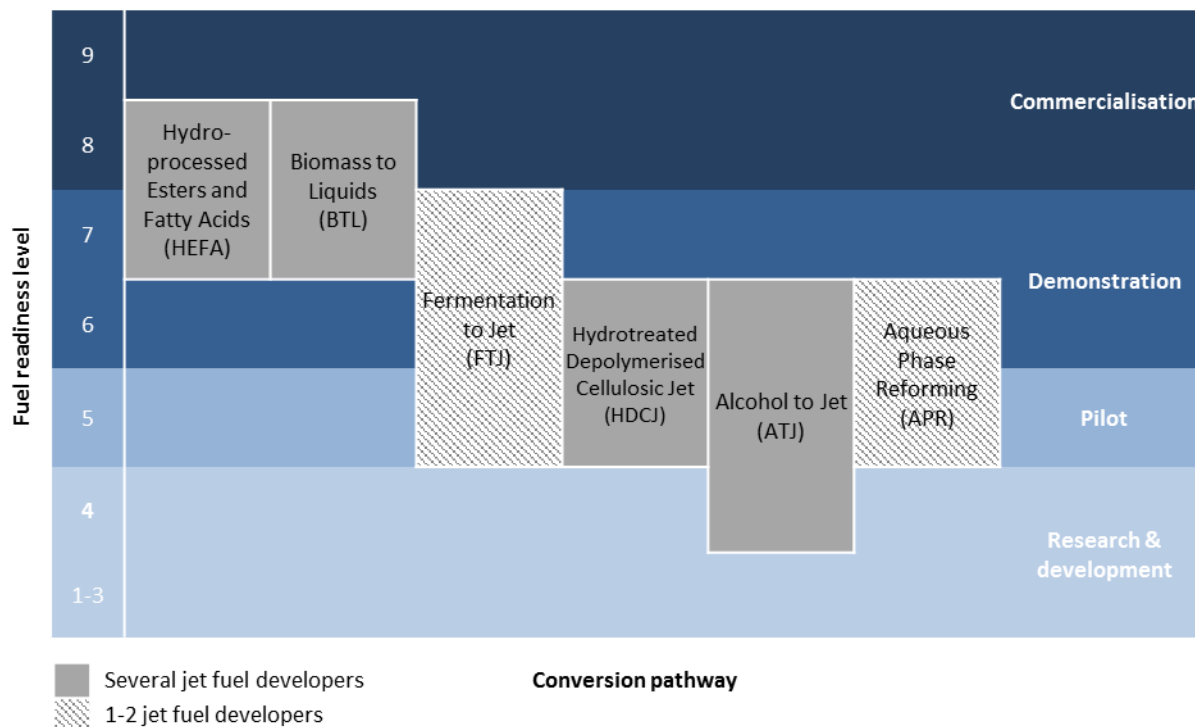
4. SUMMARY

Decarbonisation of the aviation industry is expected to rely heavily on increased uptake of biojet fuel. Within Europe second generation lignocellulosic feedstocks are considered to have the greater potential for production of sustainable and financially competitive biojet than vegetable and waste oil resources, from which the majority of biojet is currently produced.

The CAAFI Fuel Readiness Level (FRL) scale enables comparison of the commercial maturity of biojet production technologies according to 'toll gate' achievements. This paper's FRL assessment indicates that second generation biojet technologies vary considerably in terms of their technological and commercial maturity and commercial robustness. The most highly developed pathway, biomass to liquids, is being supported by multiple fuel developers and is in the very early stages of commercialisation (FRL 7-8). Other fuel conversion pathways are in the demonstration and pilot phases (4-6), with some being pursued by only one or two companies and thus more vulnerable to individual companies experiencing difficulties (Figure 1). Several partnerships exist between biofuel developers and the aviation industry, and **Error! Reference source not found.** over a dozen commercial, demonstration and pilot facilities to produce biojet are operational or under development worldwide.

The observed rate of technological development within the biojet field to date, as well as biofuels more generally, suggests that biojet technologies could progress by up to 2 FRLs by 2020 – allowing most of the pathways examined by this study to reach at least the early stages of commercialisation. However the pace and extent of new deployment will depend on the development of ambitious and enforceable biojet policy. Further, the FRL scale has been designed to consider the maturity of individual biojet production pathways in isolation, ignoring possible 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 option to retrofit existing first-generation ethanol facilities to produce butanol and/or to process lignocellulosic feedstocks. Such synergies could have a significant impact on the future development of biojet.



Current fuel readiness levels of biojet conversion technologies

The HEFA pathway is illustrated for comparison since the majority of biojet produced to date has been made from vegetable and waste oils via this process. HEFA is considered to be at FRL 7-8 because it is listed in international standards and some fuel purchase agreements exist with airlines (EBTP, 2015). However potential for large-scale deployment is limited by the high cost of the raw feedstock (de Jong et al., 2015).

5. ACKNOWLEDGEMENTS

This research has been conducted as part of the Fuel Supply Chain Development and Flight Operations (RENJET) project, funded by the EIT Climate-KIC. The project aims to lay the basis for a self-sustaining network of regional renewable jet fuel supply chains based on sustainable European feedstock sources.

We gratefully acknowledge the support of the paper's advisory group, drawn from RENJET's partner organisations: Imperial College London, University of Utrecht, SkyNRG, KLM and Schiphol Airport.

This paper draws on results from the project report 'Establishing a European renewable jet fuel supply chain: the technoeconomic potential of biomass conversion technologies' by Mawhood, Rodriguez Cobas and Slade (2014).

6. REFERENCES

- Academic1. (2014). Interview with Becky Mawhood, 19th September.
- Arbogast, S., Bellman, D., Paynter, J. D., & Wykowski, J. (2013). Advanced biofuels from pyrolysis oil ... Opportunities for cost reduction. *Fuel Process. Technol.*, 106, 518–525. doi:10.1016/j.fuproc.2012.09.022
- Arup URS, & E4tech. (2013). *Advanced Biofuel Feedstocks – An Assessment of Sustainability*. UK: ARUP URS & E4tech.
- ATAG. (2014). *Aviation: Benefits Beyond Borders*. Geneva, Switzerland: Air Transport Action Group.

- Bauen, A., Howes, J., Bertuccioli, L., & Chudziak, C. (2009). *Review of the potential for biofuels in aviation*. London: E4tech.
- BIOCUP. (2011). *Publishable Final Activity Report. Co-processing of upgraded bio-liquids in standard refinery units*. BIOCUP. Retrieved from [http://www.biocoup.com/index.php?id=21&tx_ttnews\[tt_news\]=38&tx_ttnews\[backPid\]=120&cHash=862e1cd3a5](http://www.biocoup.com/index.php?id=21&tx_ttnews[tt_news]=38&tx_ttnews[backPid]=120&cHash=862e1cd3a5)
- CAAFI. (2014). Fuel Readiness Level. Commercial Aviation Alternative Fuels Initiative. Retrieved from http://www.caa.fi.org/information/pdf/FRL_CAAFI_Jan_2010_V16.pdf
- CCC. (2009). *Meeting the UK aviation target – options for reducing emissions to 2050*. London: Committee on Climate Change.
- Chandler, C. (n.d.). KiOR, Twin Creeks among innovative no-goes, 18 April 2015. *The Clarion-Ledger*,. Retrieved April 21, 2015, from <http://www.clarionledger.com/story/money/business/2015/04/18/kior-twin-creeks-among-innovative-goes/26013175/>
- Chiaramonti, D. (2013). The EU FP7 Biolyfe project and the Proesa® industrial solution for cellulosic ethanol production. *[Presentation]*. Chemtex/Mossi & Ghisolfi Group, XX ISAF – Stellenbosch, SA 25-27/03/13. Retrieved from http://academic.sun.ac.za/microbiology/Documents/ISAF_PDF_for_web/Plenaries/David_Chiaramonti.pdf
- Cobalt Technologies. (2012). Cobalt And The Naval Air Warfare Center Team Up To Produce A Renewable Jet Fuel From Bio N-Butanol, 20 March 2012. Retrieved from http://www.cobalttech.com/news-item/March_20_2012.html
- Consultant1. (2014). Interview with Becky Mawhood and Evangelos Gazis, 14th November.
- De Jong, S., Hoefnagels, R., Faaij, A., Slade, R., Mawhood, R., & Junginger, M. (2015). A Techno-economic Analysis of Short-term Production Strategies for Renewable Jet Fuels – The Path towards Fossil Fuel Price Parity. *Biofpr, Submitted*.
- EBTP. (2015). Advanced Biofuels for Air Transport. *European Biofuels Technology Platform*. Retrieved May 29, 2015, from http://www.biofuelstp.eu/aviation-biofuels.html#demo_flights
- Energine.com. (2014). Toulouse - Paris-Orly : un vol hebdomadaire alimenté en biocarburant, 27 October 2014. Retrieved April 21, 2015, from <http://superincumbency53.rssing.com/browser.php?indx=23752199&item=76>
- Fulcrum Bioenergy. (2015). Fulcrum BioEnergy. Retrieved April 20, 2015, from <http://fulcrum-bioenergy.com/>
- GSR. (2013). Rapid evidence assessment toolkit. *Civil Service*. Civil Service: Civil Service. Retrieved from <http://www.civilservice.gov.uk/networks/gsr/resources-and-guidance>
- IATA. (2013). *IATA 2013 Report on Alternative Fuels*. Montreal, Canada and Geneva, Switzerland: International Air Transport Association.
- InterGovt1. (2015). Interview with Sierk de Jong and Evangelos Gazis, 11th February.
- Khangura, S., Konnyu, K., Cushman, R., Grimshaw, J., & Moher, D. (2012). Evidence summaries: the evolution of a rapid review approach. *Systematic Reviews*, 1, 10.
- La Monica, M. (2014). Why Genetic Engineering Hasn't Delivered Cheap Diesel from Sugar. *MIT Technology Review*. Retrieved April 20, 2015, from <http://www.technologyreview.com/news/524011/why-the-promise-of-cheap-fuel-from-super-bugs-fell-short/>
- Lane, J. (2015). Fulcrum BioEnergy: Biofuels Digest's 2015 5-Minute Guide, 23 February 2015. Retrieved April 20, 2015, from <http://www.biofuelsdigest.com/bdigest/2015/02/23/fulcrum-bioenergy-biofuels-digests-2015-5-minute-guide/>

- Lee, D. S., Lim, L. L., & Owen, B. (2013). *Bridging the aviation CO2 emissions gap: why emissions trading is needed*. Manchester, UK: Centre for Aviation Transport and the Environment, Manchester Metropolitan University.
- Mawhood, R., Cobas, A. R., & Slade, R. (2014). *Establishing a European renewable jet fuel supply chain : the technoeconomic potential of biomass conversion technologies*. London.
- NABC. (2012). Making Oils with Low Oxygen Content—Catalytic Fast Pyrolysis. National Alternative Biofuels Consortium. Retrieved from http://www.nabcprojects.org/pdfs/making_oils_with_low_oxygen_content.pdf
- Nabi, M. N., Rahman, M. M., Islam, M. A., Hossain, F. M., Brooks, P., Rowlands, W. N., ... Brown, R. J. (2015). Fuel characterisation, engine performance, combustion and exhaust emissions with a new renewable Licella biofuel. *Energy Conversion and Management*, 96, 588–598. doi:10.1016/j.enconman.2015.02.085
- PR Newswire. (2014). Avianca Brasil And Byogy Renewables Forge Initiative To Drive The Global Approval of Alcohol-To-Jet (ATJ) Renewable Jet Fuel, April 22, 2014. Retrieved April 20, 2015, from <http://www.prnewswire.com/news-releases/avianca-brasil-and-byogy-renewables-forge-initiative-to-drive-the-global-approval-of-alcohol-to-jet-atj-renewable-jet-fuel-256265611.html>
- Radlein, D., & Quignard, A. (2013). A short historical review of fast pyrolysis of biomass. *Oil and Gas Science and Technology*.
- Rumizen, M. (2013). *ASTM D4054 Users' Guide*. CAAFI.
- Rumizen, M. (2014). FAA CLEEN II and COE (FAA Alternative Fuels R&D Programs). *[Presentation]*. CAAFI, 28 January 2014.
- Solena Fuels. (2014). Solena Fuels' Projects. Solena Fuels. Retrieved from <http://www.solenafuels.com/index.php/projects>
- Southwest Airlines. (2014). Southwest Airlines Announces Purchase Agreement With Red Rock Biofuels, 24 September 2014. Retrieved May 28, 2015, from <http://www.swamedia.com/releases/southwest-airlines-announces-purchase-agreement-with-red-rock-biofuels?l=en-US>
- Steiner, J. J., Lewis, K. C., Baumes, H. S., & Brown, N. L. (2012). A Feedstock Readiness Level Tool to Complement the Aviation Industry Fuel Readiness Level Tool. *BioEnergy Research*, 5(2), 492–503. doi:10.1007/s12155-012-9187-1
- Swedish Biofuels. (2011). NEWS & SEMINARS. Retrieved from <http://www.swedishbiofuels.se/news-seminares>
- Venderbosch, R. H., & Prins, W. (2010). Fast pyrolysis technology development. *Biofuels, Bioproducts and Biorefining*, 4(2), 178–208. doi:10.1002/bbb.205
- Virent. (2013). VIRENT DELIVERS PLANT-BASED JET FUEL TO U.S. AIR FORCE RESEARCH LABORATORY FOR TESTING. Retrieved from <http://www.virent.com/news/virent-delivers-plant-based-jet-fuel-to-u-s-air-force-research-laboratory-for-testing/>
- VTT. (2014). Synthetic fuels and biorefining. VTT. Retrieved from http://www.vtt.fi/research/technology/synthetic_fuels_and_biorefining.jsp?lang=en
- Wesoff, E. (2010). LS9's Genetics Breakthrough: Will it Produce Biofuels at Scale? 29 July 2010. GreenTechMedia. Retrieved from <https://www.greentechmedia.com/articles/read/LS9s-Biofuel-Production-Breakthrough>