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Sustainable Aviation Fuels

Status, challenges and prospects of drop-in liquid fuels, hydrogen and electrification in aviation

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Aviation fuel demand is expected to continue to grow over the next decades and continue to rely heavily on kerosene fuel for use in jet engines. While efficiency and operational improvements are possible ways to reduce greenhouse gas (GHG) emissions, decarbonisation will need to heavily rely on low carbon kerosene drop-in alternatives. Currently, alternative fuels make up a very small share of fuel used in aviation, but their commercialisation is making good progress. Hydrogen offers a longer-term alternative fuel option but requires aircraft design and fuelling infrastructure changes. Electrification is emerging as an option for providing propulsion in aircraft, either in pure form in small aircraft or in hybrid mode in larger aircraft. This paper reviews the status, challenges and prospects of alternative fuels and electrification in aviation.

1. Introduction

Early research into alternative fuels for aviation was conducted following the fuel price increases in the USA in the 1970s (1) driven by concern around costs and security of supply. Today, with the aviation industry responsible for around 2% of all human-induced carbon dioxide emissions (2), its estimated contribution to manmade climate change more than double this when non-CO_2 impacts are taken into account (3), and rapid growth expected over the next decades, the development of alternative aviation fuel is driven largely by concerns around climate change. Global aviation activity grew by 140% between 2000 and 2019 (4) and passenger numbers have been anticipated to continue to grow at a compound annual growth rate of 3.5% over the next two decades (5).

Policies are beginning to be put in place which aim to reduce GHG emissions from the aviation sector. In 2016 the International Civil Aviation Organization (ICAO) adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) which aims to stabilise net CO_2 emissions from international civil aviation at 2020 levels (6). Whilst the remit of ICAO only covers international aviation, an increasing number of measures are being put in place by national governments which cover domestic flights and international flights. Flights within the European Union (EU) are included in the EU Emissions Trading System (EU ETS) since 2012. Domestic aviation is included in New Zealand's Emissions Trading Scheme and other states such as Canada and China have indicated that domestic aviation will be brought within a national carbon pricing scheme (7).

Even taking into account fuel efficiency improvements that can be achieved by more modern aircraft design and improved operational measures, low-carbon fuels will be essential in order to meet targets for the decarbonisation of the sector (8). Several countries or regions including California (9), the UK (10) and The Netherlands (11) have included aviation fuel within national support schemes for low carbon fuels on an opt-in basis. Norway has introduced blending mandates for alternative fuels in aviation, and a number of other countries including Sweden and The Netherlands are considering similar policies (12).

In the past 20 years substantial progress has been made in the production and use of alternative aviation fuels. In February 2008 a Virgin Atlantic, UK, Boeing 747 (The Boeing Company, USA) became the first aeroplane flown by a commercial airline on a blend of kerosene and bio-jet fuel, and the first scheduled commercial flights on bio-jet fuel began in 2011 (13). Today more than 100,000 commercial flights have been carried out using alternative liquid aviation fuel (13), and at the time of writing there were six alternative fuel pathways certified by ASTM International, USA (14). Two additional ones have been approved in 2020.

One of the main challenges for low-carbon fuels replacing fossil kerosene is matching the same fuel energy density. The energy consumption of an aircraft is proportional to its mass and that is why the fuel energy density and the weight of aircraft components are key factors. Bio-jet has almost identical energy density to fossil kerosene, while hydrogen's volumetric energy density is an order of magnitude lower, and electrochemical batteries' volumetric and mass energy densities are also an order of magnitude lower (**Figure 1**).

This paper reviews the status of alternative fuel options for the aviation sector, covering liquid fuels, hydrogen and electricity. A schematic overview of all alternative fuel routes for aviation is provided in **Figure 2**. The paper then explores the prospects for future demand and supply of alternative drop-in liquid aviation fuels to 2030.

2. Renewable Drop-in Kerosene Alternatives

Renewable drop-in kerosene alternatives are synthetic liquid fuels produced from biogenic feedstocks or using renewable hydrogen and CO_2 (from waste streams or from the atmosphere) which are functionally identical to fossil jet kerosene. There are several possible routes to produce renewable drop-in kerosene based on different feedstocks and technology variants. **Table I** summarises their technology status.

The costs of alternative fuels are substantially higher today compared to fossil kerosene, with costs ranging between two and five times the price of conventional jet fuel (global average price paid at the refinery for aviation jet fuel in October 2019 was about US$600 per million tonne). The lowest alternative fuel costs today are associated with the most commercially mature route consisting of the large scale hydroprocessing of used cooking oils (UCOs), animal fats and raw vegetable oils (16).

The GHG emissions savings from renewable routes will generally be substantial, but vary, largely depending on the emissions associated with producing the raw materials used in their production. It is generally expected that savings will be between about 95% in the case of renewable electricity based routes and 65% for routes based on conventional crops, with savings from routes based

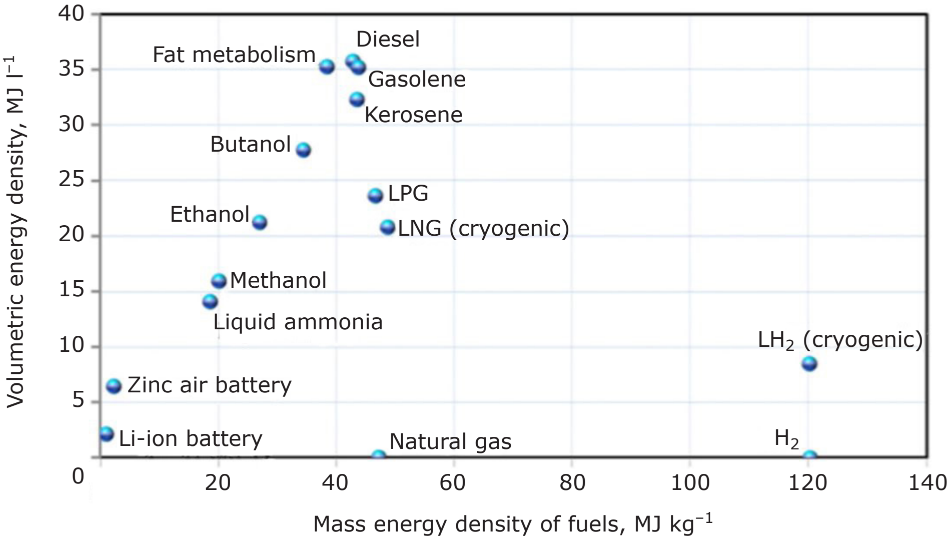

Fig. 1. Comparison of various energy sources for aviation (15)

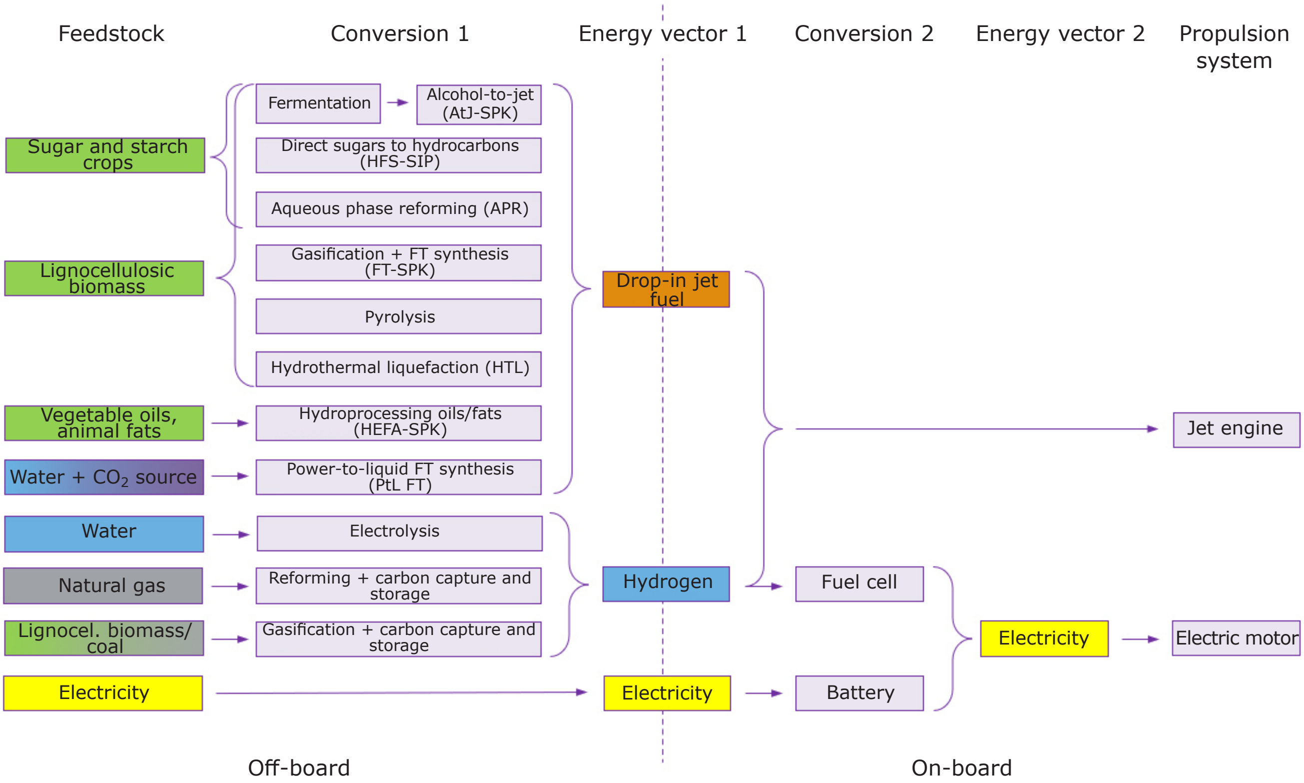

Fig. 2. Overview of alternative fuel routes for aviation

Table I Summary of Technology Readiness Level and Scale of Production of Drop-in Jet Fuels

Route	Technology status[a]	Largest plant, kilotonne $year^{-1}$ [b]
Hydroprocessed esters and fatty acids-synthetic paraffinic kerosene (HEFA-SPK)	Commercial (TRL 8)	1653 (planned)
Alcohol-to-jet-SPK (AtJ-SPK)	Demonstration (TRL 6–7)	82 (planned)
Hydroprocessing of fermented sugars-synthesised isoparaffins (HFS-SIP)	Prototype (TRL 5, lignocellulosic sugars), pre-commercial (TRL 7, conventional sugars)	81 (operational)
Fischer-Tropsch-SPK (FT-SPK)	Demonstration (TRL 6)	225 (planned)
Pyrolysis	Demonstration (TRL 6)	138 (planned)[c]
Aqueous phase reforming (APR)	Prototype (TRL 4–5, lignocellulosic sugars), demonstration (TRL 5–6, conventional sugars)	0.04 (operational)[d]
Hydrothermal liquefaction	Demonstration (TRL 5–6)	66 (planned)
Power-to-liquid FT (PtL FT)	Demonstration (TRL 5–6)	8 (planned)[e]

[a] TRL = technology readiness level
[b] Here 'tonne' refers to a generic tonne of liquid fuel and not specifically to jet fuel
[c] Pyrolysis oil
[d] Bio-crude
[e] Blue-crude

on biomass wastes somewhere in that range (17). Electricity used to produce e-fuels is generally supplied through the grid. The renewability of this electricity needs to be guaranteed through accounting procedures which also need to assure that the same renewable electricity is not double-counted for other uses. In the case of fuels based on energy crops, it will be important to consider their sustainability with regard to land use change impacts (18).

2.1 Synthetic Paraffinic Kerosene Produced from Hydroprocessed Esters and Fatty Acids (HEFA-SPK)

The HEFA route is the most mature alternative fuel pathway (currently at TRL 8) and it is certified by ASTM International as HEFA-SPK (14). HEFA is produced through hydroprocessing of vegetable oils and animal fats. Hydrogen is used to convert unsaturated compounds such as alkenes and aromatics into paraffins and cycloalkanes, which are more stable and less reactive. The process is the same as for hydrotreated vegetable oil (HVO) production but includes an additional isomerisation step that lowers the fuel freezing point. The energy conversion efficiency of oils and fats into HEFA-SPK (and other byproducts) is about 76%, the highest efficiency of bio-jet fuel routes (17). The conversion energy efficiency is calculated as the ratio of the total energy input (feedstock, electricity, natural gas and hydrogen) to the total energy content of the liquid products (in general jet, diesel, gasoline, heavy fuel oil and naphtha). Gaseous products (for example, methane) are excluded from the denominator.

Because of its maturity and simplicity compared to other routes, HEFA is the only alternative fuel in commercial use. Depending on the plant size and deployment stage, the production cost of HVO ranges between €1100 and €1350 per tonne. Upgrading to HEFA incurs a relatively small additional cost, associated with the isomerisation step. The main limitation of this route is feedstock availability. UCO and tallow represent a relatively small resource globally, and the supply of virgin vegetable oil is constrained by land availability and sustainability concerns. Novel crops are being investigated in terms of potential and sustainability, such as camelina, carinata and oil-bearing algae. Fermentation of sugars to lipids is also being considered to produce feedstock for HEFA plants (see later subsection).

2.2 Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)

The AtJ process turns alcohols into jet fuel through the following reactions: dehydration, oligomerisation, hydrogenation, isomerisation and distillation. The alcohol used can be produced through conventional processes involving fermentation of sugar or starch crops such as sugarcane, corn and wheat, or through advanced routes from lignocellulosic feedstocks, such as woody and grassy feedstocks and wastes. Currently, most developers are focused on upgrading conventional alcohols, but there are larger demonstration plants planned using advanced routes to alcohols that may be operational by 2020. AtJ-SPK blends up to 50% v/v are certified by ASTM International since 2016, though the technology is currently at TRL 6–7 (14). Certain AtJ routes, depending on the catalytic process used, produce a jet fuel containing aromatics, and efforts are underway for certification of 100% use of jet fuel derived from these routes.

AtJ routes are attractive as they can convert various types of alcohols (such as ethanol, methanol and isobutanol) from a wide range of sources into jet fuel as well as other hydrocarbons. Additionally, the AtJ route offers logistical flexibility because the alcohol catalysis plant does not need to be co-located with alcohol production, and alcohols can be conveniently transported and stored. The main weaknesses of this pathway may be the selectivity of jet fuel production. An issue to consider in relation to this route is the opportunity cost of using the alcohols directly in transport applications (for example road and marine) as opposed to converting them to jet fuel, at the cost of additional capital expenditure and some efficiency loss. Jet fuel costs produced *via* this route could be 20–40% higher than the ethanol feedstock on an energy basis, with the lower end of the range being for high ethanol input prices and the higher end of the range for lower ethanol input price.

2.3 Synthesised Isoparaffins Produced from Hydroprocessed Fermented Sugars (HFS-SIP)

Genetically modified microorganisms can be used to convert sugar into hydrocarbons or lipids. These routes are known as direct sugars to hydrocarbons (DSHC) routes, and there are three main routes under development whose products can be further processed into jet fuel: heterotrophic algae or yeast converting sugars into lipids within their cells; genetically modified yeasts which consume sugars and excrete long-chain liquid alkenes (such as farnesene); genetically modified bacteria consuming sugars and excreting short-chain gaseous alkenes (such as isobutene). Currently biological routes almost exclusively use conventional sugar feedstocks, although pilot projects are testing cellulosic sugars. DSHC routes using conventional sugar feedstocks are at TRL 7–8, while the same processes based on cellulosic feedstocks are at TRL 5. A specific route based on the production of farnesane from sugar is certified as hydroprocessing of fermented sugars (synthetic iso-paraffinic fuels (HFS-SIP)) and can be blended with fossil kerosene up to a maximum of 10% (14).

However, at present, potential DSHC developers are targeting the chemical, pharmaceutical, food and feed markets, which are generally higher value than bulk transport fuels. This in turn helps to prove the technology and reach the scale and lower production costs that may be required for fuels. The complexity and low efficiency of converting lignocellulosic sugars into fuels through DSHC translates into high feedstock cost and high energy consumption, which makes DSHC the most expensive alternative fuel route. HFS-SIP costs have been projected to remain high at above €4000 per tonne (19).

2.4 Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)

The gasification with Fischer-Tropsch (Gas+FT) synthesis process transforms lignocellulosic biomass or solid waste into fuels, such as naphtha, gasoline, diesel and jet fuel, as well as other valuable coproducts. The process consists of the following key steps: feedstock pretreatment (sorting, sizing and drying), gasification, syngas clean-up and conditioning, FT catalysis, distillation and hydrocracking. And may involve additional steps such as isomerisation and catalytic reforming depending on the type of fuel produced. The jet fuel produced through the Gas+FT route is certified as FT-SPK and can be blended with fossil kerosene up to 50% (14). While a commercially mature route exists for coal and natural gas-to-liquid routes, the bio-based route is only now approaching TRL 7–8.

While the individual components of a biomass gasification to FT fuel route are commercially demonstrated in different applications such as biomass gasification to heat and power applications and coal-to-liquid plants, the integrated application of biomass gasification to FT fuel has yet to be demonstrated at scale. Challenges faced by this route are the economic viability of scaling down processes to scales suitable for biomass and waste-based systems, the design of processes and catalysts better suited to relatively small scale systems, including catalyst selectivity, the design of systems that can cope with biomass and syngas heterogeneity and the overall efficiency of integrated systems (20). An option for this route could be to produce FT waxes that could then be co-processed at oil refineries.

2.5 Pyrolysis and Upgrading

Pyrolysis transforms lignocellulosic biomass or solid waste into an intermediate bio-crude oil, which can then be upgraded to fuels. The fast pyrolysis to bio-crude oil process is at TRL 8, with several first commercial facilities selling the pyrolysis oil for heating applications. However, refinery upgrading of pyrolysis oils to a finished fuel product is only at the early demonstration stage (TRL 6), with batch production in limited trial runs. The dedicated upgrading of pyrolysis oil *via* hydro-deoxygenation (HDO) is currently at TRL 3–4, with pilot activities such as the Horizon 2020 4REFINERY project (21). Therefore, the overall route from pyrolysis to jet fuel is at most at TRL 6. KiOR, USA, had embarked on the ASTM International certification process for bio-kerosene from fast pyrolysis but the company filed bankruptcy (22). By 2019, the catalytic pyrolysis process (IH^2), developed by Shell, the Netherlands, was in Testing Phase 1 of the ASTM International's ASTM D4054-19 qualification procedure (14).

A range of pyrolysis-type technologies are possible that can process a wide range of feedstocks (even low-quality wet feedstocks). Bio-crude oil could be transported to centralised dedicated or fossil refinery facilities for upgrading to fuels. The challenges with crude pyrolysis oil are its high water, acidity and oxygen content, as well as viscosity and chemical instability, though the quality of the oil is heavily dependent on the pyrolysis process (20). Transport of pyrolysis oil may require some pre-processing and specialist infrastructure. To date there is no commercial process for upgrading pyrolysis oil to finished fuel in dedicated plants. However, research into materials and catalysts for such systems is ongoing (23).

2.6 Aqueous Phase Reforming

The APR process catalytically converts biomass-derived oxygenates (such as sugars, sugar alcohols and polyols) in an aqueous solution into hydrogen, CO_2 and a mixture of alkanes, acids, ketones and aromatics (24). A series of condensation reactions then lengthen the carbon chains in the mixture of hydrocarbons. This mixture then undergoes hydroprocessing, isomerisation and distillation.

APR using conventional sugars is at TRL 5–6 as a result of pilot scale plants operated by Virent Inc, USA. APR derived bio-crude using lignocellulosic sugars has been produced and upgraded to bio-kerosene at laboratory scale (25). Aviation kerosene produced *via* APR is in Phase 2 of the ASTM International certification procedure and referred as hydro-deoxygenated synthetic kerosene (HDO-SK) (14).

Unlike other reforming processes, APR operates in wet conditions which reduces the costs of dewatering certain feedstocks like sugars. However, this process has low selectivity to liquid hydrocarbons (high gaseous yields) and short catalysts lifetime due to deactivation and coking (20). These two characteristics make APR expensive from a capital and operational cost standpoint. APR is also gaining interest as a route for biochemicals production (26), which could lead to higher value products.

2.7 Hydrothermal Liquefaction

Hydrothermal liquefaction (HTL) is a process where biomass and water are heated at very high pressures to produce a bio-crude. The near and supercritical water acts as a reactant and catalyst to depolymerise the biomass. The bio-crude produced can then be upgraded similarly to the pyrolysis route. The higher molecular weight distribution makes HTL oil more suitable for diesel production, but gasoline and jet are possible adding hydrocracking steps. HTL is well suited to process very wet biomass (sewage sludge, manure, micro and macro algae), as well as some lignocellulosic feedstocks. Bio-crude production of HTL oils is currently at TRL 5–6 with small scale demonstration activities ongoing (27). Dedicated upgrading to jet fuel is at laboratory-scale (TRL 3–4). The upgrading of HTL oil in refineries is being tested as part of the Horizon 2020 4REFINERY project (28). This route has not entered the ASTM International certification procedure and is still in pre-qualification stage (14).

HTL oils typically have much lower water content, higher energy content, lower oxygen content and greater stability than pyrolysis oils, hence are expected to be cheaper to transport and require less extensive upgrading. It is expected that HTL oils could be used at high blends in refinery fluid catalytic cracking (FCC) units. With mild hydrodeoxygenation, it might be possible to co-process the bio-crude with fossil crude oil in the front end of existing oil refineries (29). Challenges of this route are the high pressure and corrosive conditions under which the process operates.

2.8 Power-to-Liquid with Fischer-Tropsch Synthesis

The PtL FT route produces liquid fuels by catalytically combining a carbon source with a hydrogen stream produced *via* electrolysis. This pathway requires three 'feedstocks': electricity, water and a concentrated source of CO_2. The maturity of the PtL FT route depends on the maturity of single components and the design configuration chosen, with some systems being demonstrated at small scale (TRL 5–6). High-temperature PtL employs solid oxide electrolysers (SOE), which are more efficient but less mature than other electrolysis technologies (for example, alkaline electrolysers) (30). CO_2 from concentrated sources like biogas upgrading, ethanol production or beer brewing or CO_2 waste streams from industrial processes are commercially available, but other sources, such as direct air capture, are at an earlier stage of development and commercialisation (TRL 6–7) (31). FT synthesis is a well-established process at large scale, but at the demonstration stage for small scale applications (TRL 6–7) (20). FT-SPK produced through PtL is certified under ASTM International as long as the FT synthesis is based on iron or cobalt catalysts (D7566 Annex 1, article A1.4.1.1).

Operating costs for this route can be very high depending on the cost of electricity. Specific capital costs are currently high as the technology is at the early demonstration stage, and the potential to reduce these through scaling and learning remains to be demonstrated (32). Technology developers are also working on different FT catalysts with different selectivities that could provide more direct routes to desired fuels and be more economically viable at relatively small scales. The technology also requires concentrated flows of CO_2, which might constrain the location of these plants in proximity to large industries. Despite being at very early stage with just a handful of active developers, PtL is a pathway attracting widespread interest as a result of its potential to produce fuels with very low GHG emissions and subject to less feedstock constraints and sustainability issues compared to bio-based fuels.

2.9 Demand and Supply Scenarios for Drop-in Kerosene Fuels

Today global use of aviation fuel for commercial international and domestic aviation is around 280 million tonne year^{-1} (33), however less than 0.1% of this is currently alternative or low-carbon fuel (34).

The current global capacity for HEFA production from dedicated hydroprocessing and co-processing in refineries is around 5 million tonne year^{-1} (35). With incentives for the use of alternative fuel in the road transport sector substantially stronger than in the aviation sector, the majority of the output from hydroprocessing plants today goes to substituting diesel in the road transport sector, as opposed to producing HEFA for aviation. Therefore, in 2018 less than 0.1 million tonne of HEFA aviation biofuel was actually produced (34). Nevertheless, hydroprocessing outputs require relatively minor treatment to produce aviation HEFA, meaning that HEFA production could scale-up fairly rapidly if policy were to make the use of alternative fuels in the aviation sector competitive with their use in the road transport sector.

Production capacity of sustainable aviation fuel (SAF) from all other routes is substantially lower (less than 0.1 million tonne in total), but plants are planned or being built that will progress the commercialisation of these routes (shown in **Figure 3**).

For example, Fulcrum BioEnergy, USA, is building a 31,000 tonne year^{-1} jet fuel plant based on gasification of municipal solid waste and FT synthesis (36); Lanzatech, USA, in collaboration with Virgin Atlantic are planning an AtJ plant in the UK (37); and Velocys, UK, in collaboration with British Airways, UK and Shell have provided funding to support development of a plant based on gasification of municipal waste and FT synthesis also in the UK (38).

As HEFA is currently the only SAF production technology at commercial scale, it is likely to dominate global SAF production capacity over the next decade or so. However, production of HEFA relies on the use of oils and fats as feedstock, and concerns around the sustainability of oil crops means that HEFA production is likely to be increasingly limited to the use of waste fats and oils unless other sustainable sources of oils are developed. Estimations from a number of sources suggest that around 20 million tonne year^{-1} of UCO and tallow could be collected globally (total arisings will be higher, but not all can be collected and used). E4tech Ltd, UK, carried out analysis based on Ecofys Ltd, UK, 2014 (39) and World Bank, USA, data on population (40). Even assuming that virgin vegetable oil currently used for fatty acid methyl ester (FAME) production (24.4 million tonne in 2017) was diverted into HVO or HEFA production instead, the total available feedstock would still be fairly limited compared to aviation fuel consumption.

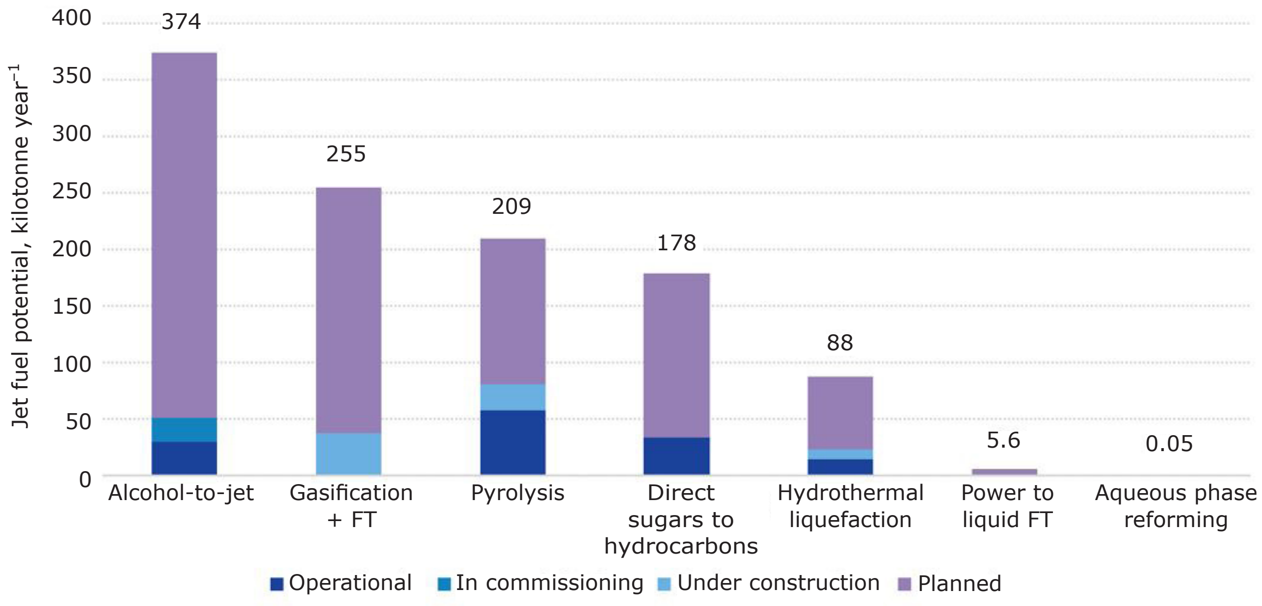

Fig. 3. SAF potential production capacity (excluding oil-based routes) as of June 2019 (35). Operational capacity refers to potential jet fuel production volumes. Pyrolysis oil and farnesene produced in the pyrolysis and DSHC plants are not currently being upgraded to jet fuel

Therefore, in the longer-term SAFs are likely to be produced from a range of lignocellulosic waste biomass sources, lignocellulosic or oil crops with a low risk of causing direct and indirect negative environmental and social impacts and renewable electricity (**Figure 4**).

However, the technologies to process lignocellulosic feedstocks into SAF are still at an early stage of development and commercialisation. Ramping-up from the demonstration-scale or first-of-a-kind commercial FT and AtJ plants, currently planned or under construction, to the construction of multiple commercial-scale plants will happen over a period of at least 10 years. Other biofuel routes and PtL routes are likely to take longer to achieve multiple commercial scale plant output, as they are at earlier stages of development and demonstration, there are fewer companies currently developing them and production costs are high.

Despite the current low production volumes, the opportunity for SAF production is large, and the imperative is strong if decarbonisation targets are to be met. The International Energy Agency (IEA, France) 2°C scenario (2DS) anticipated that even with substantial improvements in aviation efficiency and modal switching to high-speed rail for some journeys, there would still be a requirement for around 150 million tonne year^{-1} of SAF in 2060 from international aviation alone (45). With the introduction of the CORSIA mechanism over the next decade, and an increasing number of governments considering the introduction of SAF blend mandates or other policy measures to promote the uptake of SAF, growth is likely to accelerate over the coming years.

3. Hydrogen

A transition to hydrogen in civil aviation requires major aircraft and infrastructure changes. However, the potential for hydrogen as a widespread clean energy source in the future also leads to interest in its use in aviation. In August 2019 the German government announced the 'Leipzig Statement for the Future of Aviation', proposing the introduction of a hydrogen in aviation strategy by the end of 2019 (46). Use of hydrogen, both as a source of propulsion power and on-board power, has the potential to reduce noise pollution, increase efficiency and reduce GHG emissions associated with the aviation sector as long as hydrogen is produced from a renewable source, from other potentially low carbon energy sources such as nuclear or from fossil sources with carbon capture and storage.

While hydrogen has a much higher gravimetric energy density than kerosene, its volumetric energy density is much lower and both characteristics are critical to airframe design and performance (**Figure 1**). Due to hydrogen's low volumetric energy density, redesign of the airframe is required to accommodate the highly-insulated tanks required to store liquid hydrogen (LH_2) (47).

3.1 Hydrogen Turbofan

In 2000, the European Commission commissioned a study to Airbus called 'Cryoplane' (48), one of the objectives being to explore the conceptual design of an aircraft equipped with hydrogen-fuelled turbo-

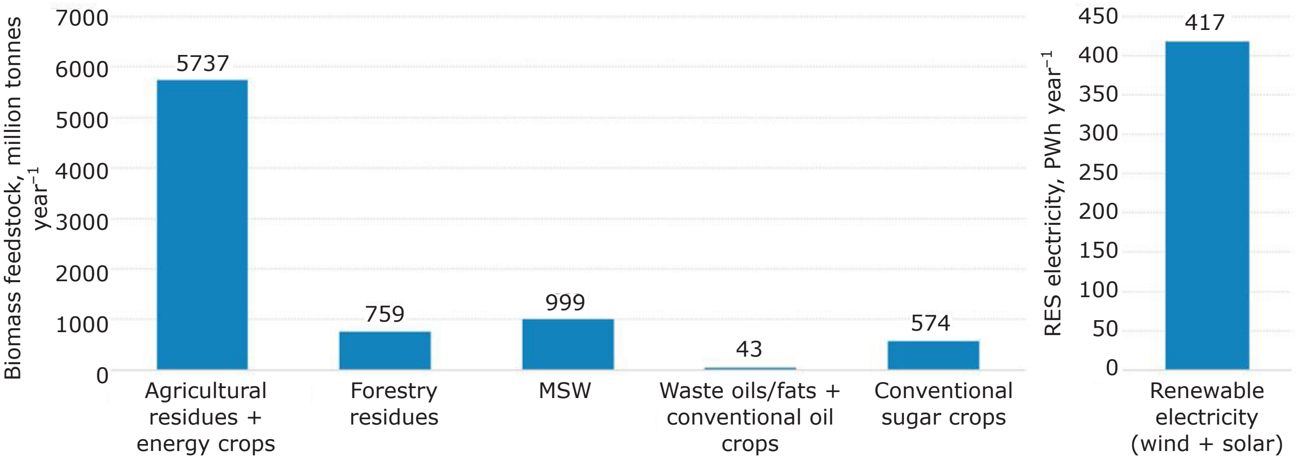

Fig. 4. Global 2050 feedstock availability (E4tech Ltd analysis based on (39, 41–44)

engines and cryogenic tanks to store LH_2. The study found that energy consumption increases by 10% compared to a reference kerosene aircraft, due to the additional weight of the hydrogen tanks (48). More recent studies (49, 50) argue that the Cryoplane project adopted a 'minimal change' approach to wing planform and engine design for the hydrogen aircraft. They show that when airframe and engine design are optimised for a hydrogen-fuelled aircraft then an energy saving up to 12% is achievable on long-haul aircraft compared to a kerosene benchmark. However, short-haul flights are penalised in terms of energy consumption when switching to hydrogen.

Modifications to the turbo-engine are required when using hydrogen due to a different composition of combustion gases and variations between the properties of hydrogen and kerosene (for example calorific value and volumetric density). Modifications affect several engine parts, such as burners, fuel ducts, cooling system and turbine blades (47). Adoption of hydrogen as an aviation fuel will also require redesign of the fuel supply chain, including on-the-ground storage and refuelling.

3.2 Hydrogen Fuel Cell Aircraft

Hydrogen can also be used in fuel cells (FCs), and both the proton exchange membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) are options being considered for use in aviation. Hydrogen FCs convert chemical energy into electrical energy that could power on-board electrical equipment, or an electric propulsion system.

FCs could be used on-board in parallel to or in place of auxiliary power units (APUs). Traditional APUs consist of a small gas turbine supplying power for electrical and pneumatic loads when the aircraft is stationary as well as back-up power while cruising. FCs could see a gradual integration in aircraft APUs through powering systems currently powered by batteries, such as emergency door systems (47). A report by The Boeing Company suggested hydrogen SOFC-powered APUs for all non-propulsion loads in the aircraft would reduce fuel consumption for on-board energy by 40% during cruising compared with traditional APUs (47). However, it is important to bear in mind that auxiliary units account for a small portion of the total energy consumption of an aircraft.

There have been several projects to develop hydrogen FC aircraft, focusing on small low-speed aircraft. The HyFlyer project, led by ZeroAvia, USA, aimed to decarbonise medium range, six-seater aircraft by replacing the conventional propeller powertrain with a compressed (5000 psi) hydrogen PEMFC system (51). ZeroAvia flight tested its prototype powertrain, using a Piper PA-46 Light Sport Aircraft (Piper Aircraft, USA) (52, 53). National Aeronautics and Space Administration (NASA), USA, funded a project by the Center for Cryogenic High-Efficiency Electrical Technologies for Aircraft (CHEETA) to develop an aircraft that uses a LH_2 PEMFC system to power fully electric fans. One of the aims of the project was to demonstrate the potential of cryogenic hydrogen for larger aircraft (54). A research consortium led by The German Aerospace Center (DLR) developed HY4, a four-seater hydrogen FC aircraft (55), which completed its first flight in 2016 (56). The powertrain consists of a PEMFC coupled to a single 80 kW electric motor and supported by a battery. About 10 kg of hydrogen is stored in gaseous form in a tank at 437 bar. HY4 has a maximum weight of 1.5 tonne and can fly at 145 km h^{-1} for about 1000 km.

4. Electricity

Aviation electrification has been a trend since the 1960s, with many auxiliary systems increasingly electrified owing to the relative lightweight and higher efficiency compared to mechanical systems. Electric propulsion has also seen development since the 1970s, but so far it has been limited to demonstration or leisure activities (57). Electrically enhanced propulsion could provide significant benefits, including fuel and emissions savings and noise reduction, but technical challenges associated with battery energy and power density remain yet. Like automotive electrification, various degrees of electrification and different architectures are possible.

4.1 Hybrid Electric Aircraft

In hybrid-electric systems, where an electric motor and a turbofan are configured in series or parallel, an electric battery can supply power to optimise overall flight energy consumption and emissions. The electric motor runs together with the turbofan when high thrust is needed, or alone when low thrust is needed such as during cruising. This mechanism enables downsizing of turboengines and increased fuel economy (58).

Large industry players have worked on demonstrating the hybrid-electric architecture for future application in the large commercial aircraft segment. In 2017, Airbus, Siemens AG, Germany, and Rolls-Royce, UK, established a collaboration to develop the E-Fan X, a hybrid-electric aircraft demonstrator (59). They planned to replace one of the four jet engines in a BAE 146/RJ100 airliner with a 2 MW electric motor powered by a Rolls-Royce AE2100 gas turbine power-generation system and a lithium-ion battery pack (60, 61). Boeing and NASA partnered in a study called Subsonic Ultra Green Aircraft Research (SUGAR), to develop a hybrid-electric aircraft named 'Volt' (62) equipped with twin-engines. The engines were designed to burn fuel when the power requirement is high (such as during take-off), and to use electricity to supplement or replace power from the turbo engines while cruising. The EU Horizon 2020 Modular Approach to Hybrid Electric Propulsion Architecture (MAHEPA) project was set up as a collaboration between small and medium-sized enterprises (SMEs) and academic parties including Pipistrel Vertical Solutions, Slovenia, DLR and Delft University of Technology (TU Delft), The Netherlands. The team worked on developing two four-seater aircraft with the objective, among others, of collecting real-world data on hybrid-electric flights. The configuration of the first prototype being built by MAHEPA is a series hybrid-electric powertrain based on a reciprocating internal combustion engine connected to the propeller (63). The second prototype is a four-seater aircraft based on a FC hybrid powertrain.

4.2 Full-Electric Aircraft

Full-electric propulsion (battery as the only energy storage) could lead to zero onboard emissions and very high levels of energy efficiency and noise reduction. For these reasons policymakers are starting to show interest in electric planes. Norway, for example, has announced that all of its short-haul flights will be electric by 2040 (64).

At the time of writing, there were more than 150 electric aircraft development programmes around the world, although the majority of them focused on the urban air taxi, also known as passenger drone, and general aviation (defined as civil non-commercial aviation, i.e. small aircraft for private transport and recreational activities) (57). The general aviation segment is seen as a 'test bench' for further development. With lighter weight and short range, the technical requirements of the general aviation segment are more suited currently to a higher degree of electrification.

One of the innovations, enabled by full-electric propulsion, which is expected to deliver the benefits of full electrification is 'distributed electric propulsion'. This propulsion strategy is based on the optimal placing of multiple electrically driven propellers across the aircraft wetted surface. An example of distributed propulsion is the Lilium Jet (Lilium GmbH, Germany): a full-electric five-seater aircraft, with 36 fans distributed to enable vertical take-off and landing (VTOL). With a range of 300 km, the Lilium Jet was designed for intracity and regional commuting. In 2019, Lilium GmbH announced the aim of launching its air taxi service in several cities by 2025 (65, 66).

Several initiatives, involving tech and aerospace actors, have been set up to develop novel aircraft designs using full-electric powertrains aimed at the air taxi market. For example, Kitty Hawk, USA, backed by Google, USA, worked with Boeing to develop a two-seater with a 100 km range using 12 lifting rotors, which was expected to be used by Air New Zealand for air taxi (67). Uber Technologies Inc, USA, the ride-hailing app company, has been linked with at least five aircraft manufacturers developing VTOL technology (68). One of these manufacturers is Aurora Flight Sciences, USA, a subsidiary of the aerospace major Boeing. Airbus also began an air taxi project called Vahana (69).

Another player, Eviation Aircraft Ltd, Israel, has produced a full-electric prototype (Alice) designed to take up to nine passengers, with a range of 650 miles, and capable of flying at 240 knots at 10,000 feet. It utilises Honeywell's fly-by-wire avionics, three electric motors producing around 900 kW of power, and Li-ion batteries supplying 900 kWh of energy, with a recharge ratio of 2:1, meaning 30 min of charging are needed for every hour in the air (70).

Despite very promising benefits, full-electric propulsion is confronted with a fundamental limitation with regard to energy storage in the form of battery energy density. Current state of the art Li-ion battery has an energy density of 0.9 MJ kg^{-1}, which theoretically could go up to 1.4 MJ kg^{-1}, but this is still an order of magnitude smaller than jet fuel's 43 MJ kg^{-1}. One promising novel battery chemistry, $Li-O_2$ is claimed to have a theoretical gravimetric density of 12 MJ kg^{-1}, still far short of kerosene (71). A further limitation is posed by the power-to-weight ratio of electric propulsion systems which has been historically lower than turbofans, though significant advances have been made in motor power density (72).

Electrification of aviation requires significant developments in battery energy and power density, as well as in other areas as airframe design, motor design, power electronics, cooling, heat recovery and power systems integration. Issues such as battery safety, charging and power infrastructure also need consideration for an increased electrification of aviation.

5. Conclusions

The SAF and propulsion options described in this review span across different levels of technical maturity, economic viability and current applicability to different types of aircraft. **Table II** provides a summary of these options, highlighting key technical, environmental and economic characteristics.

Renewable drop-in kerosene is an attractive decarbonisation option for aviation because it does not require modification of the aircraft airframe and engine and refuelling infrastructure. Today it is commercially produced in low volumes for use in commercial flights from a limited number of airports. Its production cost is currently significantly higher than the fossil kerosene price, representing the main challenge to its uptake, which will depend on strong policy support. While hydrogen is a very appealing fuel that can be derived from a range of renewable sources and produced from fossil sources with carbon capture and storage, its use in medium and long-haul aircraft requires a radical redesign of the engine and airframe, as well as the fuel supply chain, including on-the-ground storage and refuelling, leaving it a prospect for the long term.

Hybrid and full electric aviation are gaining traction with several projects and prototypes being developed to demonstrate the technology and trial new aircraft concepts, involving research organisations, small companies, as well as major aircraft manufacturers. Small full-electric planes (up to 10-seaters) are likely to see commercial deployment in the near term. But, the technical requirements of medium and long-haul aircraft (weight, seat capacity, speed and range requirements) cannot be met with current battery technology. Without a breakthrough in battery chemistry, electric propulsion is unlikely to be used in commercial aviation beyond the smaller short-haul flights. However, as technological progress is made, hybrid electric solutions could emerge for larger aircraft, furthering hybrid powertrain and airframe integration and contributing to the reduction of fossil kerosene use in aviation.

Glossary

APR	aqueous phase reforming
APU	auxiliary power unit
AtJ	Alcohol-to-jet
CAAFI	Commercial Aviation Alternative Fuels Initiative
CHEETA	Center for Cryogenic High-Efficiency Electrical Technologies for Aircraft
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DSHC	direct sugars to hydrocarbons
FAME	fatty acid methyl ester
FC	fuel cell
FCC	fluid catalytic cracking
FT	Fischer-Tropsch
GHG	greenhouse gas
HDO	hydro-deoxygenation
HEFA	hydroprocessed esters and fatty acids
HFS	hydroprocessing of fermented sugars
HTL	hydrothermal liquefaction
HVO	hydrotreated vegetable oil
LH_2	liquid hydrogen
MAHEPA	Modular Approach to Hybrid Electric Propulsion Architecture
PEMFC	proton exchange membrane fuel cell
PtL	power-to-liquid
SAF	sustainable aviation fuel
SIP	synthesised isoparaffins
SK	synthetic kerosene
SOFC	solid oxide fuel cell
SPK	synthetic paraffinic kerosene
SUGAR	Subsonic Ultra Green Aircraft Research
TRL	technology readiness level
UCO	used cooking oil
VTOL	vertical take-off and landing

Table II Summary of SAF and Propulsion Technology Options

Technology option	Maturity	CO_2 emissions	Range	Passengers	Economics
Fossil jet – turbofan (medium-haul)	Nth commercial	110 g CO_2 RPK^{-1} (73) [a]	Medium	~150	Fossil jet price ~€530 $tonne^{-1}$
Fossil jet – turbofan (long-haul)	Nth commercial	75–95 g CO_2 RPK^{-1} (73)	Long	~400	Fossil jet price ~€530 $tonne^{-1}$
Bio-jet – turbofan	1st commercial	20–90% CO_2 savings (@ 100% bio-jet) compared to fossil jet depending on feedstock (74)	Short, medium, long	Up to 400	Bio-jet price ~3–5 times fossil jet
Hydrogen – turbofan	Prototype	17 g CO_2 RPK^{-1} using green hydrogen from solar photovoltaic (66 g CO_2 kWh^{-1} H_2) (50)	Short, medium	Up to 400	Higher capital expenditure (CAPEX) compared to conventional aircraft due to insulated H_2 tanks. Current H_2 prices ~10 times fossil jet, on energy basis (75)
Hydrogen – FC + motor	Prototype	6 g CO_2 RPK^{-1} using green hydrogen from solar photovoltaic (66 g CO_2 kWh^{-1} H_2) (76)	Short	Up to 10	Higher CAPEX compared to conventional aircraft due to insulated H_2 tanks + FC system, but lower maintenance required. Current H_2 prices ~10 times fossil jet (on energy basis) (75)
All electric – battery + motor	Prototype	63 g CO_2e RPK^{-1} @ 315 g CO_2 kWh_e^{-1} grid (EU28, 2015) 19 g CO_2e RPK^{-1} @ 100 g CO_2 kWh_e^{-1} grid (77) [b,c]	Short, medium	Up to 150	High CAPEX battery packs, but potentially lower maintenance required. Current electricity prices ~3 times fossil jet (on energy basis) (78), partially offset by higher efficiency for short-haul aircraft
Hybrid electric – battery + motor/ turbofan	Prototype	Up to 53% energy savings compared to conventional equivalent (79)	Short, medium, long	Up to 150	Cost of additional electric system (battery + motors) offset by reduced fuel expenditure

[a] RPK = revenue passenger kilometres
[b] CO_2e = CO_2 equivalents
[c] kWh_e = kilowatt hour electric

References

1. G. Hemighaus, T. Boval, C. Bosley, R. Organ, J. Lind, R. Brouette, T. Thompson, J. Lynch and J. Jones, "Alternative Jet Fuels", Chevron Corporation, Texas, USA, 2006, 16 pp
2. 'Facts and Figures', Air Transport Action Group (ATAG): https://www.atag.org/facts-figures.html (Accessed on 9th April 2020)
3. D. S. Lee, D. W. Fahey, P. M. Forster, P. J. Newton, R. C. N. Wit, L. L. Lim, B. Owen and R. Sausen, *Atmos. Environ.*, 2009, **43**, (22–23), 3520

4. J. Teter, P. Le Feuvre, M. Gorner and S. Scheffer, 'Aviation', in "Tracking Transport", International Energy Agency (IEA), Paris, France, May, 2019
5. 'IATA Forecast Predicts 8.2 Billion Air Travelers in 2037', Press Release No. 62, International Air Transport Association (IATA), Montreal, Canada, 24th October, 2018
6. 'Fact Sheet: CORSIA', International Air Transport Association (IATA), Montreal, Canada, 1st September, 2019
7. G. Nelson, 'Contribution of the Global Aviation Sector to Achieving Paris Agreement Climate Objectives', Climate Action Network (CAN), Bonn, Germany, 2nd April, 2018
8. "Sustainable Aviation CO_2 Road-Map", Sustainable Aviation, UK, December, 2016, 83 pp
9. 'CARB Amends Low Carbon Fuel Standard for Wider Impact', California Air Resources Board (CARB), California, USA, 27th September, 2018
10. "RTFO Guidance Part One: Process Guidance 2019: 01/01/19 to 31/12/19", Department for Transport, London, UK, May, 2019, 73 pp
11. O. Meijerink, "The Voluntary RED Opt-in for Aviation Biofuels: Identifying Opportunities within the 28 EU Member States", SkyNRG, Amsterdam, The Netherlands, 2019, 101 pp
12. 'Proposal for Sweden to Follow Norway's Lead and Mandate Use of Sustainable Aviation Fuels from 2021', GreenAir Online, London, UK, 7th March, 2019
13. 'Sustainable Aviation Fuels (SAF)', International Air Transport Association (IATA): https://www.iata.org/en/programs/environment/sustainable-aviation-fuels/ (Accessed on 20th April 2020)
14. 'Fuel Qualification', Commercial Aviation Alternative Fuels Initiative (CAAFI): http://www.caafi.org/focus_areas/fuel_qualification.html (Accessed on 12th September 2019)
15. F. Yin, A. Gangoli Rao, A. Bhat and M. Chen, *Aerosp. Sci. Technol.*, 2018, **77**, 217
16. N. Pavlenko, S. Searle and A. Christensen, "The Cost of Supporting Alternative Jet Fuels in the European Union", International Council on Clean Transportation (ICCT), Washington DC, USA, 2019, 20 pp
17. S. de Jong, K. Antonissen, R. Hoefnagels, L. Lonza, M. Wang, A. Faaij and M. Junginger, *Biotechnol. Biofuels*, 2017, **10**, 64
18. H. Valin, D. Peters, M. van den Berg, S. Frank, P. Havlik, N. Forsell and C. Hamelinck, "The Land Use Change Impact of Biofuels Consumed in the EU", Ecofys BV, Utrecht, The Netherlands, 27th August, 2015, 261 pp
19. S. de Jong, R. Hoefnagels, A. Faaij, R. Slade, R. Mawhood and M. Junginger, *Biofuels Bioprod. Biorefining*, 2015, **9**, (6), 778
20. "Innovation Outlook: Advanced Liquid Biofuels", International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates, October, 2016, 132 pp
21. 'Horizon 2020 Energy and Transport: Compendium of Projects Implemented by INEA', European Commission, Brussels, Belgium, November, 2017
22. "Biofuels for Aviation: Technology Brief", International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates, January, 2017, 52 pp
23. 'Biomass to Fuels: IH^2 Commercial Process Optimisation', Shell: https://www.shell.com/business-customers/catalysts-technologies/licensed-technologies/benefits-of-biofuels/ih2-technology/process-optimisation.html (Accessed on 20th October 2019)
24. A. V. Kirilin, 'Aqueous-Phase Reforming of Renewables for Selective Hydrogen Production in the Presence of Supported Platinum Catalysts', PhD Thesis, Department of Chemical Engineering, Åbo Akademi University, Turku, Finland, 2013
25. "Advanced Drop-in Biofuels: UK Production Capacity Outlook to 2030", Department for Transport, London, UK, 24th October, 2017, 91 pp
26. 'BP Partners with Virent and Johnson Matthey on Virent's Bioforming® Process for Production of Bio-paraxylene', Virent Inc, Wisconsin, USA, 4th March, 2019
27. 'Facilities', Licella Holdings: https://www.licella.com.au/facilities/ (Accessed on 2nd October 2019)
28. 'Scenarios for Integration of Bio-Liquids in Existing REFINERY Processes' European Commission, Brussels, Belgium, 1st May, 2017
29. J. Hoffmann, C. U. Jensen and L. A. Rosendahl, *Fuel*, 2016, **165**, 526
30. O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson and S. Few, *Int. J. Hydrogen Energy*, 2017, **42**, (52), 30470
31. P. Schmidt, W. Weindorf, A. Roth, V. Batteiger and F. Riegel, "Power-to-Liquids: Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel", German Environment Agency, Dessau-Roßlau, Germany, September, 2016, 36 pp
32. C. Malins, "What Role is There for Electrofuel Technologies in European Transport's Low Carbon Future?", Cerulogy, London, UK, 2017, 86 pp
33. 'Data and Statistics', International Energy Agency (IEA): https://www.iea.org/data-and-statistics/data-tables?country=WORLD&energy=Oil&year=2015 (Accessed on 20th April 2020)

34. P. Le Feuvre, 'Are Aviation Biofuels Ready For Take Off?', International Energy Agency (IEA), Paris, France, 18th March, 2019
35. 'Advanced Biofuels Database', E4tech Ltd, UK, December 2019
36. 'Sierra Biofuels Plant Bright Future', Fulcrum Bioenergy Inc: http://fulcrum-bioenergy.com/facilities/ (Accessed on 21st September 2019)
37. 'UK Government Grant to Develop World First Waste Carbon to Jet Fuel Project', LanzaTech, Illinois, USA, 4th July, 2018
38. M. Mace, 'British Airways and Shell Back Plans for UK Sustainable Jet Fuel Plant', Edie, East Grinstead, UK, 17th July, 2019
39. G. Toop, S. Alberici, M. Spoettle, H. van Steen and U. Weddige, "Trends in the UCO Market", Ecofys, London, UK, 7th March, 2014, 31 pp
40. 'Population, Total', The World Bank: https://data.worldbank.org/indicator/sp.pop.totl (Accessed on 3rd October 2019)
41. 'UK and Global Bioenergy Resource Model', Department for Business, Energy and Industrial Strategy, London, UK, 8th March, 2017
42. J. S. Gregg and S. J. Smith, *Mitig. Adapt. Strateg. Glob. Change*, 2010, **15**, (3), 241
43. "OECD-FAO Agricultural Outlook 2019-2028", OECD Publishing, Paris, France, 2019, 326 pp
44. 'Global Energy Resources Database', Shell: https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenarios-energy-models/energy-resource-database.html#iframe=L3dlYmFwcHMvRW5lcmd5UmVzb3VyY2VEYXRhYmFzZS8jb3Blbk1vZGFs (Accessed on 15th April 2020)
45. "Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations", International Energy Agency (IEA), Paris, France, 6th June, 2017, 443 pp
46. 'Germany Unveils Plan for Climate-Friendly Aviation', Deutsche Welle, Bonn, Germany, 21st August, 2019
47. A. Baroutaji, T. Wilberforce, M. Ramadan and A. G. Olabi, *Renew. Sustain. Energy Rev.*, 2019, **106**, 31
48. 'Liquid Hydrogen Fuelled Aircraft – System Analysis', Final Technical Report, Airbus Deutschland GmbH, Germany, 24th September, 2003
49. D. Verstraete, *Int. J. Hydrogen Energy*, 2013, **38**, (34), 14824
50. D. Verstraete, *Int. J. Hydrogen Energy*, 2015, **40**, (23), 7388
51. J. Bogaisky, 'Startups Bet Hydrogen Fuel Cells Are Ready for Takeoff in Aviation', Forbes Media, New Jersey, USA, 14th August, 2019
52. 'Press Release: Hyflyer Zero-Emission Aircraft Flight Tests Set for Orkney', The European Marine Energy Centre Ltd, Orkney, UK, 18th September, 2019
53. 'ZeroAvia Unveils Hydrogen Fuel Cell Powertrain for Aviation', Green Car Congress, 15th August, 2019
54. D. L. Larson, 'NASA Funds Aviation Research on a New Fuel Concept', Phys.Org, Science X Network, Isle of Man, UK, 13th May, 2019
55. 'Delivering the Future', H2Fly GmbH, Stuttgart, Germany: http://hy4.org (Accessed on 16th January 2020)
56. 'Zero-Emission Air Transport – First Flight of Four-Seat Passenger Aircraft HY4', H2Fly GmbH, Stuttgart, Germany, 29th September, 2016
57. R. Thomson, 'Electrically Propelled Aircraft Developments Exceed 200 for the First Time', Roland Berger GmbH, Munich, Germany, 15th January, 2020
58. 'Electric, Hybrid, and Hydrogen Aircraft – State of Play', in "2019 Environmental Report: Aviation and Environment", Ch. 4, International Civil Aviation Organization (ICAO), Montreal, Canada, 2019, pp. 124–130
59. C. Vaughan, 'UK Announces £300m Green Transport Fund', PlaceTech, Manchester, UK, 28th August, 2019
60. E-Fan X, Airbus: https://www.airbus.com/innovation/future-technology/electric-flight/e-fan-x.html (Accessed on 24th September 2019)
61. G. Norris, 'Airbus and Rolls-Royce Freeze E-Fan X Hybrid-Electric Demo Design', Aviation Week Network, New York, USA, 19th June, 2019
62. C. E. Howard, 'Boeing and NASA Unveil Lightweight, Ultra-Thin, More Aerodynamic Transonic Truss-Braced Wing Concept', SAE International, Pennsylvania, USA, 11th January, 2019
63. MAHEPA Project, Home: https://mahepa.eu/ (Accessed on 16th January 2020)
64. 'Norway Aims for All Short-Haul Flights to be 100% Electric by 2040', The Guardian, London, UK, 18th January, 2018
65. P. Dzikiy, 'Lilium's New All-Electric Five-Seater Air Taxi Prototype Completes Test Flight', Electrek, New York, USA, 16th May, 2019
66. A. J. Hawkins, 'Electric Air Taxi Startup Lilium Completes First Test of its New Five-Seater Aircraft', The Verge, Vox Media, Washington DC, USA, 16th May, 2019
67. 'Flying Taxis Are Taking off to Whisk People around Cities', The Economist, London, UK, 12th September, 2019

68. A. J. Hawkins, 'Uber's 'Flying Taxis' will be Built by These Five Aerospace Companies', The Verge, Vox Media, Washington DC, USA, 8th May, 2018
69. Z. Lovering, 'Step Inside Alpha Two', Acubed, California, USA, 20th May, 2019
70. J. Bailey, 'Who Is Alice? – An Introduction to the Bizarre Eviation Electric Aircraft', Simple Flying, London, UK, 26th June, 2019
71. L. Dray, "Low-Carbon Aviation: How Far Can We Go?", University College London (UCL) Energy Seminar, London, UK, 2nd April, 2019
72. A. R. Gnadt, R. L. Speth, J. S. Sabnis and S. R. H. Barrett, *Prog. Aerosp. Sci.*, 2019, **105**, 1
73. B. Graver, K. Zhang and D. Rutherford, "CO_2 Emissions from Commercial Aviation, 2018", International Council on Clean Transportation (ICCT), Washington DC, USA, 2018, 13 pp
74. J. Bosch, S. de Jong, R. Hoefnagels and R. Slade, "Aviation Biofuels: Strategically Important, Technically Achievable, Tough to Deliver", Grantham Institute, Imperial College London, UK, 2017, 16 pp
75. 'Cost to Refill', California Fuel Cell Partnership: https://cafcp.org/content/cost-refill (Accessed on 27th January 2020)
76. 'HY4 – Zero-Emission Passenger Flights', German Aerospace Center (DLR), Cologne, Germany, 26th November, 2015
77. A. W. Schäfer, S. R. H. Barrett, K. Doyme, L. M. Dray, A. R. Gnadt, R. Self, A. O'Sullivan, A. P. Synodinos and A. J. Torija, *Nat. Energy*, 2019, **4**, 160
78. 'Electricity Price Statistics', Eurostat: https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics#Electricity_prices_for_non-household_consumers (Accessed on 27th January 2020)
79. M. K. Bradley and C. K. Droney, "Subsonic Ultra Green Aircraft Research: Phase II – Volume II – Hybrid Electric Design Exploration", NASA/CR–2015-218704/Volume II, National Aeronautics and Space Administration (NASA), Washington DC, USA, 2015, 233 pp

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