PERSPECTIVES FOR AERONAUTICAL RESEARCH IN EUROPE

PARE

CHAPTER 19

Sustainable fuels for the new Green Deal

Final Report

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1. Introduction

In this chapter, the state-of-the-art concerning the characteristics, the processing technologies, the issues relative to source availability, sustainability and ethical impact of the different alternative aviation fuels are discussed.

Climate change calls for urgent measures by decision-makers worldwide, and these will have a relevant impact on aviation. Achieving an early and meaningful impact is critical in light of the 'climate emergency' as seen by Europe's citizens, recognised by the European Parliament and highlighted in the Commission's agenda for the Green Deal.

The successful implementation of the EU Green Deal in aviation depends on the European aeronautics industry's ability to develop new technologies able to face climate changes. In order to maintain a leading role in the aviation industry, EU needs to strongly support R&I. In fact, US and China, as EU competitors are going to put in place significant packages for the aeronautics industry.

Commercial aviation accounts for about 2% of global carbon emissions and about 12% of all CO_2 emissions from the transportation sector. But CO_2 emissions from commercial aircraft are expected to triple by 2050, as both passenger air travel and air freight surge worldwide, and aviation's share of transportation-sector emissions is ballooning as cars and trucks become more fuel-efficient. Carbon emissions are not the only environmental challenge posed by a growing aviation sector. Nitrogen oxides, particulates, noise, and lead pollution also impact often disadvantaged communities living near airports.

Aviation is considered as the most difficult-to-decarbonize transport sector. One possibility to dramatically reduce emissions within the aviation sector is through the use of low-carbon alternative fuels (Figure 19.1)

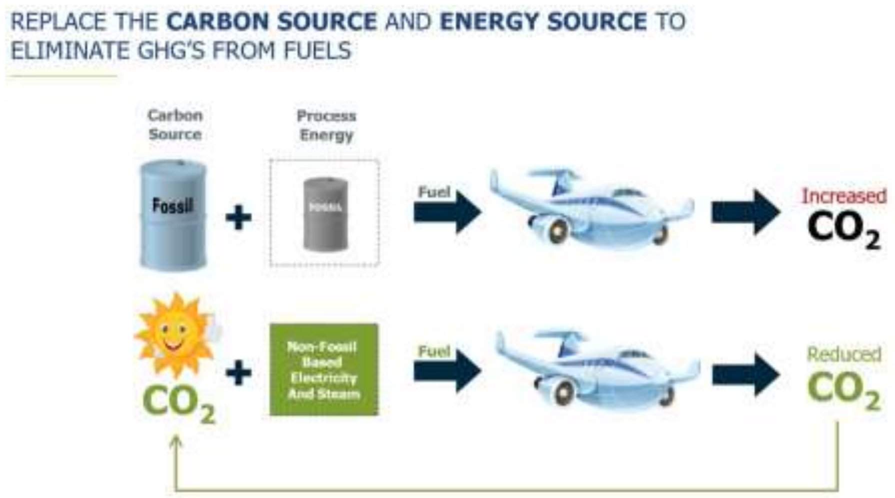

Figure 19.1. The pathway for reduction of GHGs (Green House Gases)

Although some progress has been made in alternative jet fuels, significant challenges remain in commercializing advanced fuel conversion processes as well as in setting-up alternative fuel production chain (from feedstock supply to fuel conversion), blending, and delivering new fuels.

Strong policy support for advanced fuel technologies is needed to shift from petroleum-based fuels to sustainable, low-carbon alternatives in the mid-century time frame. In the near to medium term, it will also be important to support sustainable feedstock supply chains. Because it will likely take a long time to fully deploy a high share of liquid fuel demand, stronger incentives will be needed in the 10 to 15-year time frame [1].

As illustrated in Figure 2, the International Air Transport Association (IATA) aims at reducing by 50% CO_2 emissions, compared to the 2005 level. Consequently, the search for new alternative fuels for aircraft seems to be a necessary solution from energy security and environmental perspective. If aviation wants to reduce its greenhouse gas emissions, it has to turn to biofuels.

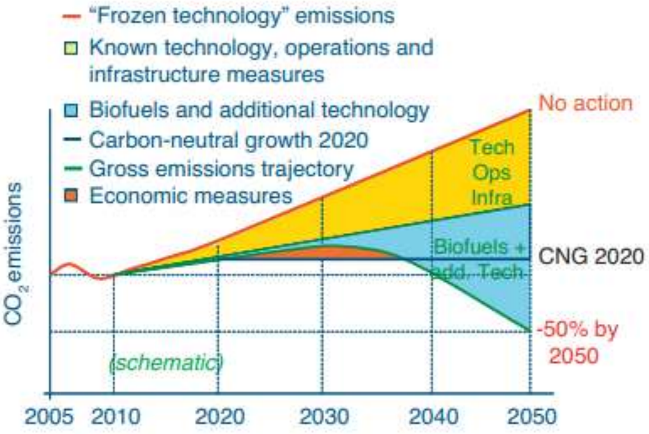

Figure 19.2. CO2 emissions reduction targeted by IATA (Source IATA).

To decarbonize, the aviation industry needs new, low-carbon propulsion technologies and/or new fuels [2] [3, 4]. New propulsion technologies include battery- and turbo-electric technologies, as well as hydrogen combustion in turbines and fuel cells that power electric motors.

Battery-electric and hybrid-electric aircraft, although not dealt with in this chapter are being developed. Battery technology has vastly improved in the last 20 years. For aviation, however, batteries still suffer from low gravimetric energy densities of 0.2 to 0.5 kilowatt-hours per kilogram and limited life-time cycles [5]. This limits their applicability as a sole power source to very short flights (i.e., for commuter and potentially regional aircraft). While energy density is improving, battery technology would need a major breakthrough to be applicable for longer ranges. In addition to that, fast charging or battery exchange systems would require significant changes to the airport infrastructure. Batteries can, however, be applied in combination with conventional propulsion ("turbo-electric aircraft") or hydrogen fuel cells [6, 7, 8, 9]. In flight, battery-electric propulsion has the best climate impact because it causes no emissions or emission-related effects[1].

Sustainable aviation fuel includes biofuels from biomass or waste (cooking oils and fats), followed by advanced biofuels that are synthesized from, e.g., solid feedstock, biomass like crops, or algae; other SAF option is power-to-liquid fuels, also known as synfuels synthesized from hydrogen and CO2 taken from industrial, biomass or direct-air capture.

Biofuels have the advantage of being "drop-in fuels" that do not require changes in aircraft and fuel infrastructure and are applicable across all aircraft segments. The International Renewable Energy Agency (IRENA) projects biofuel availability to be around 100 to 150 exajoules (EJ), which would be sufficient to power a large proportion of aviation [10]. Biofuels are already commercially available. But biofuels' reliance on feedstock, changes in land use, high water use, and/or monoculture (i.e., the production of a single crop) means that the aviation industry will be competing with other interests that need the feedstock for other purposes.

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[1] Beyond in-flight emissions, electricity for battery-electric aircraft and the production of batteries also needs to come from renewables for a truly decarbonized solution.

In Synfuels, unlikely biofuels, electricity is used to firstly produce hydrogen and to capture carbon, combining the two into a kerosene-like fuel. Synfuel can also be used in current aircraft engines and the fuel infrastructure and is hence suitable for all segments [11, 12, 13].

Hydrogen can be used as a fuel for aircraft when it is combusted in an H2 burning engine or reacted in a fuel cell powering electric motors. Despite the three times higher gravimetric energy density compared to kerosene, hydrogen requires larger volume and hence larger tanks on-board the aircraft and adjusted aircraft designs. The size and weight of H2 tanks pose major limitations for high energy demand on long-range flights – potentially reducing economics significantly for long-range aircraft [14, 15]. From a fuel-supply perspective, hydrogen has other advantages since it can be produced directly from renewable energy and synergies with other hydrogen-dependent sectors can be realized. The only difference for other industries is that additional liquefication capacity will be needed. A growth in hydrogen demand across sectors would unlock scale effects partially mitigating the initial cost disadvantages.

1.1. Toward the Green Deal

The European Green Deal [16] aims to 'transform the EU into a fair and prosperous society, with a modern, sustainable and competitive economy allowing to reach in 2050 no net emissions of greenhouse gases and where economic growth relies on efficient resource usage. At the same time, the Industrial Strategy for Europe [17] recently launched highlights the importance of industrial leadership in making the transformation to a green and digital Europe fit for the future. It states among other things that "...*there should be a special focus on sustainable and smart mobility industries*".

The Clean Aviation trajectory matches the two horizons towards climate neutrality in the Green Deal legislative proposal (Figure 19.3).

The Clean Aviation trajectory defines two clear horizons towards climate neutrality by 2050.

- 2030: demonstrating and introducing low-emissions aircraft concepts exploiting the research results of Clean Aviation, making accelerated use of sustainable fuels and optimised 'green' operations so that these innovations can be offered to airlines and operators by 2030 for an entry into service [EIS] in the 2030-2035 timeframe;
- 2050: climate-neutral aviation, by exploiting future technologies matured beyond the Clean Aviation phase coupled with full deployment of sustainable aviation fuels and alternative energy carriers.

The aerospace industry, and in general all the aviation sector, if suitably supported by adequate policies, has the responsibility and, the potentialities to support Europe's competitiveness and improve connectivity permitting the transitions towards climate neutrality and digital leadership.

Sustainable aviation fuels (SAF) are essential to address de-carbonizing the economy. They have reduced particulates, nitrogen, sulfer and critical greenhouse gases. Since electrification is still far away for commercial aircraft, and although energy efficiency is possible, it cannot make the required impact alone. Sustainable biofuels for this sector are a must. The International Civil Aviation Organization (ICAO) forecasts that we need at least 170 new SAF production facilities per year from 2020 to 2050, but other estimates evidence figures higher than that. SAF delivers real environmental and public health benefits that many persons care about.

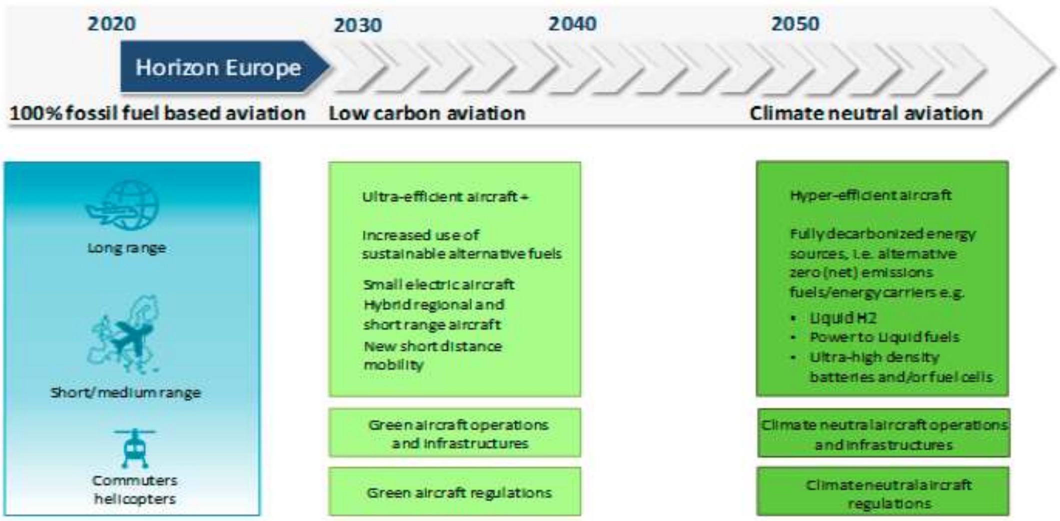


Figure 19.3. Possible trajectory towards climate neutral aviation [18]

1.2. Cost scenario

In Table 19.1 [19] the price of fuel in the reference scenario is projected to increase to approximately 930 Euro/ton; the aviation demand has been corrected for this by assuming that the fuel price remains constant at 600 Euro/ton, which results in a 13% cheaper ticket price. This step was undertaken in an attempt to unpick the demand reduction measures built into the reference scenario to avoid double-counting them, and to avoid relying on an increase in fuel price to reduce demand. E-fuels made from hydrogen and CO that is captured from air cost about 5 Euros per litre, but this could drop to around 0.9 Euros per litre longer term. This option is currently not applied on a commercial scale [20].

Parameter	2020	2050	Description/notes
Kerosene price (Euro/t)	600	600	Assumed constant
Fuel price fraction of ticket price (domestic & intra EU)	25%	25%	Literature [21]
Fuel price fraction of ticket price (extra EU)	20%	20%	
Extra improvement on fleet compared to the BaU	0%	6%	0.2% per annum from 2020. This metric includes fuel and operational efficiency
Gen II aircraft	0%	3%	From 2040, 1% per year ingress of 30% more efficient aircraft design
Advanced biofuels (ktoe)	50	7500	In 2020 the amount of 50 kton is assumed to be available, requires 33% year on year growth.
CO2 price Euro/t	30	150	From ETS, VAT, kerosene tax
PtL price Euro/t	5000	2100	Literature [22]
PtL conversion efficiency	38%	50%	Literature [23]

Table 19.1. Projection of the price of fuel [19]

Following the previous considerations, a roadmap [19] for European aviation decarbonisation has recently being calculated. Based upon the 2016 EU Reference Scenario at "Energy, transport and GHG emissions: trends to 2050", incremental decarbonisation measures are considered in several scenarios, for Europe only.

Scenario Business as Usual (BaU): This scenario involves minimum differences over the Reference Scenario 2016 defined by the EU:

- Fleet fuel efficiency is assumed to improve 1% per year as results of a combination of technical and logistical improvements.
- There are no changes in demand.
- €600/ktoe price is assumed for fuel in 2050.
- Energy demand will increase a 23% in the period from 2015 to 2050.
- Passenger activity is expected to grow by 80% from 2015 to 2050, from 722 million departing passenger movements to 1,117 million.

Fleet efficiency: it is assumed that aviation will be able to achieve additional fleet fuel intensity improvements of 0.2% per year, which implies up to 6% by 2050.

Gen II aircraft: This scenario considers that new and more efficient aircraft will be available in the market, such as are bubble type, strut wings, etc. These designs will be around 30% more efficient than current conventional models and will picks up 1% of the demand passengers per year.

Aviation pricing: This additional measure considers a reduction in passenger demand.

- A climate change levy of 150€ per tonne of CO_2 is estimated to bring a reduction of 12% in demand.
- Conversion factor is 3.15 tCO_2 per tonne of fuel.
- Fuel cost assumed to be 25% of short-haul ticket price and 20% of long haul.
- IATA / Intervista price and income elasticities are considered with an equivalent value to -0.48 for all EU departing flights.
- As a consequence, ticket prices are expected to increase by 17% over BaU.

Biofuels: This scenario assumes that a production of 7500 ktoe of biofuels will be available in 2050, with a S-curve growth beginning from 2020.

PtL demand: This scenario assumes that 100% of PtL aviation demand will be met by 2050. Due to the high prices of e-fuels, demand will suffer an additional reduction. PtL consumption from 2020 follows an S-curve (a logistic function). Alternative fuel uptake is assumed to increase in line with an S-curve; other measures are assumed to increase linearly.

Figure 19.4 shows the CO_2 emissions forecasted under the previous scenarios from 2000 to 2050. It can be shown that there might be an opportunity for rapid decarbonisation from 2030 onwards, as a result of the combination of the proposed measures: demand reduction, efficiency measures, advanced biofuels and electrofuels. That decarbonisation aims to curb CO_2 emissions to approximately 2010 levels. This inflation point is followed by a rapid CO_2 decrease up to 2050 when the CO_2 emissions from the departing flights EU are estimated to be zero. Figure 4 (right) shows how the measures stack up in terms of liquid fuel consumption. However, this analysis only considers EU geographical scope; emissions form inbound flights or flight outside the European Union are not considered in the study.

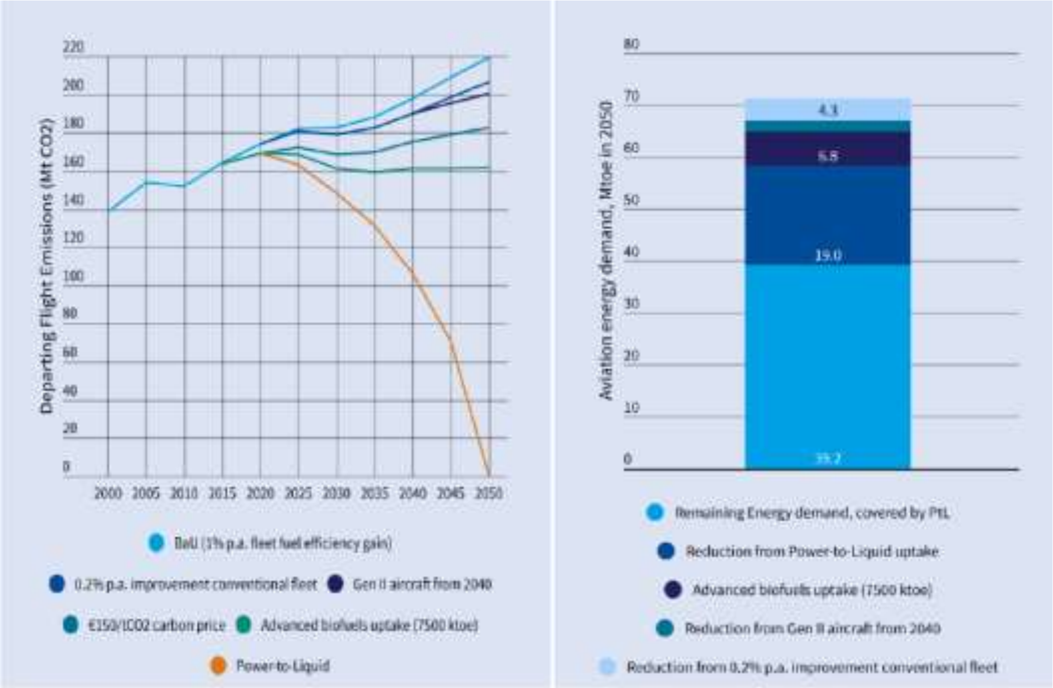


Figure 19.4. (Left) Reduction in European departing flight CO2 emissions. (Right) PtL consumption of European departing flights in 2050 after demand reduction measures have been applied [19].

One of the biggest measures is the reduction in demand from PtL. Note that in 2050, the demand reduction from the charges equivalent to €150/tonne of CO2 has been nullified, as the kerosene no longer has a fossil component. Aside from being a driver for more efficient aircraft and their operations, the importance of the carbon pricing can be seen in the cumulative emissions savings. They have been calculated to reduce emissions by 180 Mt CO2 cumulatively over the 2020 to 2050 period, compared to no price. With the remaining 39.2 Mtoe, at the price of 2.100€/tonne of fuel, this equates to an annual fuel bill for airlines fuelling in Europe exceeding €82 billion. This compares to approximately €35 billion today spent on fossil kerosene.

Demand levels off from 2030 with an increasing share of PtL, owing to both its uptake and price. The 2050 passenger activity is equivalent to the business as usual activity in the early 2030s. Thus an increase in overall passenger activity is still envisaged in this analysis. However, as passengers will be travelling further, this does not equate to a greater number of total flights. Modal shift will be most successful for short segment flights, while longer flights contribute significantly to the passenger activity metric as a single flight can usually take more passengers a multiple further. Thus, growth in activity does not justify increasing the capacity of airports, particularly in Western Europe, where many airports are at capacity. Limiting growth by simply avoiding airport expansion is an effective way to keep downward pressure on demand.

2. State of the art

The carbon emitted at higher altitudes is potentially even more harmful than sea level emissions. Advanced biofuels are the only really viable option. The aeronautic industry has to find liquid fuels that can be used by the existing infrastructure [24]. To understand the state of the art in the decarbonisation of the aviation sector, a relevant aspect is to know what airliners have done until now.

2.1 The way of the sustainable aviation fuels up to 2017

At the 2011 Paris Air Show, major European stakeholders set a goal of 600 million gallons (2 million metric tons) of annual sustainable biojet production by 2020 under a new program called Biofuel Flightpath. For Flightpath, the European Commission has teamed with Airbus, Lufthansa, Air France/KLM, British Airways and biofuel producers Choren Industries, Neste Oil, Biomass Technology Group and UOP.

Air France completed its first biofuel-powered scheduled passenger flight, running on a 50/50 combination of traditional jet fuel and jet fuel produced from used cooking oil. Together with "optimised" air traffic management (ATM), the flight saved roughly 50% of its CO_2 emissions, bringing the per-passenger emissions rate down to 54g per kilometre.

Iberia flew the country's first commercial flight using a 25% blend of biojet fuel made from camelina. The inaugural flight using an Airbus A320 flew from Madrid to Barcelona. The fuel was produced by UOP LLC, a unit of U.S.-based Honeywell International Inc. and certified by the oil company Repsol YPF SA.

Finnair operated an Airbus biofuel flight between Amsterdam Schiphol and Helsinki. A 50% blend of biofuel produced from recycled vegetable oil and kerosene was provided by SkyNRG, a consortium launched by KLM, North Sea Group and Spring Associates to develop a sustainable supply chain for aviation biofuel.

KLM Royal Dutch Airlines became the first airline in the world to operate a commercial flight carrying 171 passengers on aviation biofuels. Flight KL1233 – a Boeing 737-800 – took off from Schiphol bound for Charles de Gaulle in Paris carrying 171 passengers. KLM's first commercial flight to Paris was operated on biokerosene produced from used cooking oil. The fuel was supplied by Dynamic Fuels via SkyNRG, the consortium co-founded by KLM in 2009 with the North Sea Group and Spring Associates.

Lufthansa discontinued the flight trial, using renewable jetfuel, from Frankfurt to Washington because of the problems is securing long-term sources of the biofuel. In all, 1,187 biofuel flights were operated between Hamburg and Frankfurt. CO_2 emissions were reduced by 1,471 tonnes. Total consumption of the biokerosene mix amounted to 1,556 tonnes. Overall, Neste and Lufthansa found that the aircraft and their engines performed excellently. The condition of the combustion chambers, turbines, and fuel systems of their engines was exemplary both during and at the conclusion of the trial. Usage of NExBTL fuel resulted in 1% lower fuel consumption compared to regular fossil jet fuel.

Aeromexico began using a 25% biofuel mixture on its flights from Mexico City to San Jose, Costa Rica. As part of the "Green Flights" project designed to reduce greenhouse gas emissions, a Boeing 737 used a mixture of 75% conventional jet fuel and 25% synthetic paraffin biokerosene.

Alaska Airlines reported that its decision to use biofuel was limited to 20% because of lack of supply. With the fuel produced in Louisiana from used cooking oil, refined in Texas and sourced by a broker the Netherlands, the supply chain was very difficult. The cost was $17 per gallon compared to $3.14 per gallon for A1 jet fuel.

American Airlines began its first biofuel flights in mid-2012 using a Boeing eco-Demonstrator airplane to complete the flight. Around the same time, the company signed agreements with two biojet suppliers as well as a purchase agreement. The airline announced its MOUs for biofuels supply at the CAAFI meeting in DC last week.

Azul Airlines in Brazil announced that Amyris's innovative renewable jet fuel sourced from Brazilian sugarcane had passed all required testing. It has been used during a demonstration flight on an Embraer 195 aircraft powered by GE's CF34-10E engines. The "Azul+Verde" (a Greener Blue) flight took place in 2012 during the Rio+20 United Nations Conference on Sustainable Development. Amyris's renewable jet fuel has been designed to be compliant with Jet A/A-1 fuel specifications and provide equivalent performance versus conventional petroleum-derived fuel in a range of metrics, including fit-for-purpose properties and greenhouse gas emission reduction potential. The feedstock for renewable jet fuel is sugarcane, a highly desirable biomass that can be produced sustainably in large-scale quantities in Brazil and other tropical countries. This is one of the first fuels supplied directly from an advanced fermentation. The upgrading has been done by Honeywell's UOP.

Porter Airlines successfully conducted the first biofuel-powered flight in Canada. A test program was launched in 2010. The airline flew one of its Bombardier Q400 turboprops from Toronto City Airport to Ottawa using a 50/50 blend of biofuel and Jet A1 fuel in one of its engines. This was the final step in a two-year project with Targeted Growth, Bombardier Aerospace, and Pratt and Whitney Canada, the manufacturer of the PW150A engines that power the Q400 aircraft.

In May 2010, ten organizations partnered to form the Brazilian Alliance for Aviation Biofuels (Aliança Brasileira para Biocombustíveis de Aviação – ABRABA). The objective of the alliance was to promote public and private initiatives to develop and certify sustainable biofuels for aviation.

Netherlands-based SkyNRG supplied LAN Chile and Air BP Copec for its first commercial flight with second-generation jet fuel. The flight, which operated between the Chilean cities of Santiago and Concepcion, was conducted on an Airbus from the A320 family with CFM56-5B motors. The fuel came from used cooking oil.

Virgin Atlantic within 2015 planned flights with biofuel on its routes from Shanghai and Delhi to London Heathrow as LanzaTech and partners develop facilities in China and India.

Thomson Airways used cooking oil and regular jet fuel in flights from Birmingham to Lanzarote. The airline experienced delays with testing and safety clearances.

Etihad n the United Arab Emirates has delivered acceptance of a new Boeing 777-300ER, flown from Seattle to Abu Dhabi which was completed using biofuel. The biofuel was supplied by Holland's SkyNRG, sourced from recycled vegetable cooking oil.

South African Airlines noted that South Africa limits biofuel feedstocks to sorghum, sugar cane, sugar beet and jatropha.

United Airlines, Boeing, Honeywell's UOP, the Chicago Department of Aviation and the Clean Energy Trust announced the formation of the Midwest Aviation Sustainable Biofuels Initiative (MASBI), designed to advance aviation biofuel development in a 12-state region holding significant promise for biomass feedstock, technology development, job creation and sustainable commercialization.

The China Air Transport Association (CATA) stated that they oppose having their flights into Europe included in the European Union's Emissions Trading Scheme. The ETS requires that all emitters buy permits for each tonne of CO2 released, above a certain cap. The program started on January 1, 2012, and included most carriers. CATA stated that would ask their government in Beijing to look into countermeasures for European carriers flying into China.

Boeing and All Nippon Airways reported that a 787 Dreamliner flew for the first time-powered in part by sustainable biofuels. This was the first-ever transpacific biofuel flight, using biofuel made mainly from used cooking oil and emitted an estimated 30% less CO_2 emissions when compared to today's similarly-sized airplanes.

Japan Air Lines in 2009 tested camelina, jatropha and algae-based biofuels in a 747-300 test slight from Tokyo's Haneda airport. The fuel was processed by UOP, and used in a no-passenger test flight using Pratt & Whitney JT9D engines, and used a mixture of 84% camelina, nearly 16% jatropha, and less than 1% algae. The biodiesel was mixed in a B50 blend with conventional jet fuel.

Thai Airways International launched a workshop jointly with the Ministry of Energy and PTT Public Company to focus on aviation biofuels, as a first step in the country's effort to develop this sector. Thai Airways announced plans to power a commercial passenger flight using only biofuel.

Indian Oil announced that it is working with Airbus, Kingfisher Airline and UOP to conduct biofuel test flights. Indian Oil, a state-run corporation has signed pacts with Canadian universities and Pratt & Whitney to further their ambitions to join the growing group of countries pursuing bio-avjet.

Qantas launched Australia's first commercial biofuels flight from Sydney to Adelaide using a 50/50 blend of cooking-oil derived jet fuel. Qantas was operating under the AUS$500,000 Emerging Renewables Program grant, which enables Qantas to partner with Shell Australia for a feasibility study of long-term aviation biofuels. Other airlines in the country such as Virgin Australia have also worked on aviation biofuels programs.

2.2 The way of the sustainable aviation fuel form 2018-2020

In the last years, new attempts have been made toward the way of sustainable aviation fuel [25].

In October 2018 World Energy announced a $350 million investment over the next two years to complete the conversion of its Paramount, California facility into one of the cleanest fuel refineries in the world. The project should enable World Energy Paramount to process 306 million gallons annually. The conversion to renewable jet, diesel, gasoline and propane is deemed to reduce both refinery and fuel emissions while supporting more than 100 advanced, green economy jobs.

In December 2018 Shell Aviation and SkyNRG commenced the supply of sustainable aviation fuel (SAF) to international airlines KLM, SAS and Finnair at San Francisco Airport (SFO). The fuel is also produced by World Energy, currently the only SAF refinery worldwide. The initial phase of that arrangement aims to pave the way for longer-term, more resilient supply chains for sustainable aviation fuels and reduce the carbon emissions of flights from SFO and other airports. Shell Aviation is the first major fuel supplier to support SFO in its ambition to expand the use of sustainable aviation fuel in its operations. In April 2018, Shell released its most definitive statement yet on its low-carbon future and committed to 50% lower emissions by 2050 and net-zero by 2070 in its operations and emissions from its fuels. In its analysis of future energy demand, Shell noted that the global energy demand is set to increase from 570 exajoules to 1000 by 2070 and it will take extraordinary measures to meet the stringent carbon-reduction goals set in the Paris Agreement. The Lufthansa Group has a long history of testing and supporting the development of sustainable aviation fuel, introducing it to daily operations at San Francisco [25].

In May 2019 KLM Royal Dutch Airlines has committed itself for a 10-year period to the development and purchase of 75,000 ton of sustainable aviation fuel a year. KLM is the first airline in the world to invest in sustainable aviation fuel on this scale. SkyNRG, the global market leader for sustainable aviation fuel (SAF), will develop Europe's first dedicated plant for the production of SAF in Delfzijl. The production facility will specialise in producing SAF, bioLPG and naphtha, primarily using regional waste and residue streams as feedstock. The plant will be the first of its kind in the world. The construction of this facility, which is scheduled to open in 2022, is a concrete step towards fulfilling KLM's sustainability ambitions and contributing to the broader industry plan "Smart and Sustainable". SHV Energy, the global leader in LPG distribution, will also invest in the facility and will purchase the bioLPG produced [26].

In August 2019 British Airways and Shell invested nearly £3 million Velocys and that an application for planning permission to build an aviation biofuel production facility near the Humber in North Lincolnshire has been submitted for approval to local authorities. Half a million metric tons of MSW is expected to be used as feedstock annually at the proposed site [27].

In November 2019 Bombardier received their first shipment of sustainable aviation fuel (SAF) at their facilities in Montreal. Avfuel provided the inaugural shipment of 7,300 gallons of Gevo-produced SAF to fuel Bombardier's new customer aircraft deliveries. In their press release, Bombardier stated that this is a first step to deploying SAF at all of their facilities as SAF supply becomes more readily available worldwide [28].

The Green Aviation Research and Development Network (GARDN), SkyNRG, Waterfall Group and Vancouver Airport Authority have announced the launch of the industry-led initiative BioPortYVR to increase the supply of sustainable aviation fuel (SAF) in Canada in November 2019. SAF is not currently widely available in Canada. Meanwhile, demand is growing in the country as the airline industry looks to reduce its carbon footprint. BioPortYVR will consider and evaluate the viability of implementing regional supply chains to distribute SAF to airlines at Vancouver International Airport (YVR) and surrounding airports through demand centres, known as BioPorts. In the coming months, the project partners will engage with stakeholders to develop a series of actionable recommendations for the introduction of SAF at YVR [29].

On November 2019 EasyJet announced it is going carbon neutral immediately. Europe's fifth-largest airline said it would become the first major airline in the world to operate net-zero carbon flights. The offset projects EasyJet will invest more than $30 million over the next year have been certified to deliver carbon reductions that would not otherwise have happened and do not inadvertently lead to an increase in emissions elsewhere. EasyJet says they have already reduced the amount of carbon it emits every kilometre each passenger flies by more than one-third since 2000 by utilizing more fuel-efficient aircraft and operating practices. The airline view offsets as a temporary measure to reduce their carbon footprint in the short-term while they work to support longer-term efforts, including the development of new technology [30].

On December 2019 Air France has announced their collaboration with World Energy and Shell to fuel flights from San Francisco International Airport (SFO) using sustainable aviation fuel (SAF) starting June 1, 2020. This announcement is in line with Air France's other sustainability commitments, including offsetting 100% of CO2 emissions from domestic flights beginning January 2020 and reducing CO2 emissions by 50% per passenger per kilometre compared with 2005 by 2030 [31].

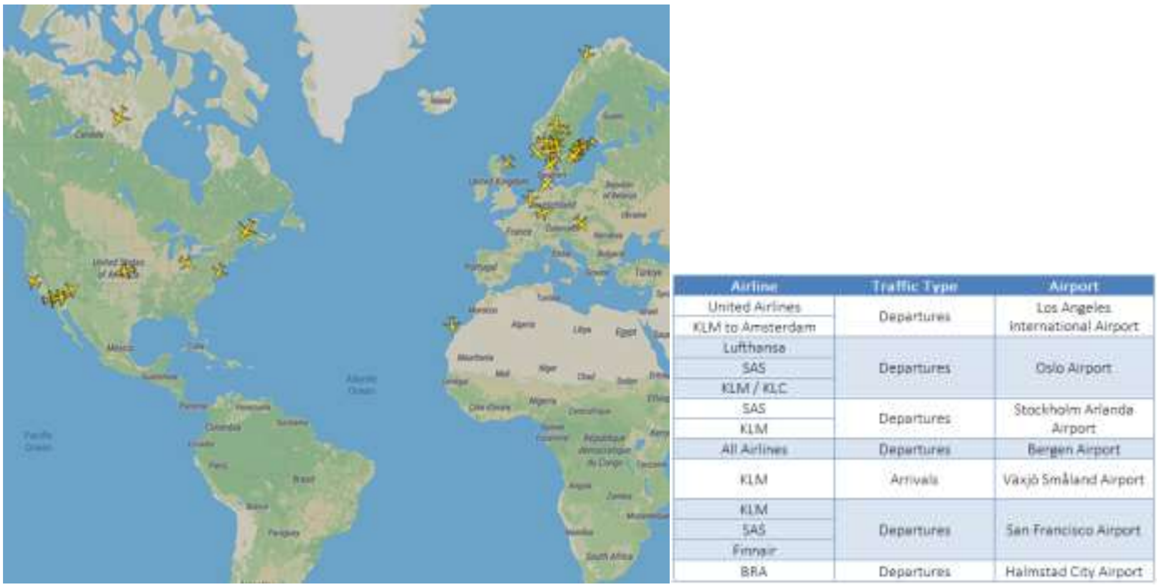
In January 2020 from the UK comes news that Shell Aviation and World Energy inked a collaboration to develop a scalable supply of sustainable aviation fuel. The agreement is intended to be a multi-year collaboration, with both companies acknowledging that the path to lower carbon emissions in aviation requires long-term commitment and collaboration. As part of the collaboration, Shell Aviation and World Energy also announced that they had initiated the supply of SAF to Lufthansa Group at San Francisco International Airport. The supply will reduce Lufthansa's carbon emissions on intercontinental flights on three routes operated by Deutsche Lufthansa and Swiss International Air Lines from SFO to Frankfurt, Munich and Zurich. The deal represents one of the most significant SAF supply contracts globally, with up to one million gallons of SAF to be supplied to Lufthansa over the duration. It is the largest contracted SAF volume to be delivered to SFO since the airport announced its ambition to expand the use of SAF in its operations last year.

The SAF is produced by World Energy at its refinery in Paramount, California, from a feedstock of agricultural waste fats and oils. This CARB-certified and RSB-certified Low Carbon Fuel meet strict sustainability standards and is blended with conventional jet fuel at a ratio of up to 30%, resulting in a fuel that has significantly lower lifecycle carbon emissions. In general, lifecycle carbon emissions from SAF can be at least 80% lower than conventional jet fuel. SAF is supplied to airports through existing airport infrastructure and can be used by airlines without requiring technical modification to their current fleets.

By 2019, Virgin Australia has fueled more than 700 flights and flown more than 1 million kilometres, domestic and international, using Gevo, Inc's alcohol-to-jet fuel [32]. Gevo, Inc is committed to going after the entire gallon of sustainable aviation fuel, potentially leading to a negative carbon footprint. Virgin Atlantic was working to regularly use fuel derived from the waste gases of steel mills, with LanzaTech. British Airways wanted to convert household waste into jet fuel with Velocys. United Airlines committed to 900 million US gal (3,400,000 m3) of sustainable aviation fuel for ten years from Fulcrum BioEnergy (to be compared to its 4.1 billion US gal (16,000,000 m3) fuel consumption in 2018), after its $30 million investment in 2015, and will develop up to five biofuel factories near its hubs.

From 2020 Qantas Airways will start using a 50/50 blend of SG Preston's biofuel, for its Los Angeles-Australia flights also providing fuel derived from non-food plant oils to JetBlue Airways during 10 years. At its sites in Singapore, Rotterdam and Porvoo, Finland's Neste should improve its renewable fuel production capacity from 2.7 to 3.0 million t (6.0 to 6.6 billion lb) a year by 2020, and is increasing its Singapore capacity by 1.3 million t (2.9 billion lb) to reach 4.5 million t (9.9 billion lb) in 2022 by investing €1.4 billion ($1.6 billion) [33].

In Figure 19.5 are reported, based on publically available information, airports and airlines involved in ongoing alternative fuel purchase, updated to 2019. Due to the fuel blending procedures at these airports, it is not possible to determine the quantity of alternative fuel being used on any flight that appears on this live feed. Batches of fuel have also been delivered to several other airports [34].



Airline	Traffic Type	Airport
United Airlines KLM to Amsterdam	Departures	Los Angeles International Airport
Lufthansa SAS KLM / KLC	Departures	Oslo Airport
SAS KLM	Departures	Stockholm Arlanda Airport
All Airlines	Departures	Bergen Airport
KLM	Arrivals	Växjö Småland Airport
KLM SAS Finnair	Departures	San Francisco Airport
BRA	Departures	Halmstad City Airport

Figure 19.5. Airports and airlines involved in ongoing alternative fuel purchase (2019)

According to ICAO, today, the situation of distributing blended alternative fuels is as follows [35]:

- 185,000 commercial flights since 2011
- 5 technical SAF pathways certified & 4 more pre-2020
- Growing locations offering daily flights
- 2018 SAF volume = approximately 0.01% of total fuel demand

- A number of major construction announcements in the past 18 months
- Approximately 6 billion SAF liters in a forward purchase agreement
- More than 40 airlines have developed experience using SAF

In Figure 19.6 the global activity in the field of aviation biofuels up to 2019 is reported. The main companies reported produce different kind of SAF, as described in Table 19.2.

Figure 19.6. Global SAF activity

In figure 19.7 is reported the IATA analysis with the estimation of annual global production potential of SAF, considering the prevision of development of new production facilities and SAF capacity already announced. The bar error is related to the difference between a low take-up of SAF from production facilities (lower numbers) and a high take-up, driven by policy and airline decision making. The top numbers represent the full possible output of SAF production already in operation, under construction or in advance planning and financing.

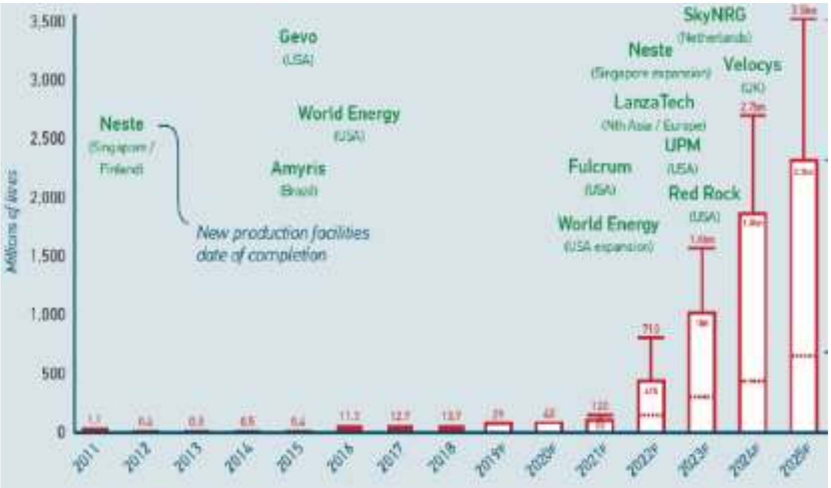


Figure 19.7. Sustainable aviation fuel ramp-up

In Table 19.2 is reported an overview of the first flights and companies that used sustainable fuels.

Carrier	Date of first SAF flight	Details
Air New Zealand	December 2008	Technical test flight on a Boeing 747
Japan Airlines	January 2009	Technical test flight on a Boeing 747
Finnair	July 2011	Series of flights on an Airbus A320-family aircraft between Amsterdam and Helsinki
Interjet	July 2011	Commercial flight on an Airbus A320 between Mexico City and Tuxtla Gutierrez
AeroMexico	August 2011	Commercial flight on a Boeing 777 between Mexico City and Madrid
Iberia	October 2011	Commercial flight on an Airbus A320 between Madrid and Barcelona
Thomson Airways	October 2011	Commercial flight between Birmingham and Arrecife on a Boeing 757
Air France	October 2011	Series of flights on an Airbus A320-family aircraft between Toulouse and Paris
Air China	October 2011	Technical test flight on a Boeing 747
Alaska Airways	November 2011	Series of commercial flights on Bombardier Q400 and Boeing 737 aircraft
Thai Airways	December 2011	Commercial flight on a Boeing 777 between Bangkok and Chiang Mai
Etihad Airways	January 2012	Delivery flight on a Boeing 777 from Seattle to Abu Dhabi
Latam Airways	March 2012	Series of flights in Latin America
Porter Airlines	April 2012	Demonstration flight on a Bombardier Q400 from Toronto to Ottawa
Jetstar Airways	April 2012	Commercial flight between Melbourne and Hobart on an Airbus A320
Air Canada	June 2012	Two commercial flights from Toronto to Mexico City
KLM	May 2014	Commercial flight from Amsterdam to Aruba on Airbus A330-200
GOL Lineas Aéreas	June 2014	Series of flights during the FIFA World Cup
Nextjet	June 2014	Commercial flight from Karlstad to Stockholm
Finnair	September 2014	Commercial flight from Helsinki to New York on Airbus A330
Lufthansa	September 2014	Scheduled flight from Frankfurt to Berlin
Scandinavian Airlines	November 2014	Flights between Stockholm and Ostersund and Trondheim and Oslo on Boeing 737 aircraft
Norwegian Airlines	November 2014	Flight between Bergen and Oslo on a Boeing 737
Hainan Airlines	March 2015	Commercial flight between Shanghai and Beijing on a Boeing 737
Alaska Airlines	June 2016	Two commercial flights from Seattle to San Francisco and Washington D.C.
Alaska Airlines	November 2016	Commercial demonstration flight from Seattle to Washington D.C. on Boeing 737-800

Carrier	Date of first SAF flight	Details
Braathens Regional Airlines	February 2017	Commercial flight from Stockholm to Umeå on ATR 72-600
Air Canada	April 2017	Series of five test flight between Montreal and Toronto
Singapore Airlines	May 2017	Series of trans-Pacific flights between Singapore and San Francisco on Airbus A350 aircraft
Various	November 2017	Commercial flights on 'Fly Green Day' from Chicago by Lufthansa, United Airlines, Etihad, Cathay Pacific Airways, Emirates, Japan Airlines, Korean Air Atlas Air and FedEx
Hainan Airlines	November 2017	Commercial flight from Beijing to Chicago on Boeing 787
China Airlines	December 2017	Delivery flight of A350-900 from Toulouse to Taipei
Qantas	January 2018	Commercial flight from Los Angeles to Melbourne on Boeing 787-9
Air Canada	May 2018	Commercial flight from Edmonton to San Francisco on A320-200
SpiceJet Airlines	August 2018	Demonstration flight on Bombardier Q400 from Dehradun to Delhi
jetBlue Airways	September 2018	Delivery flight of A321 from Mobile, Alabama to New York
Etihad Airways	January 2019	Commercial flight from Abu Dhabi to Amsterdam on Boeing 787
China Southern Airlines	February 2019	Delivery flight of A320NEO from Toulouse to Guangzhou
Braathens Regional Airlines	May 2019	'Perfect Flight' from Halmstad to Stockholm on ATR 72-600
Various	May 2019	21 private aircraft flew to Geneva to the annual European Business Aviation Convention & Exhibition (EBACE)
United Airlines	June 2019	Eco-friendly commercial "Flight For the Planet" from Chicago to Los Angeles
Delta	July 2019	Delivery flight of A321 from Mobile, Alabama to Kansas City (first in series of 20 delivery flights to Delta powered by sustainable fuels)
Egyptair	July 2019	Delivery flight of Boeing 787 from Seattle to Cairo
Finnair	August 2019	First two flights backed by "Push for change" initiative from San Francisco to Helsinki

Table 19.2 Summary of flights that used sustainable fuels up to 2019 [36]

According to the International Energy Agency (IEA), at the start of 2019 just five airports in the world were using biofuels (SAFs that come from biological sources like plants) in regular supply [37]. These were:

- Bergen Airport, Norway
- Brisbane Airport, Australia
- Los Angeles International Airport, United States
- Oslo Airport, Norway
- Stockholm Arlanda Airport, Sweden.

As it concerns airlines, a few have invested in making SAFs part of their regular operations. KLM is one of the airlines leading the way in sustainability and, at the end of last year, was looking to introduce biofuel at its hub in Amsterdam Schiphol Airport. In 2019, United Airlines purchased 10 million gallons of biofuel to use in the next two years. Delta Air Lines is hoping to make biofuels from debris from the forest floor, and SAS allows its passengers to buy blocks of biofuel-powered sections on their flight.

2.3 European projects related to SAF in H2020 program

There are 43 projects financed by the H2020 program linked to SAF and among them, 25 are specifically funded for the study of SAF (Table 19.3), 13 ended on June 2020. The total amount funded by EU is M€ 84.8, and 188 countries have been involved.

Topic	Acronym	Title	ID	End date
FETFLAG	ENERGY-X	ENERGY-X: Transformative chemistry for a sustainable energy future	820444	29/02/2020
IT	HIGHER	HIGHER: High performance Engine for Light Sport Aircraft	710622	31/05/2016
	SABRE	Transforming the biodiesel industry to meet Europeâ€™s need for sustainable aviation fuel: business feasibility study, technical validation and real-world demonstration	717852	31/08/2016
JTI	ACTIonRCraft	Anti-Crash lightweight fuel bladder Tank Integrated on a new RotorCraft	714249	19/12/2020
	TRADE	Turbo electRic Aircraft Design Environment (TRADE)	755458	30/06/2020
LCE	KEROGREEN	Production of Sustainable aircraft grade Kerosene from water and air powered by Renewable Electricity, through the splitting of CO2, syngas formation and Fischer-Tropsch synthesis	763909	31/03/2022
	MacroFuels	Developing the next generation Macro-Algae based biofuels for transportation via advanced bio-refinery processes	654010	31/12/2019
	SUN-to-LIQUID	SUNlight-to-LIQUID: Integrated solar-thermochemical synthesis of liquid hydrocarbon fuels	654408	31/12/2019
	FlexJET	Sustainable Jet Fuel from Flexible Waste Biomass	792216	31/03/2022
	BIO4A	Advanced sustainable BIOfuels for Aviation	789562	30/04/2022
	ADVANCEFUEL	Facilitating market roll-out of RESfuels in the transport sector to 2030 and beyond	764799	31/08/2020
	ETIP Bioenergy - SABS	European Technology and Innovation Platform Bioenergy â€" Support of Advanced Bioenergy Stakeholders 2016 - 17	727509	31/08/2018
LC	ALTERNATE	ASSESSMENT ON ALTERNATIVE AVIATION FUELS DEVELOPMENT	875538	31/12/2022
	BL2F	Black Liquor to Fuel by Efficient HydroThermal Application integrated to Pulp Mill	884111	31/03/2023
	BioSFerA	BIOfuels production from Syngas FERmentation for Aviation and maritime use	884208	31/03/2024
	GLAMOUR	GLycerol to Aviation and Marine prOducts with sUstainable Recycling	884197	30/04/2024
MG	MMTech	New aerospace advanced cost-effective materials and rapid manufacturing technologies	633776	30/04/2019
	JETSCREEN	JET Fuel SCREENing and Optimization	723525	31/10/2020
	H3PS	H3PS-High Power High Scalability Aircraft Hybrid Powertrain	769392	30/04/2021
	ENABLEH2	ENABLing cryogEnic Hydrogen based CO2 free air transport (ENABLEH2)	769241	31/08/2021
MSCA	NextGen Airliners	Designing Next-Generation Aircraft via High-Fidelity Computational Models and Optimization	658570	30/11/2016
SC5	Solaris	Solaris Energy Tobacco	697720	31/12/2015
SESAR	PJ08 AAM	Advanced Airspace Management	731796	31/12/2019
SMEInst	SOLARIS	Solaris energy tobacco for the creation of a European sustainable biojet fuel value chain	778030	31/08/2019

Table 19.3. SAF projects financed by the H2020 program. Data available from the CORDIS EUROPA platform by a query performed on June 2020 (keywords used: aviation, aeronautic, biofuel, advanced biofuel, sustainable aviation fuel)

In Figure 19.8 it is possible to notice that as it concerns the coordinator of the project, the highest number is for Italy and United Kingdom, followed by Germany.

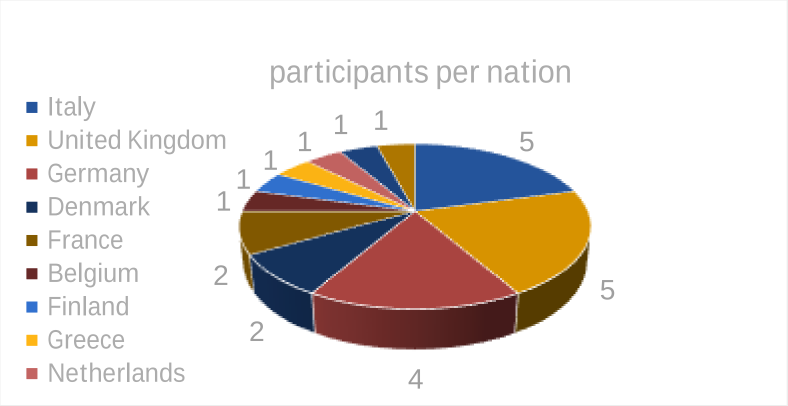


Figure 19.8. Distribution of H2020 projects on SAF per coordinator's nationality

As the contribution of EU to the projects is considered, the United Kingdom has the highest contribution (€ 24.734.539), followed by Italy and Germany (respectively € 15.217.675 and € 15.147.324).

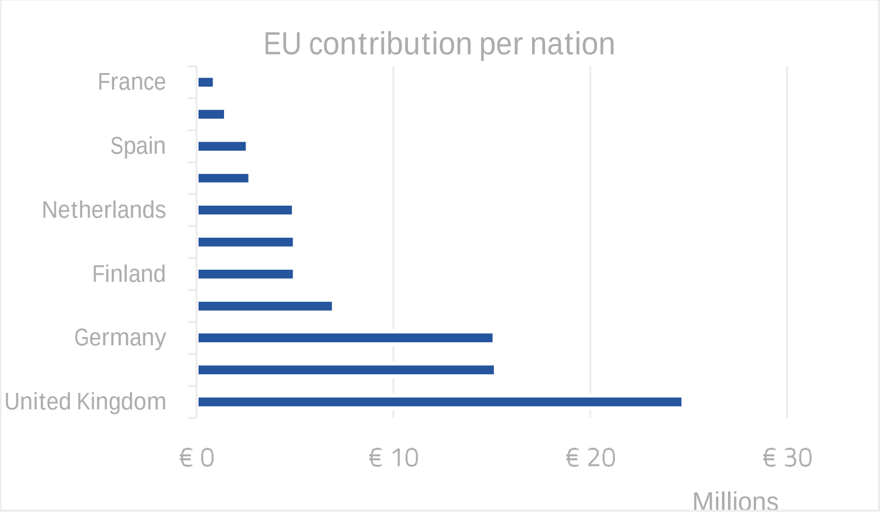


Figure 19.9. EU contribution on H2020 projects on SAF per nation

Increasing the global SAF production capacity is a challenge, as it requires large industrial investments in a moment when SAF is not yet economically competitive with Conventional Aviation Fuels (CAF). Two new H2020 projects have been recently launched: BIO4A [39] and FlexJetFuels [40]. These projects aim at increasing the biojet production capacity in the EU, favouring the market uptake of SAF, also addressing the logistics and distribution, the social, economic and environmental assessment, and the supply of residual lipids. In addition, BIO4A will investigate the sourcing of sustainable lipids from drought-resistant oil crops cultivate in EU MED marginal lands.

3 Sustainable Aviation Fuels: Advanced Biofuels

3.1 Pathways to Sustainable Aviation Fuels

The pathway needed to bring innovation to industrial scale in the Sustainable Aviation Fuels (SAF) is long and complex. The development of industrial-scale demonstration plants requires significant investments, most often in the order of more than a hundred million €. These industrial initiatives are normally difficult to finance, as risks associated with innovation are relevant. For these reasons, the curve describing the innovation pathway, as for many projects, is similar to a Mountain of Death shown in Figure 19.10 showing a collapse, mostly for financial reasons.

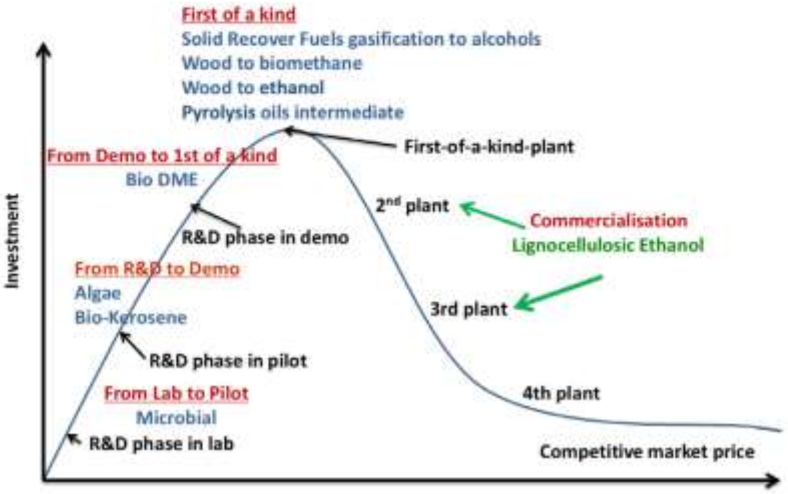


Figure 19.10. "Mountain of Death" for innovative biomass technologies [38]

As it regards air transports, the possible pathways to develop new biomass-based aviation biofuel chains are numerous and positioned at different stages of the Mountain of Death

A summary of the most relevant process chains to Aviation biofuels is shown in Figure 19.11.

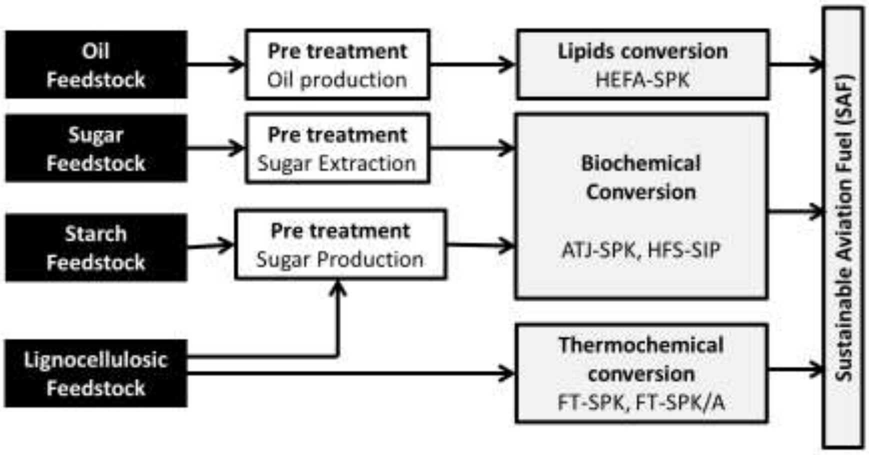


Figure 19.11. Major Aviation Biofuels process routes [41]

Decarbonizing the aviation bringing new fuels in commercial flights requires to go through a long and expensive route encompassing certification, which is governed by the following main norms:

- ASTM D1655 Standard Specification for Aviation Turbine Fuels
- ASTM D7566 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons;
- ASTM D4054 Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives;

To carry out the entire path necessary to certify a new aviation fuel requires significant efforts and resources, as summarized in the ASTM D4054 guideline. Moreover, moving from Tier 1-2 to Tier 3-4 of the certification route will also necessitate a significant amount (order of tens of cubic meters) of jet fuel. In general, this requires the construction of a Demo plant, which is a further investment for the developers of the new biofuel production pathways. There are therefore several obstacles and barriers, both technical and financial, to the goal of introducing a new fuel on the market.

Commercial aviation commonly uses Jet-A1 (also known as kerosene). Due to the high cost of aircrafts and the long fleet replacement time, and also to limit infrastructure changes, the aviation sector is likely to rely on liquid fuels similar to kerosene to 2050 and possibly beyond and is currently looking to drop-in sustainable fuels to the conventional, crude based, jet fuel. Renewable jet fuel—also called "biojet" or aviation biofuel, renewable jet fuel is a biomass-derived fuel that can be used interchangeably with petroleum-based aviation fuel. Certain biojet fuels can be blended up to 50% with conventional commercial and military jet (or aviation turbine) fuels by following requirements in the ASTM D7566 specification.

The composition of these new fuels is currently mostly paraffinic, being known as Synthetic Paraffinic Kerosene (SPK) or iso-paraffins. It can be blended in variable amounts up to 50%, depending on the fuel type with conventional commercial and military jet (or aviation turbine) fuel while synthetic kerosene with aromatics (SKA) fuels can be used interchangeably with fossil fuels. Blending is required with SPK fuels because they lack sufficient aromatic hydrocarbons, which are present in conventional jet fuel. While aromatic hydrocarbons are limited in jet fuel to prevent smoke formation during combustion, a minimum aromatic content is needed to cause elastomer swell in aircraft fuel systems and increase fuel density.

Some less environmentally favourable components of conventional jet fuel (e.g. sulphur) allow seals to swell in engines and prevent fuel leaks. Newer engines do not have this concern, and SAF has been performance tested at 100% in military aircraft. While SAF production volumes remain low, a blend limit does not hamper the use of SAF. However, it is expected that the blend limit will eventually increase to 100%.

There are 7 major fuel routes approved by the ASTM D7566 standard:

- Annex A1 - Fischer-Tropsch fuels using solid biomass resources (wood residues) (FT-SPK)
- Annex A2 - Hydrogenated esters and fatty acids (HEFA) fuels derived from used cooking oil, animal fats, algae, and vegetable oils (e.g., camelina) (HEFA-SPK)
- Annex A3 - Synthetic iso-paraffin from fermented hydro processed sugar (direct-sugar-to-hydrocarbon fuels) (SIP-SPK)
- Annex A4 - FT fuels with aromatics using solid biomass resources (wood residues) (FT-SKA)
- Annex A5 - Alcohol-to-jet fuels produced from isobutanol (ATJ-SPK).
- Annex A6 - Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK, or CHJ)
- Annex A7 - Hydroprocessed Hydrocarbons (HH-SPK, or HC-HEFA)

To become approved for use, SAF must meet certain specifications from ASTM. Once it has demonstrated compliance with the requirements, it is blended with no more than 50% by volume (according to current standards) with conventional jet fuel and re-tested to show compliance. The reasons for the current blend limits are to ensure the appropriate level of safety and compatibility with the aircraft fueling systems (mainly due to the level of aromatics which are necessary for the different systems). It is, however, likely that higher blend limits will be approved in the future. Once blended, SAF has the same characteristics as fossil jet fuel. The blend is then re-certified as Jet A or Jet A-1. It can be handled in exactly the same way as regular jet fuel, so no changes are required in the fueling infrastructure or for an aircraft wanting to use SAF. Any aircraft certified for using the current specification of jet fuel is able to use SAF [42].

Pathways Processes	Feedstock	Date of Approval	Blending ratio by Volume	Commercialization Proposals
Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	Biomass (forestry residues, grasses, municipal solid waste)	2009	50%	Fulcrum Bioenergy, Red Rock Biofuels, SG Preston, Kaidi, Sasol, Shell, Syntroleum
Hydroprocessed Esters and Fatty Acids (HEFA-SPK)	Oil-bearing biomass, e.g., algae, jatropha, camelina, carinata	2011	50%	World Energy, Honeywell UOP, Neste Oil, Dynamic Fuels, EERC
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (SIP-HFS)	Microbial conversion of sugars to hydrocarbon	2014	10%	Amyris, Total
FT-SPK with aromatics (FT-SPK/A)	Renewable biomass such as municipal solid waste, agricultural wastes and forestry residues, wood and energy crops	2015	50%	Sasol
Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	Agricultural wastes products (stover, grasses, forestry slash, crop straws)	2016	50%	Gevo, Cobalt, Honeywell UOP, Lanzatech, Swedish Biofuels, Byogy
Hydroprocessed Esters and Fatty Acids Plus (HEFA +)	Oil-bearing biomass, e.g., algae, jatropha, camelina, carinata	-.	50%	Boeing
Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK, or CHJ)	fatty acids and fatty acid esters, lipids that come from plant and animal fats, oils and greases (FOGs)	March 2020	50%	ARA
Hydroprocessed Hydrocarbons (HH-SPK, or HC-HEFA)	bio-derived hydrocarbons, directly from oils (triterpenes) produced by the Botryococcus braunii algae	May 2020	10%	IHI Corporation
Co-processing	Fats, oils, and, greases (FOG), from petroleum refining, biocrude	2018	5%	Chevron, Phillips66, BP

Table 19.4. Pathway processes approved by ASTM [43]

There are other 4 routes currently under approval process, plus other 15 waiting to enter the process [44]. Sustainability of those pathways depends upon the feedstock and way of production.

The Commercial Aviation Alternative Fuels Initiative (CAAFI), formed by stakeholders leading the development and deployment of alternative jet fuels for commercial aviation, reports that there are six fuels in the qualification process [45] Table 19.5 shows the pathways actively pursuing certification at various stages in the process.

ASTM Progress	Pathway	Feedstock	Task Force Lead
ASTM Balloting	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK)	Hydrocarbon-rich algae oil	IHI
Phase 2 Testing	Hydro-deoxygenation Synthetic Kerosene (HDO-SK)	Sugars and cellulosics	Virent (inactive)
	Hydro-deoxygenation Synthetic Aromatic Kerosene (HDO-SAK)	Sugars and cellulosics	Virent
Phase 1 OEM Review	High Freeze Point Hydroprocessed Esters and Fatty Acids Synthetic Kerosene (HFP HEFA-SK)	Renewable FOG	Boeing
Phase 1 Research Report	Integrated Hydropyrolysis and Hydroconversion (IH^2)	Multiple	Shell
Phase 1 Testing	Alcohol-to-Jet Synthetic Kerosene with Aromatics (ATJ-SKA)	Sugars and lignocellulosics	Swedish Biofuels, Byogy

Table 19.5. Pathways processes progress for ASTM certification

CAAFI is aware of a significant number of additional prospective pathways that are currently being pursued by multiple entities but have yet to enter the ASTM Qualification Process. These approaches have the potential to convert the carbon or hydrocarbon content of various feedstocks using biological (fermentation or microbial conversion) or thermochemical (pyrolysis, hydrothermal liquefaction, catalytic conversion, etc.) processes into the chemical components of jet fuel.

Feedstocks considered by the aviation industry[2] are lipids such as waste oils like used cooking oil (UCO), residual animal/vegetable oils from industries, vegetable oils like camelina oil, algae, cellulosic material such as tobacco, jatropha, sugars from sugarcane, lignocellulosic material, lignin residues, municipal solid wastes (MSW), dedicated energy crops. Wastes and residues that do not require land to be produced usually have less sustainability concerns. Drop-in fuels could also be produced from electric power (power-to-liquid (PTL) or sunlight (STL)).

Beside the assessment of the current technical potential, an appraisal of the maturity level of the various production pathways is summarised in a database updated by the Joint Research Centre (JRC). In Table 19.6, a summary of an extract of the data on the current installed capacity of the technologies from the database is reported [46].

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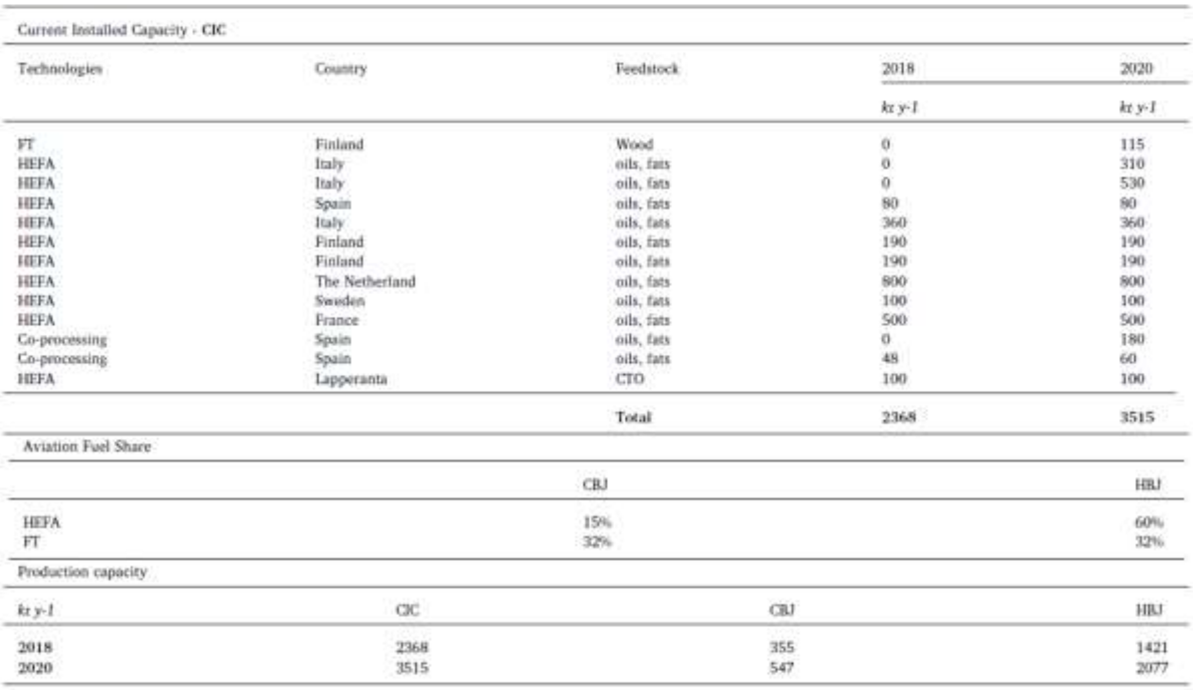
[2] The feedstocks types cannot be considered sustainable per se. Sustainability should be demonstrated along the production chain. Those mentioned above have been used in aviation because in particular production chains they have been found as sustainable according to internationally recognized standards like RSB (www.rsb.org) or ISCC (www.iscc-system.org) and the Directive 2009/28/EC.



Current Installed Capacity - CIC

Technologies	Country	Feedstock	2018 *kt y-1*	2020 *kt y-1*
FT	Finland	Wood	0	115
HEFA	Italy	oils, fats	0	310
HEFA	Italy	oils, fats	0	530
HEFA	Spain	oils, fats	80	80
HEFA	Italy	oils, fats	360	360
HEFA	Finland	oils, fats	190	190
HEFA	Finland	oils, fats	190	190
HEFA	The Netherland	oils, fats	800	800
HEFA	Sweden	oils, fats	100	100
HEFA	France	oils, fats	500	500
Co-processing	Spain	oils, fats	0	180
Co-processing	Spain	oils, fats	48	60
HEFA	Lapperanta	CTO	100	100
		Total	**2368**	**3515**

Aviation Fuel Share

	CBJ	HBJ
HEFA	15%	60%
FT	32%	32%

Production capacity

kt y-1	CIC	CBJ	HBJ
2018	2368	355	1421
2020	3515	547	2077

Table 19.6. Current installed capacity (CIC) of the technologies

Researchers are exploring a variety of methods to produce renewable hydrocarbon biofuels. Production plants may be standalone or co-located at petroleum refineries. Technology pathways explored for the production of renewable hydrocarbon biofuels include:

- Traditional hydrotreating—Used in petroleum refineries, hydrotreating involves reacting the feedstock (lipids) with hydrogen under elevated temperatures and pressures in the presence of a catalyst.
- Biological sugar upgrading—This pathway uses a biochemical deconstruction process, similar to what is used with cellulosic ethanol with the addition of organisms that convert sugars to hydrocarbons.
- Catalytic conversion of sugars—This pathway involves a series of catalytic reactions to convert a carbohydrate stream into hydrocarbon fuels.
- Gasification—During this process, biomass is thermally converted to syngas and catalytically converted to hydrocarbon fuels.
- Pyrolysis—This pathway involves the chemical decomposition of organic materials at elevated temperatures in the absence of oxygen. The process produces a liquid pyrolysis oil that can be upgraded to hydrocarbon fuels, either in a standalone process or as a feedstock for co-feeding with crude oil into a standard petroleum refinery.
- Hydrothermal processing—This process uses high pressure and moderate temperature to initiate chemical decomposition of biomass or wet waste materials to produce an oil that may be catalytically upgraded to hydrocarbon fuels.

Currently, in the United States, commercial-scale production of renewable hydrocarbon biofuels is limited. Instead, commercial facilities are largely focused on renewable diesel production.

3.1.1.1 Benefits

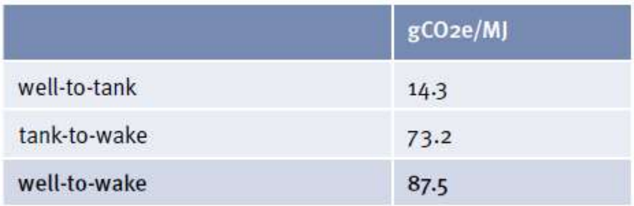
Renewable hydrocarbon biofuels offer many benefits, including:

- Engine and infrastructure compatibility—Renewable hydrocarbon biofuels are similar to their petroleum counterparts and therefore minimize compatibility issues with existing infrastructure and engines.
- Increased energy security—Renewable hydrocarbon biofuels can be produced domestically from a variety of feedstocks and contribute to job creation.
- Fewer emissions—Carbon dioxide captured by growing feedstocks reduces overall greenhouse gas emissions by balancing carbon dioxide released from burning renewable hydrocarbon biofuels.
- More flexibility—Renewable hydrocarbon biofuels are replacements for conventional jet fuel, and gasoline, allowing for multiple products from various feedstocks and production technologies.

The United States, the European Union, the Netherlands, the United Kingdom and Norway have all recently established policy mechanisms which will support the use of aviation biofuels. To gain the confidence of policy makers and the general public, such support will need to be linked to robust fuel sustainability criteria.

3.1.1.2 GHG emissions for biomass derived jet fuels

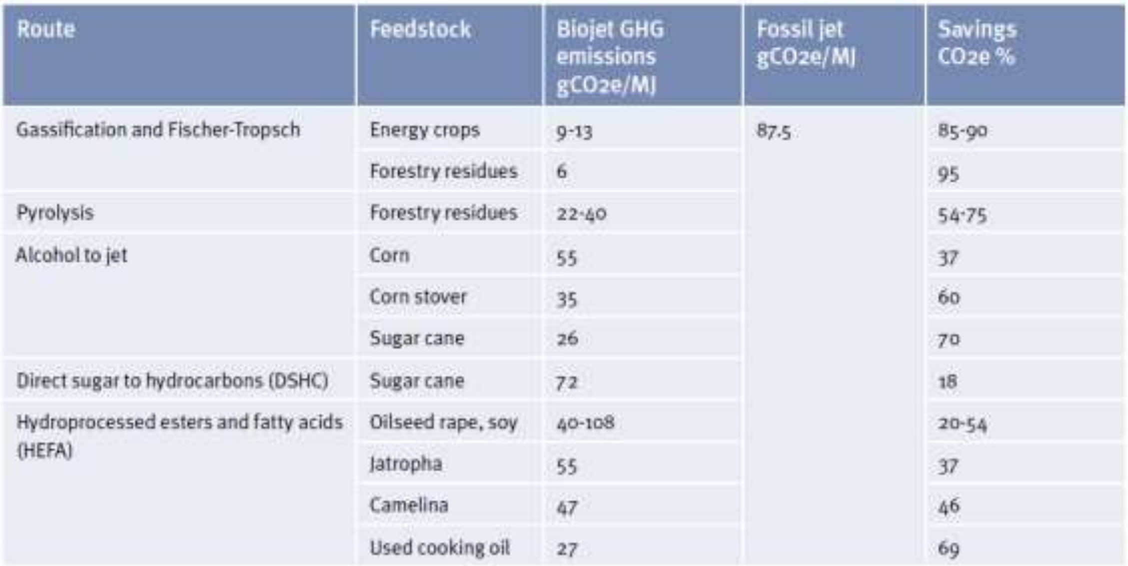
The major part (around 84%) of carbon dioxide emissions from fossil jet fuels are emitted when they are burnt in the engine, whereas around 16% of emission is associated to the production stages between oil well and fuel tank. Biojet also produces carbon dioxide when burnt, but according to the United Nations Framework Convention on Climate Change (UNFCCC) guidelines, emissions at the point of use are recorded as zero in the energy sector. For biofuels, however, the emissions related to feedstock production and chemical processing may be substantial. The whole production chain is split into two parts, well-to-tank (WTT) and tank-to-wake (TTW). An illustrative well-to-wake calculation is shown in Table 19.7 [47].



	gCO_2e/MJ
well-to-tank	14.3
tank-to-wake	73.2
well-to-wake	87.5

Table 19.7. Example well-to-wake (WTW) CO2 emission for petroleum-derived jet fuel

As shown in Table 19.8, biojet can reduce lifecycle emissions by between 20% and 95% when compared with petroleum-derived jet. However, the extent of reductions is still open to debate [48] In fact, the emissions associated with feedstock production making a significant contribution to the overall GHG intensity of the biofuel should also be taken into account. For example, biofuels obtained from energy crops and forestry residues converted via gasification and Fischer-Tropsch (FT) synthesis result in very low lifecycle GHG emissions due to the fact that the process energy is derived from the biomass itself and emissions associated with feedstock production are low. In contrast, biojet produced from conventional oil crops (via the HEFA pathway) produce a modest saving due to the high GHG emissions associated with production of the feedstock and the hydrogen for upgrading the fuel.

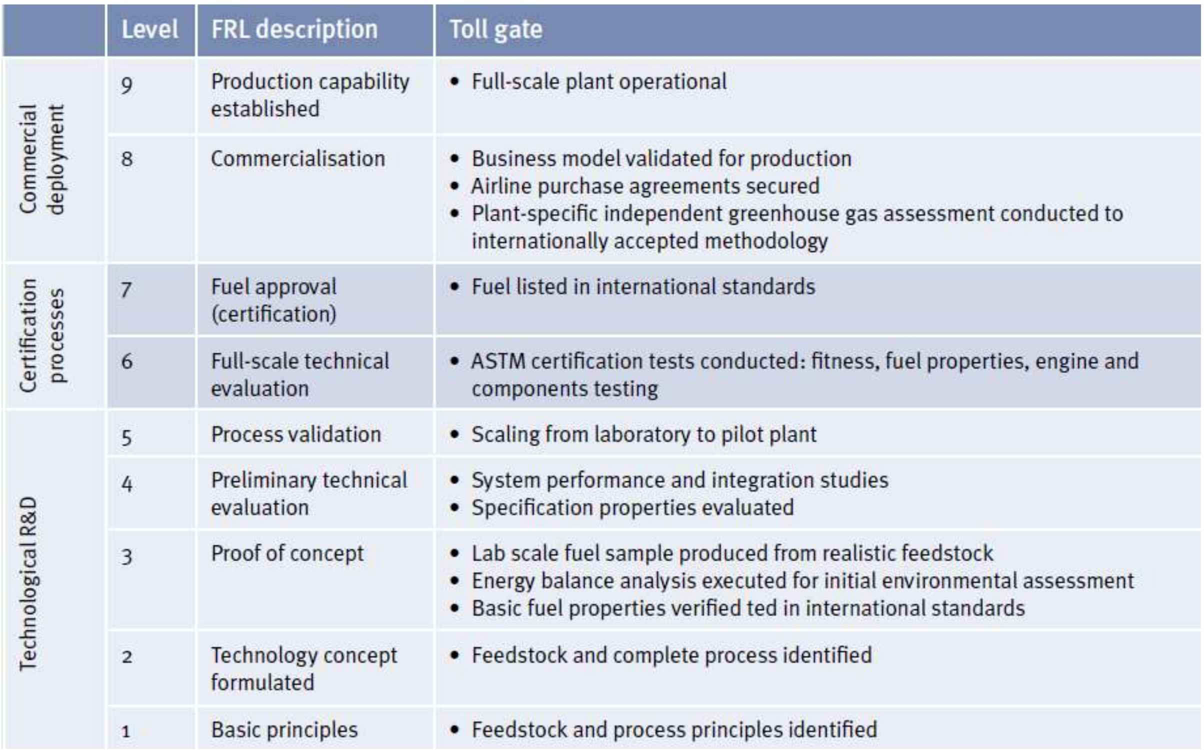


Route	Feedstock	Biojet GHG emissions gCO2e/MJ	Fossil jet gCO2e/MJ	Savings CO2e %
Gassification and Fischer-Tropsch	Energy crops	9-13	87.5	85-90
	Forestry residues	6		95
Pyrolysis	Forestry residues	22-40		54-75
Alcohol to jet	Corn	55		37
	Corn stover	35		60
	Sugar cane	26		70
Direct sugar to hydrocarbons (DSHC)	Sugar cane	72		18
Hydroprocessed esters and fatty acids (HEFA)	Oilseed rape, soy	40-108		20-54
	Jatropha	55		37
	Camelina	47		46
	Used cooking oil	27		69

Table 19.8. Well-to-wake comparisons, alternative biojet fuel routes compared to conventional jet fuel [49]

3.1.1.3 Fuel Readiness Level

The Fuel Readiness Level (FRL) [50] approach (see Table 9) corresponds to the Technology Readiness Level (TRL) framework providing a description of the progression of a technology towards commercialisation. Unlike TRL, the FRL method makes reference to the specific risks involved in developing fuels related to the fuel's composition, chemistry, and compatibility with fuelling infrastructure and aircraft. Based on the industrial experiences so far, the rate of progression is three to five years for one FRL.



	Level	FRL description	Toll gate
Commercial deployment	9	Production capability established	• Full-scale plant operational
	8	Commercialisation	• Business model validated for production • Airline purchase agreements secured • Plant-specific independent greenhouse gas assessment conducted to internationally accepted methodology
Certification processes	7	Fuel approval (certification)	• Fuel listed in international standards
	6	Full-scale technical evaluation	• ASTM certification tests conducted: fitness, fuel properties, engine and components testing
Technological R&D	5	Process validation	• Scaling from laboratory to pilot plant
	4	Preliminary technical evaluation	• System performance and integration studies • Specification properties evaluated
	3	Proof of concept	• Lab scale fuel sample produced from realistic feedstock • Energy balance analysis executed for initial environmental assessment • Basic fuel properties verified ted in international standards
	2	Technology concept formulated	• Feedstock and complete process identified
	1	Basic principles	• Feedstock and process principles identified

Table 19.9. Fuel Readiness Level [49]

3.2 Properties of the advanced biofuels

In Table 19.10 the properties of fuel categories approved by the ASTM D7566 standard are reported, in comparison with the properties of an average conventional kerosene (Jet A-1).

The Derived Cetane Numbers (DCNs) of alternative jet fuels are higher than conventional jet fuel because conventional jet fuel contains more than 20% of aromatics. The alternative fuels with higher n-paraffin content will be more reactive, resulting in higher DCNs. The ignition behaviour, which depends strongly on the fuel composition and structure, shows that alternative fuels have shorter ignition delay than conventional jet fuel [51, 52, 53, 54, 55], and the pressure increase due to ignition in the combustion chamber is higher than that of convention jet fuel. The amount of n-paraffins contained in the fuels determines the order of ignition delay [56, 51]. For the laminar flame speed, which is controlled by the heat of combustion, there is no difference between conventional and alternative jet fuels [51].

The impacts of biojet fuel on engine performance, operability, hardware, and emissions are also studied. For the engine performance tests, the Bio-SPK derived from jatropha and algae shows an improvement in the specific fuel consumption and fuel flow compared to the Jet A. The 25% and 50% Bio-SPK blends demonstrate the reduction in fuel flow by 0.7% and 1.2%, respectively.

There are no significant differences in engine acceleration response time with these blends. For the emission tests, there is a slight reduction in NOx by 1%-5% due to the differences in ambient conditions and flame characteristics. The emissions of carbon monoxide (CO) and unburned hydrocarbons are increased by 5%-9% and 20%-45%, respectively, because of the reduction of flame temperature, the influence of spray quality and flame location. The smoke emission is reduced by 13%-30% due to the lower aromatic content and higher H/C ratio. In addition, there is no engine degeneration or unusual odours found when testing the biojet fuel in engines. However, the lack of aromatic components could lead to damage to the elastomer materials in the fuel system. Blending the biojet with conventional jet fuels would ensure elastomer swelling [57].

Property	Jet A-1	SIP	HEFA	CTL	CH-kerosene	ATJ-SPK	ATJ-SKA
Acidity, total [mg KOH/g]	0.001	0.002	0.001	0.001	0.014	0.002	0.003
Aromatics [vol%]	18.1	-	-	-	19.7	-	15.8
Distillation [°C]							
IBP (°C) / Boiling Point for SIP (°C; acc. to ASTM 1120)	156.2	247a	148.9	166.0	152.1	174.6	164.8
10 vol% recovered at T [°C]	168.8		162.9	171.5	171.4	178.0	174.8
50 vol% recovered at T [°C]	189.0		210.3	179.5	200.1	180.9	186.7
T50 – T10 [°C]	20.2		47.4	8.0	28.7	2.9	11.9
90 vol% recovered at T [°C]	225.4		270.8	198.7	244.8	220.1	205.6
T90 – T10 [°C]	56.6		107.9	27.2	73.4	42.1	30.8
FBP [°C]	241.7		277.6	215.2	258.5	249.8	249.6
Residue [vol%]	1.1		1.2	1.1	1.5	1.2	1.1
Loss [vol%]	0.9		1.1	1.1	0.9	0.9	1.1
Flash point [°C]	44.5	107.5b	42.0	46.0	42.5	47.5	48.5
Density at 15°C [kg/m3]	795.6	773.1	756.7	761.2	805.2	757.1	785.9
Freezing point [°C]	-57.6	<-80.0	-54.4	-	-41.3	<-80.0	<-80.0
Lubricity [mm]	0.698	0.562	0.906	0.780	0.570	0.839	0.606
Viscosity at -20°C [mm2/s]	3.335	14.13	4.801	3.71	3.977	4.795	3.421
Existent gum [mg/100 mL]	<1	10.0	<1	<1	<1	2	1

Thermal Stability - 2.5 h at 260°C							
Deposit Rating	<1	<1	1c	<1c	<1	<1c	<1
Pres. Drop [mm Hg]	0.0	0.0	0.0c	280.0c	0.0	0.0c	0.0
Net Heat of Combustion [MJ/kg]	43.275	-	44.154	-	43.202	-	43.396
Corrosion Copper Strip. 2 h/100°C	1a	1a	1b	1a	1a	1a	1a
Smoke Point [mm]	23.5	-	-	>45.0	22.5	27.0	23.0
Naphthalene [vol%]	0.13	-	-	-	0.35	-	0.08
Mercaptane Sulphur [wt.%]	0.0014	-	<0.0003	<0.0003	-	<0.0003	-
Sulphur [wt.%]	0.0145	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table 19.10. Properties of synthetic fuels: Boiling Point of neat SIP fuel determined according to ASTM 1120; Flash Point for neat SIP fuel determined according to DIN EN ISO 2719; Thermal stability determined at 325°C

Most production and use of alternative fuels in commercial aviation has been for demonstration and/or R&I purposes. The R&I profile of the use has changed with the blended use of HEFA-SPK at Oslo airport [58] and the start of continuous production of HEFA-SPK by Altair in Los Angeles (CA) for use by United Airlines [59]. The incentive programs available in the USA and in particular in California for advanced biofuels are enabling Altair production and are also driving the building of another facility for FT-SPK based on municipal solid wastes [44]. At European level, the only incentive for airlines using biojet fuel is the EU ETS for intra-European flights but it is negligible compared with the price gap. However, at global level, there is a commitment for development and implementation a global carbon market mechanism (GMBM) from 2020 that could be an incentive for the use of sustainable, low carbon fuels but that, with the current layouts, would also be unlikely covering the price gap for biojet.

More details available on the processes for biofuels are described in the sequel. The techniques not used anymore are also reported.

3.3 FT Kerosene

3.3.1 Pathway Description

The Fischer-Tropsch (FT) process is the first approved production pathway for synthetic kerosene. The pathway consists of four main steps. In the first step, the feedstock is converted into syngas (a mixture of CO and H_2). This syngas then enters the Fischer-Tropsch step proper, where it is converted into long-chain alkanes/paraffinic waxes or olefins (low-temperature FT using a cobalt catalyst produces paraffinic waxes, high-temperature FT using iron catalyst produces olefins.), which in the subsequent step are hydrocracked and isomerized. In the final step, the raw product is distilled and separated into individual products, of which kerosene is one [60]. If the feedstock is natural gas, the syngas is produced via steam reforming (reaction with water) or via partial oxidation of the feedstock (reaction with oxygen) [61], followed by conditioning, that means the removal of particulates, adjustment of the relationship between H_2 and CO and removal of water and CO_2 [60]. If the feedstock is a solid (e.g. coal or woodchips), syngas production involves partial oxidation and steam gasification, again followed by conditioning. In addition, if the feedstock is a biomass, the pre-treatment of the feedstock will typically be necessary.

3.3.2 Approval Status

A generic approval for FT kerosene as a blendstock with a maximum blend ratio of 50% was given by ASTM in 2009 (*Annex A1*). For this purpose, a new specification ASTM D7566 was created, which is a specification for blends with synthetic kerosene. This specification is referred to in the jet fuel specification, ASTM D1655, to the effect that these blends are jet fuel; hence a blended meeting ASTM D7566 is an ASTM D1655 jet fuel. Although the approval was largely based on coal as a feedstock, the generic approval covers the product from

FT processes in general, regardless of feedstock. The FT fuels described above do not contain aromatic compounds. However, a certain percentage of aromatics is required in jet fuel to ensure seal swell and tightness of valves. This is one of the reasons why the fuel may only be used as a blend with conventional kerosene, with a maximum blend ratio of 50%. The specification also states that the blend must have a minimum aromatics content of 8%[3] [62]. Approval has been granted by ASTM in November 2015 [63] (*Annex A4*) to a semi-synthetic fuel called IPK/A which is partly synthesised via the Fischer-Tropsch process and partly from the naphtha cut produced from the coal-tar-product of coal gasification [64]. In May 2020 a new type of renewable content for refinery coprocessing of fuels from non-conventional sources: ASTM D1655 Annex A1 addition of Fischer Tropsch biocrude has been added.

The second change is the inclusion of Fischer-Tropsch (FT) biocrude as an allowable feedstock for petroleum co-processing. It's task force, and research activity was led by Fulcrum. As with the earlier approval of lipid co-processing, this co-processing will be limited to a 5% by volume limitation on both feedstock volume and synthesized final product content.

3.3.3 Availability and compatibility

Large-scale production facilities exist for the conversion of coal to liquid fuels (Sasol in South Africa) and for the conversion of natural gas (Shell in Qatar) [65]. A novel approach to feedstocks was planned by British Airways and Solena, involving a facility for the conversion of urban waste into fuel. To handle the extreme heterogeneity of this feedstock the planned facility was supposed to produce the syngas at temperatures up to 5,000°C in an O2 deprived environment [66], followed by a FT conversion [67]. This project has been terminated [68] due to October 2015, but a similar approach is now planned by Fulcrum Inc. with various airlines [69]. More than 1600 commercial flights have been done using sustainable fuel blends from 20-50% [70]. Use at the airport as non-segregated fuel has started in January 2016 in Oslo [58] increasing the number of flights, but the volumes needed to keep continuous supply are a challenge. It can be produced in large quantities, but there is no continuous production of drop-in fuels for aviation in Europe. The use outside Europe, mostly in the USA, has been promoted by military contracts and now starting from private companies.

It is a "drop-in" fuel and can be used in Turbofan powertrain technology.

3.3.4 Chemical Properties and risks

Possible feedstocks for the FT process are various. Large-scale production facilities exist for the conversion of coal to liquid fuels (Sasol in South Africa) and for the conversion of natural gas (Shell in Qatar). At both of these facilities, FT blendstock for jet kerosene is routinely produced. Conversion of biomaterial to fuel has been demonstrated at the pilot scale, but not beyond. An attempt by the German company Choren to build a demo scale plant for the FT conversion of woodchips was abandoned when Choren went bankrupt.

The Fischer–Tropsch synthesis is a well-known highly exothermic industrial process that allows the conversion of syngas into a mixture of hydrocarbons with low carbon-chain selectivity (C1–C50) over metal-based catalysts at moderate temperatures and pressures. The hydrocarbon distribution depends highly on both the operating conditions (temperature and pressure) and the catalyst composition. Oxygenated compounds such as alcohols, aldehydes, and carboxylic acids are typically produced in the process along with the hydrocarbons. Addition of promoters such as K to Fe catalysts allows for an increase in the selectivity to jet fuel range hydrocarbons. The large amount of heat released during the Fischer–Tropsch process must be removed rapidly to avoid high temperatures in the reactor, which favour the formation of CH_4 and lead to catalyst deactivation. In order to produce hydrocarbons in the jet fuel range (C9–C16), heavy hydrocarbons (waxes) can be produced first by operating at low temperatures (230°C), followed by controlled cracking and

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[3] This requirement already existed in the 1999 approval, see Moses, Wilson, Roeds.

isomerization steps to jet fuel components. Thus, conventional petrochemical units such as hydrocracking, isomerization, and fractionation are normally required after the Fischer–Tropsch reactor to adjust the molecular weight and structure of the hydrocarbons to the jet fuel range.

FT synthesis gives a product virtually free from the trace sulfur- and nitrogen-containing compounds found in conventional jet fuel. The product is also free from aromatic compounds, but this property has both advantages and disadvantages. The main advantage of the aromatic free fuel is that it is cleaner burning; FT fuel emits fewer particulates than conventional jet fuel, and, because it is sulfur-free, there are no sulfur dioxide (SO_2) or sulfuric acid ($H_2 SO_4$) aerosol emissions. However, there are two disadvantages of not having aromatics in the fuel. First, FT kerosene that meets all other jet fuel specification properties will be below the minimum density requirement. Second, the aromatics in conventional fuel cause some types of elastomers used in aircraft fuel systems to swell. There is a concern in the industry that switching from conventional jet fuel to aromatic-free FT synthetic fuel will cause some of these elastomers to shrink, which may lead to fuel leaks. The effects of aromatics on elastomers is an area of active research in the industry. A possible solution may be to find an additive that would ensure elastomer swell even in the absence of aromatics. These two disadvantages disappear if FT synfuel is blended with conventional jet fuel, although the advantage of lower emissions is reduced. The conventional jet fuel contains the aromatics that because elastomer swell and also increase the fuel density to meet the minimum requirement. The industry is using 8 % aromatics content as a guiding minimum. This minimum is based mainly on experience and could be revised, up or down, in the future.

The Fischer-Tropsch pathway to synthetic jet fuel is commonly used in biomass-to-liquid (BtL), gas-toliquid (GtL) and coal-to-liquid (CtL) processes. Instead of biomass, natural gas, and coal, respectively, hydrogen from water electrolysis is used (Figure 19.12)

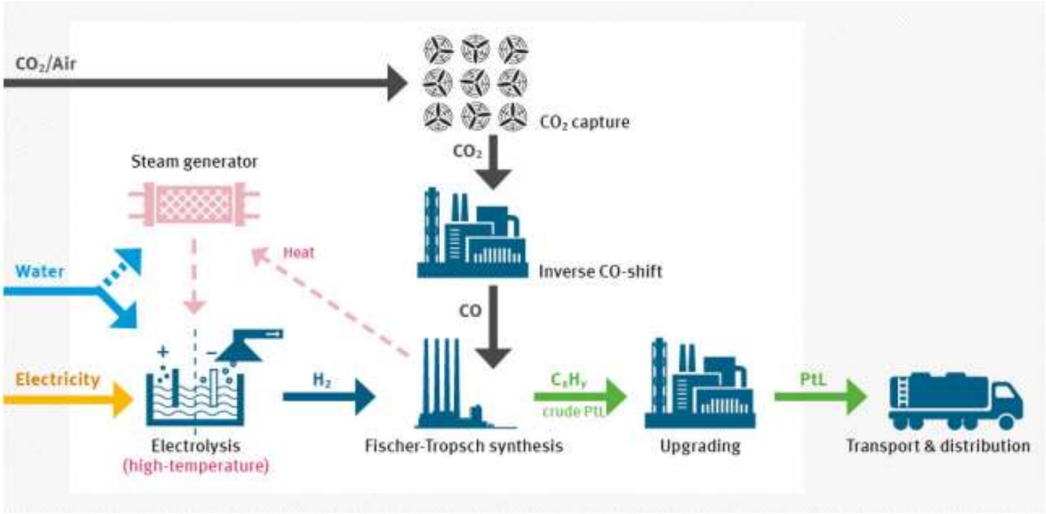


Figure 19.12. Fischer-Tropsch (FT) pathway

Coal-to-liquids (CTL) [71] is a process of producing synthetic transportation fuels from coal. The process involves gasification of coal to produce synthesis gas which is then catalytically converted to liquid fuels in a Fischer-Tropsch (FT) reactor. The density of FT fuels is usually observed to be lower than of conventional jet fuel (table 11). Thus, density may be the limiting factor for blending FT and fossil jet fuel until confirming standard values. FT blending with conventional jet fuels display a linear relationship between blend ratio and density. FT fuels are characterized with similar or slightly higher heat of combustion per unit of mass. And lower density results in lower heat of combustion per unit of volume. Like Farnesane- and HVO-blends, those with CTL display a linear relationship between blend ratio and density. Hence, parameters which describe concentrations, e.g. aromatic and sulphur content, are expected to show a linear dependence on blend ratio as well, which has been verified by sporadic measurements. Since the density of neat CTL (761.2 kg/m^3) falls below the lower limit for blends (775 kg/m³), the maximum content of CTL in the mixtures is limited and depends on the initial density of the fossil fuel.

Property	Units of measurement	Limits ASTM D1655/D7566	Results			
			Jet A-1	FT 1	FT 2	FT 3
Density at 15 °C	kg/m^3	775.0/840.0	795.0	761.2	761	756
Heat of combustion	MJ/kg	Min 42.80	43.39	n/a	44.0	43.9
Aromatics	% (V/V)	Max 25.0	13.7	0	0	0
Smoke point	mm	Max 25.0	26	> 45	n/a	n/a

Table 19.11. Properties of FT fluids and fossils jet fuel

FT lacks aromatic compounds; thus, it has a high smoke point and therefore blending FT fuel with fossil fuel leads to improvement of a smoke point. However, a certain percentage of aromatics is required in jet fuel according to the standard. This is a limiting factor to use FT fuel for blending with conventional jet fuel. Boiling range is a limiting parameter during FT fuel blending with fossil jet fuel. Initial boiling point is generally similar to conventional jet fuels, thus blending FT with fossil jet fuel will not provide easier evaporation at altitude. However, adding FT fuel may have a positive effect if crude-oil derived jet fuel has a heavy boiling range.

FT fuels are characterized with similar or slightly higher flash point (46°C compered to 44°C of conventional Jet A-1) that may cause some positive effect on blended jet fuels inflammability, improving its fire safety. FT fuel doesn't contain chemically unstable hydrocarbons and heterogenic compounds, which results in higher chemical stability comparing to conventional jet fuels. However, neat FT fuels don't meet the specification limits regarding thermal stability with a pressure drop of 280.0 mm Hg (max. 25 mm Hg acc. to ASTM D7566). FT fuel doesn't contain sulfur compounds that may influence fuel corrosiveness and exhaust gases toxicity. The freezing point curves of CTL blend with fossil fuels are shown in Figure 19.13. Given that the chemical composition of CTL is quite similar to that of HVO, the question arises, whether a comparable depression of freezing point at a certain blend ratio occurs here as well. Unlike HVO, the freezing point of CTL lies significantly below that of the fossil fuel. Therefore, due to the steep progression of the freezing point curves and the relatively rough 10 vol% increment, minor deviations in freezing point are hard to observe. At most, in the case of the first fuel, a slight irregularity in curve progression (10–40 vol% interval) can be spotted. However, these observations surely have no meaning for practical applications. Given that the freezing point of the neat CTL lies well below the upper limit for jet fuel, it can be assumed that any blends of specification compliant fossil kerosene with CTL will meet the requirements of ASTM 7566 regardless of the blend ratio [72].

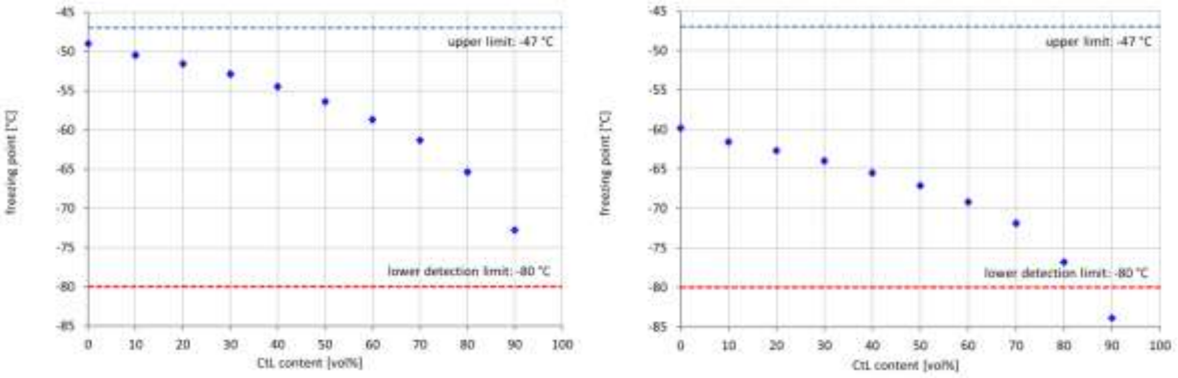


Figure 19.13. Freezing points of neat CTL, fuel 1 and respective blends with 10 – 90 vol% CTL (top) and neat CTL, fuel 2 and respective blends with 10 – 90 vol% HVO (bottom)

3.3.5 Cost, maturity, users

The gasification-FT conversion pathway is the second cheapest, particularly for MSW-derived fuels, with a range of €1.34 to €1.87 per liter. The primary costs attributable to the conversion process come from upfront capital expenses. Operating and input costs are low as a result of relatively low facility overhead, feedstock costs, and operating expenses [73]. A stochastic analysis conducted by Bann et al. (2017) [74] estimated an average baseline value of €0.95/liter for gasification-FT from MSW. Likewise, a harmonized analysis conducted by de Jong (2018) [75] estimated a levelized cost of around €1.80/ liter for gasification-FT of wheat straw.

It is a mature technology once blended up to 50% v.

3.3.5.1 Distributions

Fulcrum invested in Fulcrum Bioenergy in 2014, with 375m gallons off-take agreement over 10 years. Sierra Biorefinery (10m gallons/ year) broke ground May 2018, and the completion is expected in 2020 [76].

3.4 HEFA-Kerosene

3.4.1 Pathway Description

HEFA stands for Hydrotreated Esters and Fatty Acids. Until ASTM certification in 2011 this pathway was usually referred to as HVO, for Hydrotreated Vegetable Oils. As ASTM aims for a generic specification and some feedstocks are solid fats rather than oils, the new acronym HEFA was introduced. The production pathway is similar to the conventional refining of fossil crude oils. As a first step, the bio-material is pre-treated and prepared for the actual production. The prepared material is then reacted with hydrogen (hydro-treatment). This production step removes the oxygen and converts the material into hydrocarbons. These are subsequently cracked and isomerized to yield a mixture of n-alkanes and iso-alkanes which provide the desired good cold flow properties. Subsequent to that, the raw product is distilled and separated into individual products. Possible feedstocks for the HEFA process are more limited than for the FT process. The feedstock is a triglyceride, typically a solid fat or oil. This can be edible oils like palm oil or rapeseed oil [77], which are commercially available in large quantities but can also be oily or fatty wastes, like palm oil press residues or slaughterhouse waste. As the use of edible materials for fuel production purposes is politically contentious, there is a tendency for refiners to increasingly use waste materials. In 2013, waste and residues already accounted for some 52% of the feedstock used by HEFA market leader (Neste Oil [78]), and the corresponding figure for the third quarter of 2016 was 79% [79].

3.4.2 Approval Status

HEFA has been approved by ASTM in July 2011 (*Annex A2*), and is now covered by ASTM D7566. Like normal FT kerosene, it does not contain aromatic compounds and is only certified for use as a blend with a 50% maximum blend ratio [80]. The US company Swift Fuels has proposed producing a blend of HEFA kerosene and aromatics that requires no further blending with conventional kerosene. At the moment, they produce the Swift Jet (Mesitylene and High-Performance Aromatics) used by the AFRL in the FAA CLEEN-II Program [81].

A process using essentially the same feedstock as HEFA is currently pursued by the US company Applied Research Associates. For this process, the terminology "HEFA-SKA" is sometimes used, although the technical process is different from that for HEFA. Minimum content in aromatics related to fuel system seals is one of the limitations to unblended use while it has been identified that there the nvPM emissions lower when aromatics are also lower. Different aerosols, nvPM and shoot combustion profiles from SPK suggest different non-CO_2 effects at high altitude that would need better understood to know the real decarbonisation potential.

3.4.3 Availability and compatibility

There are currently several HEFA refineries worldwide, which typically produce road fuels. The largest operator of HEFA refineries is Neste Oil, with a total annual production capacity of two million tons [82]. Certification of HEFA as a production pathway for aviation kerosene was primarily supported by UOP. The largest HEFA kerosene batch so far has been the 800 tons produced by Neste in 2011 for the Lufthansa burnFAIR in-service evaluation. Some smaller facilities have also been or are producing limited quantities of HEFA kerosene for aviation purposes, particularly the Dynamic Fuels refinery at Geismar, Louisiana, used by SkyNRG to procure fuel for KLM [83]. However, no facilities routinely producing HEFA bio kerosene at large scale currently exist. A recent development has been the start of deliveries of HEFA kerosene to United Airlines at Los Angeles airport. These deliveries are by AltAir Paramount, from a refinery converted to the production of HEFA products, and take place on the basis of a multi-year supply contract between United Airlines and AltAir [84]. The AltAir operation only started regular production in 2016.

HEFA–SPK is anticipated to be the principal aviation biofuel used over the short to medium term. Meeting 2% of annual jet fuel demand from international aviation with SAF could deliver the necessary cost reduction for a self-sustaining aviation biofuel market thereafter. Meeting such a level of demand requires increased HEFA-SPK production capacity. If met entirely by new facilities, approximately 20 refineries would be required. This could entail investment in the region of $10 billion. Although significant, this is relatively small compared to fossil fuel refinery investment of $60 billion in 2017 alone. SAF is currently more expensive than jet fuel, as reported in Figure 19.14 that compare the costs of SAFs with jet kerosene, and this cost premium is a key barrier to their wider use. For HEFA-SPK economies of scale could be realised by refineries designed for continuous production. At current prices and today's fleet average energy efficiency, the additional cost per passenger for a 15% blend of HEFA may not be high in comparison with other elements that influence ticket prices, such as seating class, the time of ticket purchase and taxation. However, due to the competitiveness of the aviation industry, customer price sensitivity is a core consideration for airlines [85].

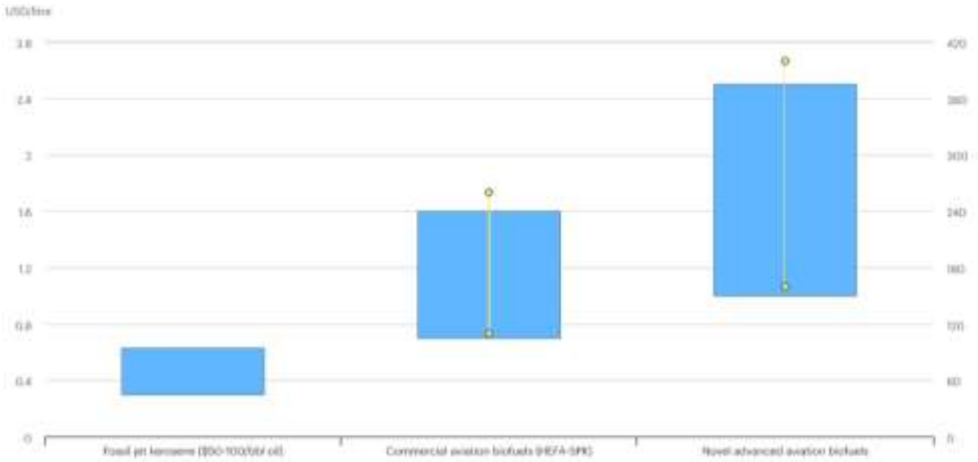
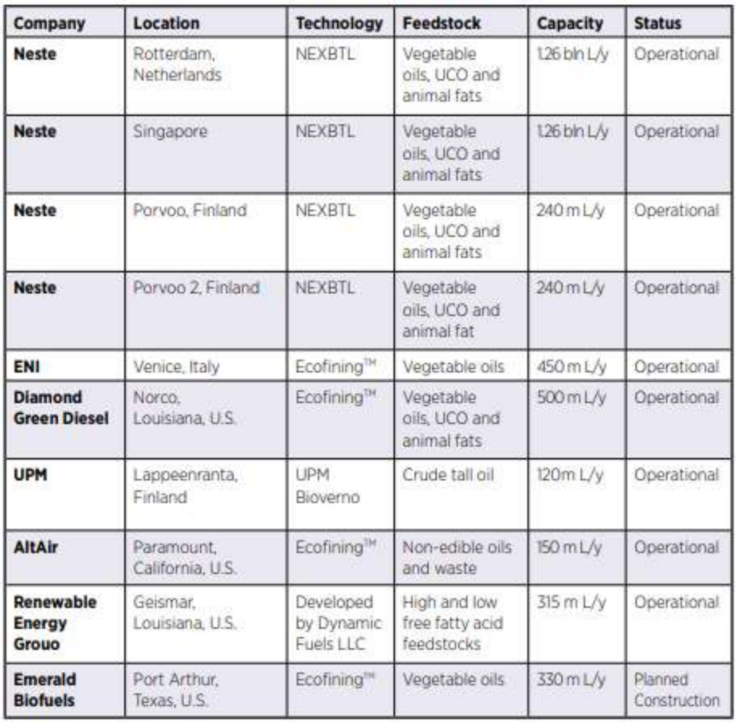


Figure 19.14. Production cost and break-even crude oil price for SAFs compared with fossil jet kerosene, 2019 [85]

Subsidising the consumption of SAF envisaged in the SDS scenario in 2025, around 5% of total aviation jet fuel demand, would require about $6.5 billion of subsidy (based on closing a cost premium of USD 0.35 litre between HEFA-SPK and fossil jet kerosene at USD 70/bbl oil prices). This is far below the support for renewable power generation in 2017, which reached $143 billion. HEFA is an industrially mature technology. In 2016 a production facility in Los Angeles (CA, USA) had started continuous production of HEFA, able to produce about 30,000 t of HEFA-SPK per year [59]. In Table 19.12 are reported the companies that produce HEFA fuels.



Company	Location	Technology	Feedstock	Capacity	Status
Neste	Rotterdam, Netherlands	NEXBTL	Vegetable oils, UCO and animal fats	1.26 bln L/y	Operational
Neste	Singapore	NEXBTL	Vegetable oils, UCO and animal fats	1.26 bln L/y	Operational
Neste	Porvoo, Finland	NEXBTL	Vegetable oils, UCO and animal fats	240 m L/y	Operational
Neste	Porvoo 2, Finland	NEXBTL	Vegetable oils, UCO and animal fat	240 m L/y	Operational
ENI	Venice, Italy	Ecofining™	Vegetable oils	450 m L/y	Operational
Diamond Green Diesel	Norco, Louisiana, U.S.	Ecofining™	Vegetable oils, UCO and animal fats	500 m L/y	Operational
UPM	Lappeenranta, Finland	UPM Bioverno	Crude tall oil	120m L/y	Operational
AltAir	Paramount, California, U.S.	Ecofining™	Non-edible oils and waste	150 m L/y	Operational
Renewable Energy Grouo	Geismar, Louisiana, U.S.	Developed by Dynamic Fuels LLC	High and low free fatty acid feedstocks	315 m L/y	Operational
Emerald Biofuels	Port Arthur, Texas, U.S.	Ecofining™	Vegetable oils	330 m L/y	Planned Construction

Table 19.12. Companies producing HEFA fuels (mainly renewable diesel)

It is a "drop-in" fuel and can be used in Turbofan powertrain technology.

3.4.4 Chemical Properties and risks

SPK is less energy-dense than a conventional jet, but it has a higher specific energy. It allows a reduction in fuel flow (kg/sec) and a small reduction in the engine exhaust gas temperature gauge (EGT). The basic bio-oils reacts with water under high temperature and pressure conditions. Could be used without blending.

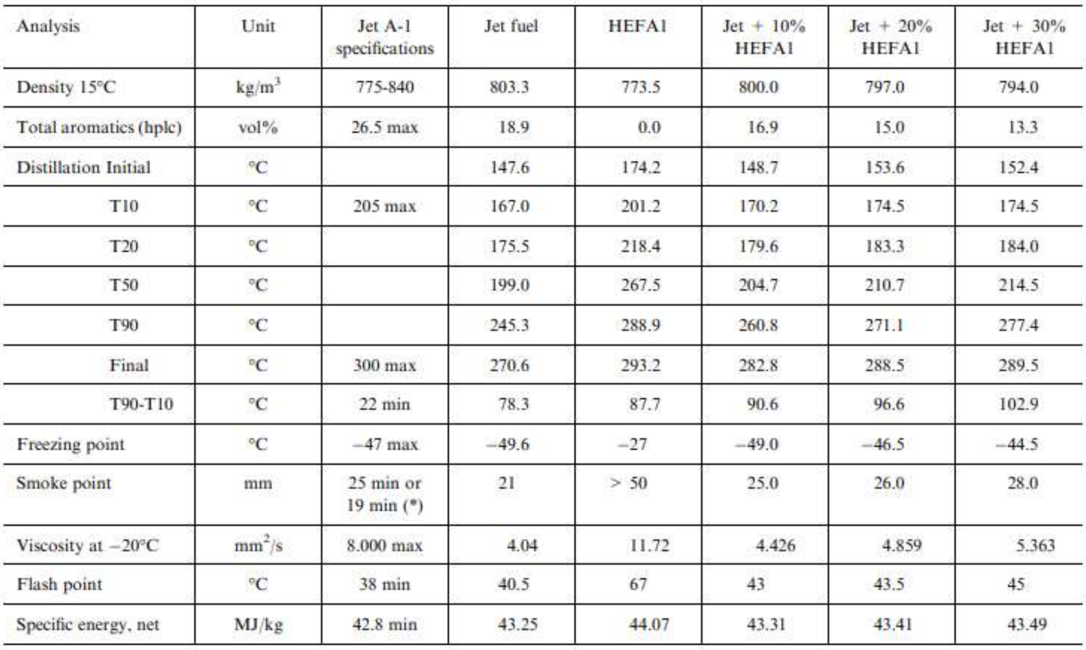
HEFA-SPK is produced by reacting an oil or fat-based feedstock with hydrogen. The primary feedstock are triglycerides, which are building blocks of fats and oils. They are derived from vegetables, animals, or waste oil found in nature. To account for the presence of oxygen and unsaturated carbon bonds, both deoxygenation and hydrogenation process steps are required to produce a saturated hydrocarbon fuel. With this conversion process, up to 50% by volume of the HEFA-SPK component can be blended with conventional Jet A, or Jet A-1 fuel.

A specific HEFA meeting the ASTM D7566 specifications has been made to evaluate the potential of such a product being blended at a high ratio (75%) in Jet A-1. The level of hydroisomerisation applied to a hydroprocessed oil improves the low-temperature properties and can be considered different strategies [86]:

- Case 1: aim for a reduced HEFA incorporation ratio for HEFA with poor cold flow properties (target: freezing point around mines 20 °C). Blends of this HEFA production (called HEFA1) with a conventional Jet A-1 prepared with 10%, 20% and 30% volume of HEFA1;
- Case 2: aim for a larger HEFA incorporation ratio than permitted by ASTM D7566: one blend of HEFA production (called HEFA2) with the same conventional Jet A-1, prepared with an incorporation ratio of 75% volume of HEFA2.

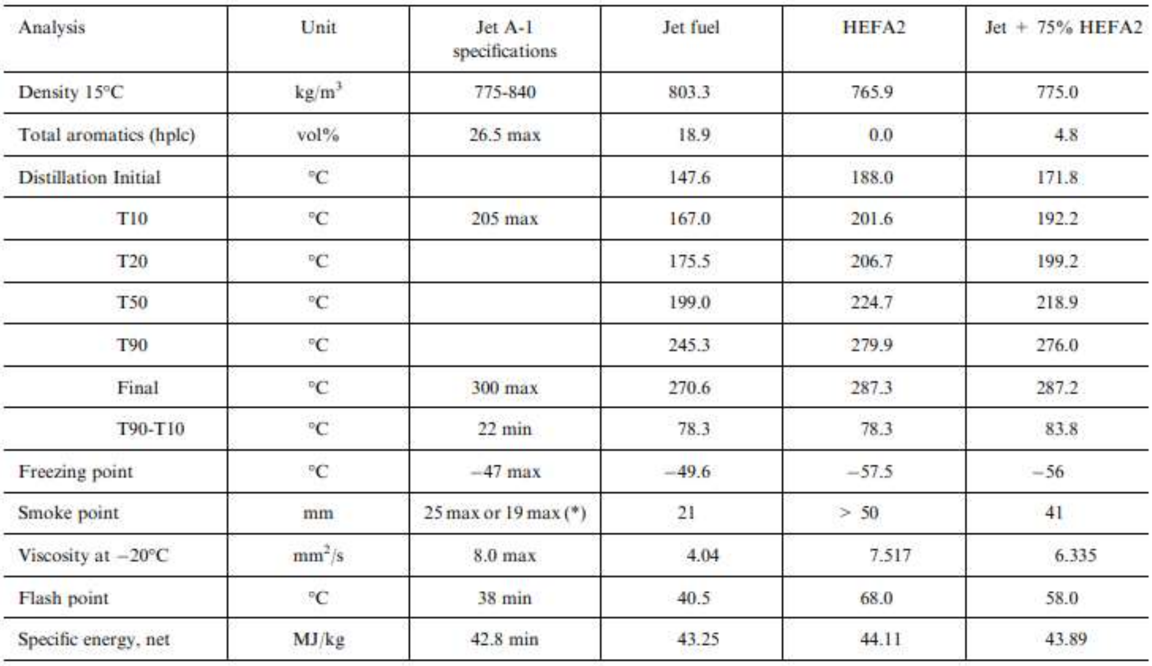
Tables 19.13 and 19.14 reports the characteristics of blends of Jet fuel A with HEFA1 and HEFA2, respectively. The main conclusions from the analysis are as follows:

- all blends have densities that match predicted densities, within method precision – the blending is reliably linear by volume, and the mixing steps have produced homogeneous blends;
- all the blends met the current ASTM specifications except for freezing point (for some blends with HEFA1) and aromatic content (blend with HEFA2);
- blending HEFA in conventional fuels produces substantial increases (improvements) in smoke point;
- all the HEFA blend fuels have Lower Heating Values (LHV) higher than the minimum limit imposed by the specification and the blending of HEFA in conventional jet fuel resulted in an increase of mass LHV as expected from the component data. If we focus on cold flow properties, the main results obtained for freezing points are presented in Figure 15. The main conclusions are:
    - HEFA1 blending ratio is limited by the freezing point. Nevertheless, significant blending ratios can be obtained before reaching this limit. With Jet fuel A this maximum blending ratio has been estimated to be 16%volume. Nevertheless, this point has to be further checked and does not represent a fixed value; there can be measurement uncertainties with freezing points of highly hydro processed fuels and the maximum ratio will also be very dependent on the freezing point of the crude oil-based component;
    - HEFA2 can be blended at any concentration without any limitation on the freezing point, due to the very good freezing point of the pure product;
    - with Jet fuel A, the blend freezing point behaviour for both HEFA seems to be close to linearity, which could mean that the maximum blending ratio could be easily calculated according to pure product properties. The blending ratio of these HEFA could consequently be adjusted, taking into account the initial freezing point of the conventional Jet A-1. Nevertheless, this point still has to be confirmed using other Jet A-1, to check that this linearity is not dependent on Jet A-1 composition. As far as viscosity is concerned, the best fit to the results is not always linear, particularly for HEFA1, a fuel whose freezing point is only slightly lower than the mines 20°C test condition. Nevertheless, starting from a viscosity of 4 mm^2/s for the pure Jet A-1 (which is representative of typical Jet A-1 available on the market), a blend of 75% HEFA2 still stays below the specification viscosity limit. Moreover, all the blends made with HEFA2 are expected to pass the ASTM D7566 viscosity limit (8 mm^2/s at -20°C). These results are presented in Figure 19.16.



Analysis	Unit	Jet A-1 specifications	Jet fuel	HEFA1	Jet + 10% HEFA1	Jet + 20% HEFA1	Jet + 30% HEFA1
Density 15°C	kg/m^3	775-840	803.3	773.5	800.0	797.0	794.0
Total aromatics (hplc)	vol%	26.5 max	18.9	0.0	16.9	15.0	13.3
Distillation Initial	°C		147.6	174.2	148.7	153.6	152.4
T10	°C	205 max	167.0	201.2	170.2	174.5	174.5
T20	°C		175.5	218.4	179.6	183.3	184.0
T50	°C		199.0	267.5	204.7	210.7	214.5
T90	°C		245.3	288.9	260.8	271.1	277.4
Final	°C	300 max	270.6	293.2	282.8	288.5	289.5
T90-T10	°C	22 min	78.3	87.7	90.6	96.6	102.9
Freezing point	°C	−47 max	−49.6	−27	−49.0	−46.5	−44.5
Smoke point	mm	25 min or 19 min (*)	21	> 50	25.0	26.0	28.0
Viscosity at −20°C	mm^2/s	8.000 max	4.04	11.72	4.426	4.859	5.363
Flash point	°C	38 min	40.5	67	43	43.5	45
Specific energy, net	MJ/kg	42.8 min	43.25	44.07	43.31	43.41	43.49

Table 19.13. Characteristics of blends of Jet fuel A with HEFA1. (*) and Naphthalenes < 3.0 wt% (D1840)



Analysis	Unit	Jet A-1 specifications	Jet fuel	HEFA2	Jet + 75% HEFA2
Density 15°C	kg/m^3	775-840	803.3	765.9	775.0
Total aromatics (hplc)	vol%	26.5 max	18.9	0.0	4.8
Distillation Initial	°C		147.6	188.0	171.8
T10	°C	205 max	167.0	201.6	192.2
T20	°C		175.5	206.7	199.2
T50	°C		199.0	224.7	218.9
T90	°C		245.3	279.9	276.0
Final	°C	300 max	270.6	287.3	287.2
T90-T10	°C	22 min	78.3	78.3	83.8
Freezing point	°C	−47 max	−49.6	−57.5	−56
Smoke point	mm	25 max or 19 max (*)	21	> 50	41
Viscosity at −20°C	mm^2/s	8.0 max	4.04	7.517	6.335
Flash point	°C	38 min	40.5	68.0	58.0
Specific energy, net	MJ/kg	42.8 min	43.25	44.11	43.89

Table 19.14. Characteristics of blends of Jet fuel A with HEFA2. (*) and Naphthalenes < 3.0 wt% (D1840)

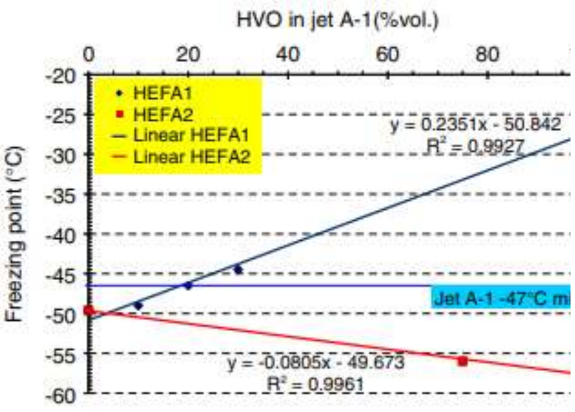


Figure 19.15. Impact of HEFA content on final blend freezing point for blends in Jet fuel A.

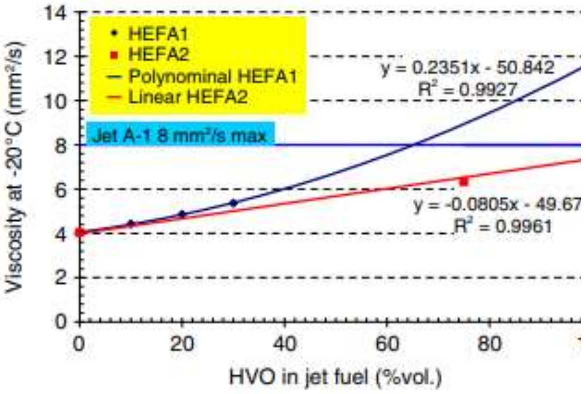
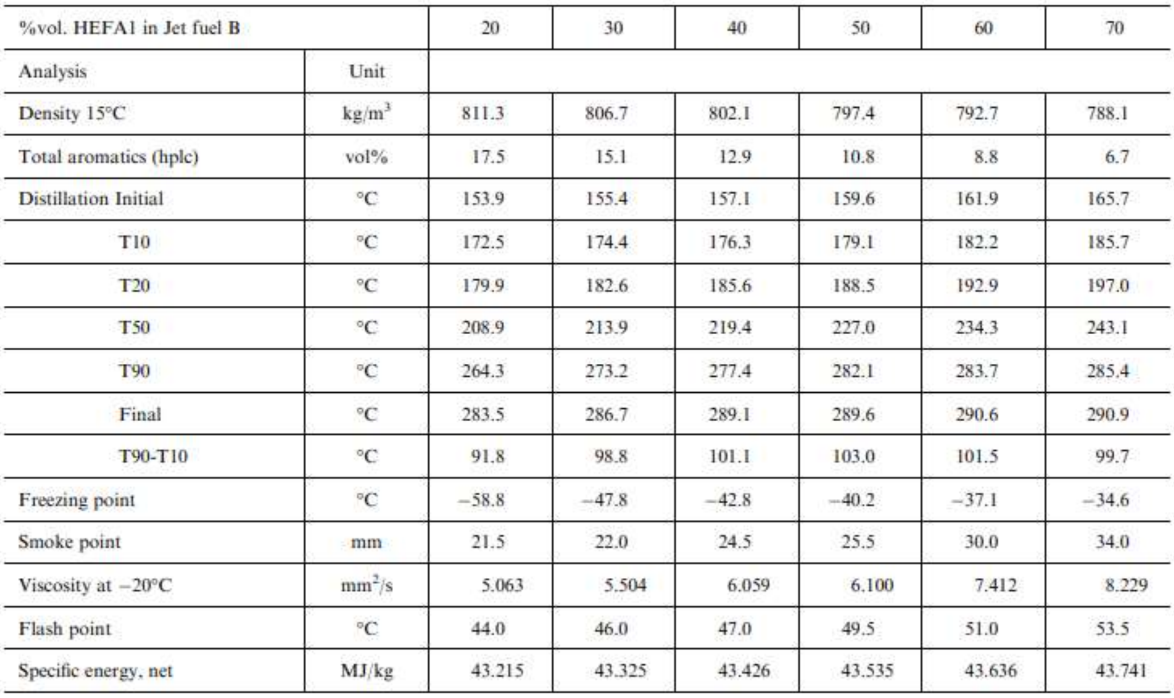


Figure 19.16. Impact of HEFA in Jet fuel A blending rate on final blend viscosity at -20 ºC.

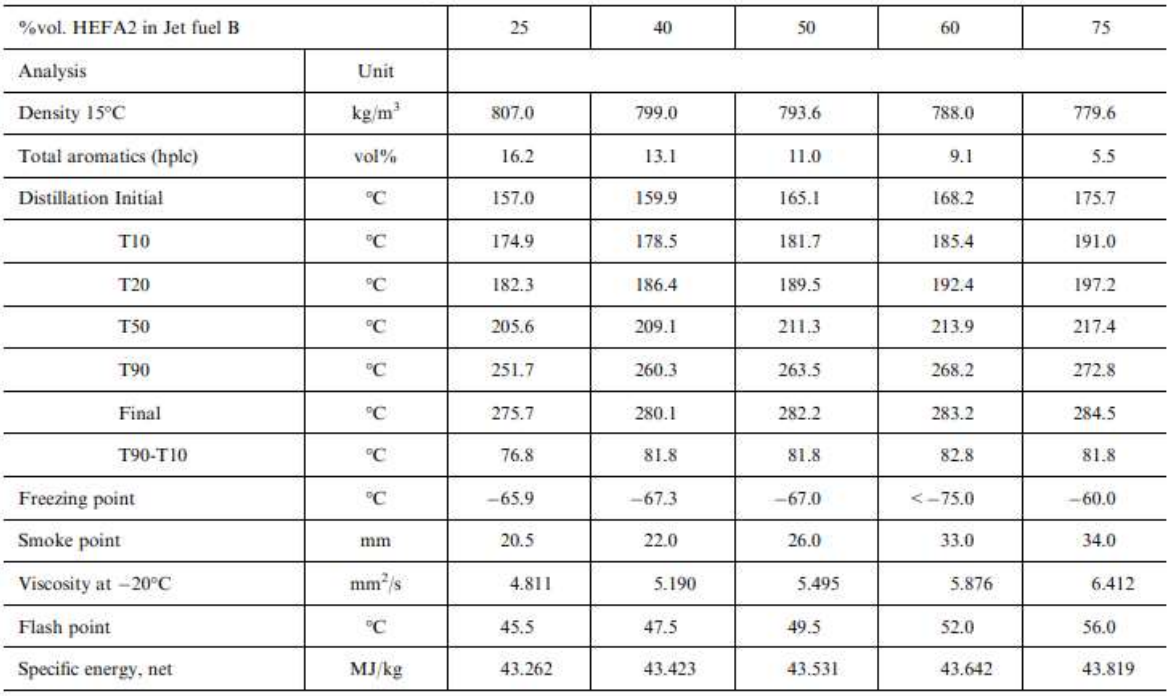
Following the blend production and test results discussed above, blends were made with another Jet A-1, Jet fuel B, that has excellent low-temperature results. It has a significantly better freeze point than average and represents a close to "best case" blend partner for a poorer freezing point HEFA component. Its freezing point of mines 64.9 °C is the highest reported for the fuel; analysts sometimes prefer not to determine freezing points accurately below an arbitrary temperature in the range mines 60 to mines 75 °C as this takes more time and/or more effort to control such low temperatures. With this greater than 15 °C improvement in freezing point compared to Jet fuel A, it was possible to consider higher levels of HEFA in the two sets of blends created. Table 19.15 and 19.16 summarises data for the seven blends created with HEFA1 and provides data for the 5 blends with HEFA2.

Table 19.16 shows that the HEFA2 blends follow an approximately linear by volume behaviour while the HEFA2 blends are better fitted by a polynomial fit. HEFA1 blends above 63% volume fail the 8 mm^2 /s limit, while all HEFA2 blends pass. The limiting factor for HEFA2 blends would be set by the 8.8% volume total aromatics by HPLC method if the 50% maximum were not applied. In summary, the maximum volume percentages of the HEFA in the two Jet A-1. Given that in a country using Jet A rather than Jet A-1 there may not be many very good freezing point fuels like Jet fuel B, this does indicate that HEFA1 will probably have an upper limit of 30 to 35% volume; more typically HEFA1 be limited to values in the range 15 to 20% volume for Jet A-1 production.



%vol. HEFA1 in Jet fuel B		20	30	40	50	60	70
Analysis	Unit						
Density 15°C	kg/m^3	811.3	806.7	802.1	797.4	792.7	788.1
Total aromatics (hplc)	vol%	17.5	15.1	12.9	10.8	8.8	6.7
Distillation Initial	°C	153.9	155.4	157.1	159.6	161.9	165.7
T10	°C	172.5	174.4	176.3	179.1	182.2	185.7
T20	°C	179.9	182.6	185.6	188.5	192.9	197.0
T50	°C	208.9	213.9	219.4	227.0	234.3	243.1
T90	°C	264.3	273.2	277.4	282.1	283.7	285.4
Final	°C	283.5	286.7	289.1	289.6	290.6	290.9
T90-T10	°C	91.8	98.8	101.1	103.0	101.5	99.7
Freezing point	°C	−58.8	−47.8	−42.8	−40.2	−37.1	−34.6
Smoke point	mm	21.5	22.0	24.5	25.5	30.0	34.0
Viscosity at −20°C	mm^2/s	5.063	5.504	6.059	6.100	7.412	8.229
Flash point	°C	44.0	46.0	47.0	49.5	51.0	53.5
Specific energy, net	MJ/kg	43.215	43.325	43.426	43.535	43.636	43.741

Table 19.15. Properties of blends of HEFA1 with Jet fuel B



%vol. HEFA2 in Jet fuel B		25	40	50	60	75
Analysis	Unit					
Density 15°C	kg/m^3	807.0	799.0	793.6	788.0	779.6
Total aromatics (hplc)	vol%	16.2	13.1	11.0	9.1	5.5
Distillation Initial	°C	157.0	159.9	165.1	168.2	175.7
T10	°C	174.9	178.5	181.7	185.4	191.0
T20	°C	182.3	186.4	189.5	192.4	197.2
T50	°C	205.6	209.1	211.3	213.9	217.4
T90	°C	251.7	260.3	263.5	268.2	272.8
Final	°C	275.7	280.1	282.2	283.2	284.5
T90-T10	°C	76.8	81.8	81.8	82.8	81.8
Freezing point	°C	−65.9	−67.3	−67.0	< −75.0	−60.0
Smoke point	mm	20.5	22.0	26.0	33.0	34.0
Viscosity at −20°C	mm^2/s	4.811	5.190	5.495	5.876	6.412
Flash point	°C	45.5	47.5	49.5	52.0	56.0
Specific energy, net	MJ/kg	43.262	43.423	43.531	43.642	43.819

Table 19.16. Properties of blends of HEFA2 with Jet fuel B

As shown, Jet fuel B has extended the range over which HEFA1 can be blended and still achieve Jet A-1 requirements. Based on the fit the highest level of HEFA1 to pass the Jet A-1 freezing point would be about 35% volume (or 30% based on actual data points). This is higher than seen with Jet fuel A. If only a Jet A freezing point needed to be met (mines 40ºC maximum), the fit and actual data points would both suggest upper limits of 51% volume. For the HEFA2 blends, the results are best described as "scattered"; all the HEFA2 blends in

Jet fuel B have very good freezing points, with no limits on HEFA2 content being caused by freeze point. Viscosity data repeat the patterns seen with Jet fuel A:

HEFA are basically composed of alkanes, and the content of aromatics is very low. Although high contents of aromatics will increase the formation of soot, aromatics are necessary (until a certain level) to avoid leaks in the seals of fuel systems. The content of aromatics in jet fuels for engine certification is typically between 15 and 23 vol.%. Because of that HEFA fuel should be blended with commercial fuels to reach the targeted level. Typical hydrocarbon composition of HEFA fuels is presented in Table 19.17.

Fuel sample	n-alkane	Iso-alkane	olefin	naphthene	aromatic	Total
HEFA from camelina1	11.7	87.3	0.1	0.9	-	100
HEFA from cameina 2	9.1	89.4	0.1	0.7	-	99.3
HEFA from tallow	12.8	86.9	0.1	0.3	-	100.1

Table 19.17. Hydrocarbon composition of HEFA fuels

At the same number of carbon atoms, the density of aromatics is higher than the density of naphthenes, which is higher than the density of paraffins. Thus, the absence of aromatics and content of more iso-alkanes in HEFA provide lower density comparing to conventional jet fuel (Table 19.18). This also results in higher energy content per unit of mass. The ratio of HEFA's density and mass-energy content provides slightly lower energy content per unit of volume compared to conventional jet fuels. Experimental results show that blending HEFA with conventional jet fuels provides improvement of mass-energy content of blends. Experimental results obtained on test jet engine show reduction of fuel consumption (up to 10%) and overall thrust-specific fuel consumption (up to 4%) of the engine that is explained by the higher mass-energy content and lower density of HEFA. Absence of aromatics in HEFA allows blending with conventional jet fuel with consequent reduction of aromatics, which are known to be the reason for PM emissions in exhaust gases and are strictly limited in fuel. Absence of aromatics and high content of alkanes (mainly iso-alkanes) provides better combustion properties, which can be proved by high values of smoke point of HEFA. However, a certain percentage of aromatics is required in jet fuel according to the standard. This is a limiting factor to use HEFA fuel for blending with conventional jet fuel.

Property	Units of measurement	Limits ASTM D1655/D7566	Results			
			Jet A-1	HEFA 1	HEFA 2	HEFA 3
Density at 15 °C	kg/m^3	775.0/840.0	788.0	779.9	773.5	765.9
Heat of combustion	MJ/kg	Min 42.80	43.45	43.70	44.07	44.11
Aromatics	% (V/V)	Max 25.0	15.8	9.4	0	0
Smoke point	mm	Max 25.0	21	n/a	> 50	> 50

Table 19.18. Properties of HEFA fuel and fossil jet fuel

Densities (ρ) of the HVO blends depend linearly on blend ratio. Since ρ of neat HVO (756.7 kg/m^3; required: 730 – 770 kg/m^3) lies below the lower limit for jet fuels and blends (775 kg/m^3), the maximum blend ratio regarding HVO content is limited. The process of fats and fatty acids conversion into HEFA initially results in synthetic hydrocarbons of diesel fuel fraction (with boiling range 280 ℃ +). Increasing severity of isomerization leads to conversion of diesel-like hydrocarbons into jet fuel hydrocarbons and later into gasoline-like hydrocarbons. Reaching optimal yields of HEFA during the production process, they are usually characterized by heavier fractional composition comparing to conventional jet fuel. HEFA are characterized with higher initial boiling points as well as final boiling points, at the same time being within the standard limits.

The ASTM D1655 requirement concerning flashpoint is a minimum of 38 °C. This is a very important property because it is directly related to fire safety when handling the fuel. Having heavier hydrocarbon composition and, thus, fractional composition, HEFA possess higher flashpoint. This product demonstrates better fire safety comparing to conventional jet fuels. For discussion of flashpoint, HVO blends of two fuels have been chosen. HVO exhibits a flashpoint of 42.0 °C which lies close to fuel (40.5 °C).

The class of oxygenated compounds that stands out is phenols, followed by alcohols. Many phenols are approved for use as antioxidants in jet fuel; however, their presence in the fuel is related to thermal and oxidative deposit. HEFA fuels almost don't contain oxygenated compounds (except small amounts of alcohol). Due to this HEFA typically has total acid number values lower comparing to conventional jet fuels [87]. Due to the processes of hydrogenation and isomerization HEFA doesn't contain chemically unstable hydrocarbons and heterogenic compounds, which results in higher chemical stability comparing to conventional jet fuels. The dependency of the freezing point on blend ratio will be discussed using two examples where (i) freezing points of the jet fuel and HVO only slightly differ and (ii) freezing points of the jet fuel and HVO differ significantly.

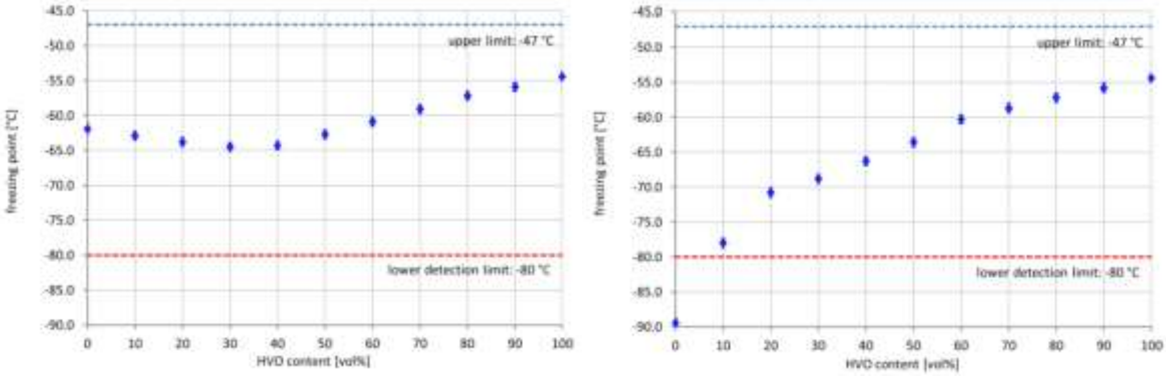


Figure 19.17. Freezing points of neat HVO, fuel 1 and respective blends with 10 – 90 vol% HVO (left) and neat HVO, fuel 2 and respective blends with 10 – 90 vol% HVO (right)

Upon blending fuels (freezing point: -61.9 °C) with HVO (freezing point: -54.4 °C), an initial lowering of the freezing point to a minimum of -64.5 °C (HVO content: 30 vol%) was observed, although HVO exhibits a higher freezing point than the jet fuel. The resulting curve remotely resembles the phase diagram of an eutectic mixture. Nevertheless, comparing the observed behaviour to that of an eutectic mixture is doubtful because the investigated blends are complex multicomponent systems and, furthermore, because of the definition of the freezing point for aviation fuels. The freezing point of fuel (-89.4 °C) is far below that of HVO. Because of this pronounced difference, the initially observed effect of depression of the freezing point for the blends cannot be observed. Yet, the slope of the resulting freezing point vs blend ratio curve shows deviance in the 20-50 vol% HVO interval. In case of the blends with the other fossil fuels, depression of the freezing point at a certain blend ratio can be observed as well. As the examples in Figure 19.17 (left) show, the effect is all the more pronounced, the more similar the freezing points of fossil fuel and HVO are. With a wear scar diameter (wsd) of 0.906 mm neat HVO exceeds the upper limit of 0.85 mm for Jet A-1 and blends. To discuss the influence of HVO on lubricity, blends with Jet A-1 samples have been chosen. Fuel offers the best lubricity among the fuels used in this study (wsd = 0.645 mm), another fuel the worst (wsd = 0.751 mm). Figure 19.17 (right) shows the dependence of lubricity on blend ratio. In the case of the first fuel, an expected worsening in lubricity by increasing the amount of HVO is observable. Yet, from the data, no exact correlation between HVO content and lubricity can be drawn. For HVO-blends with second fuel lubricity vs blend, the ratio shows no clear trend as well. Yet, the possible worsening of lubricity upon increasing the amount of HVO seems to be compensated by fossil fuel, even for high HVO contents. As already mentioned, this observation could be explained by lubricity being a surface-related effect, which is strongly influenced by the presence of minor compounds [72].

3.4.5 Cost, maturity, users

HEFA is not fundamentally different from conventional refining, and the investment required for a HEFA refinery is on the same order of magnitude as that for a conventional refinery. Operating costs per ton of product are currently still somewhat higher than for conventional kerosene but are expected to come down to the same level. However, the price of the feedstock material is typically a good deal 20 higher than the price of crude oil and has typically exceeded even the price of conventional kerosene. The expected capital costs for new renewable diesel and HEFA production facilities are expected to be in the range of several hundred million euros [88]. These fuels cost, on average, €1/liter to produce substantially less than other AJF pathways. However, HEFA production costs are unlikely to decline further in the future because they are dominated by the high cost of feedstock for vegetable and waste oils [73]. A stochastic analysis conducted by Bann et al. (2017) [74] estimated an average baseline value of €0.87/liter for the HEFA pathway. Likewise, a harmonized analysis conducted by de Jong (2018) [75] estimated a levelized cost of around €1/liter for used cooking oil (UCO) HEFA.

Mature technology once blended up to 50% v. Neste is the largest producer of HEFA, with a production capacity of 2.7 million tons/21.2 million barrels [89].

3.4.6 Distribution

In Figure 19.18 Neste cooperation with leading aviation brands for the distribution of HEFE biofuel [89] are reported.

Figure 19.18. Neste cooperation with leading aviation brands

3.5 SIP Kerosene

3.5.1 Pathway Description

SIP stands for Synthesized Iso-Paraffins produced from Hydroprocessed Fermented Sugars. SIP is the acronym under which this fuel has been certified by ASTM. Prior to ASTM certification, the pathway used to produce SIP has been referred to as DSHC (Direct Sugar to Hydrocarbons).

The production of SIP fuel consists of two major steps. In the first step, microorganisms are used to ferment sucrose and produce farnesene, which is a branched C15 alkene with four double bonds. In the next step, farnesene is converted into the respective alkane, a molecule with no double bonds, by reacting hydrogen with farnesene through a catalytic bed. The resulting product is a saturated alkane, farnesane, which in the next step is then purified by distillation to produce an aviation-grade. The final resulting SIP fuel ideally consists purely of farnesane, although in practice traces of remaining farnesene and olefins (partially hydrogenated farnesene) may be present in the final product as well as some other trace by-products [90]. This is a unique molecule vs the incumbent what is more complex. It has reported that the 10% blend ratio could be difficult to be higher. It produces lower pollutants (PMs up to -60%, and S) and potential lower NOx emissions.

Although SIP fuel is currently produced using sugar from sugarcane as a feedstock, it can potentially be produced from all kinds of plant sugars, including cellulosic sugars [91]. It is therefore conceptually possible to eventually produce SIP fuel from woody biomass and avoid conflict with food use.

3.5.2 Approval Status

SIP fuels were approved as a kerosene blendstock in June 2014, and are now covered by *Annex A3* of ASTM D7566. Unlike FT- and HEFA fuels, SIP fuels are only approved to a maximum blend ratio of 10% [92]. The lower maximum blend ratio is due to the SIP fuel solely consisting of one single compound, namely farnesane, although all the tests were also performed at 20% incorporation and show no deviation as compared to conventional jet fuel.

3.5.3 Availability and compatibility

There is currently only one producer of SIP kerosene blendstock, which is Total/Amyris. It is used at Lab'line demonstration project and some Airbus delivery flights, but not used on a continuous basis. It can be used blended with fossil jet fuel up to 10% v/v [43]. The technology is at an early commercial stage with low availability. It is still needed an integrated, fuel-centric research, investigating the effects of fuel composition on operations and emissions, where fuel is varied for otherwise identical conditions, and the effects identified. Such research should include fuels outside the current experience base for fossil fuels, to identify risks and opportunities.

It can be used in Turbofan powertrain technology.

3.5.4 Chemical properties and risks

ASTM revised its jet fuel standard, paving the way for airlines to use Synthesized Iso-Paraffin (SIP) farnesane (isoalkane 2,6,10-trimethyl dodecane) (generically, Direct Sugar to Hydrocarbon, DSHC) as a jet fuel component in commercial airlines globally [93]. The revised standard, D7566, developed by ASTM Committee on Petroleum Products, Liquid Fuels, and Lubricants, now includes the use of renewable farnesane as a blending component in jet fuels for commercial aviation in blends of up to 10% (Figure 19.19).

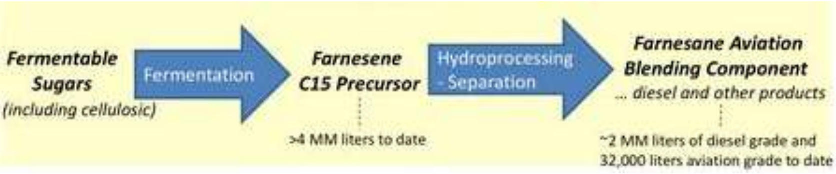


Figure 19.19. Renewable farnesane as a blending component in jet fuels

Farnesane can reduce greenhouse gas (GHG) emissions by up to 80% compared to petroleum fuels. When blended with Jet A/A1 fuel at 10%, farnesane can also reduce particulate matter emissions, decreasing pollution near airports and major metropolitan areas. There are two pathways to produce jet fuel from intermediate sugar feedstocks. First is via catalytic upgrading of sugars and sugar intermediates to hydrocarbons [94, 95]. Second is the biological conversion of sugars and sugar intermediates to hydrocarbons. The ASTM Standard D7566 includes five annexes with approved conversion processes for the production of alternative aviation fuels (AAF).

SIP Kerosene are synthetic hydrocarbons that are produced by hydroprocessing and fractionation of farnesene derived from the fermentation of sugars. This conversion is also known as direct sugars to hydrocarbons (DSHC). Possible sugar feedstocks can include sugar cane and beets, corn grain, and pretreated lignocellulosic biomass. The sugars are aerobically fermented into a farnesene intermediate using yeast cells. To obtain farnesene, the intermediate is separated into a solid and liquid part and further into an oil and aqueous phase using centrifugation. With this conversion process, up to 10% by volume of the SIPHFS component can be blended with conventional Jet A or Jet A-1 fuel. The general process methodology for biological conversion of biomass to jet fuel is shown in Figure 19.20 where biomass is first pretreated, undergoes enzymatic hydrolysis, and the solubilized C_5 and C_6 sugars are separated and concentrated. After concentration, the hydrolysate is sent to biological conversion (either aerobic or anaerobic), where the intermediate hydrocarbon product is produced. The product is separated and can undergo finishing steps such as oligomerization and hydrotreating to create jet fuel.

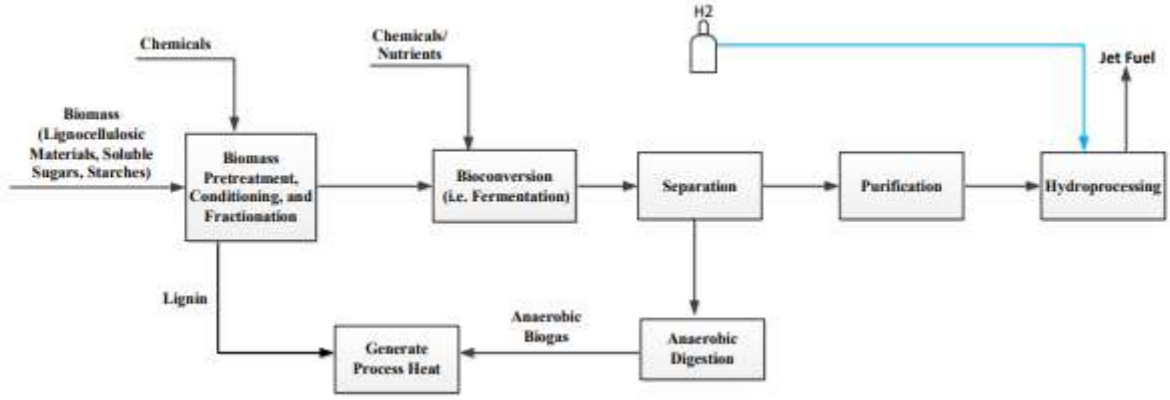
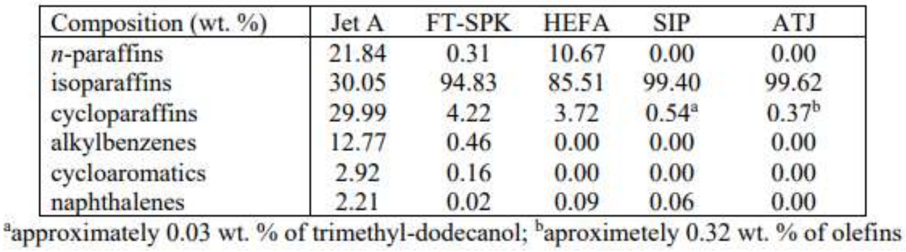


Figure 19.20. Biological conversion of sugar-to-jet fuel

The life-cycle GHG emissions are around 15 gCO_2e/MJ, an approximate 82% reduction compared with conventional Jet A/A-1 fuels. However, sugarcane could induce land-use change, which was not considered in the study above. The GHG emissions associated with sugarcane production and transport, according to the study, are primarily dominated by farm input and the emissions of N_2O from the soil, which contribute 84 gCO_2e/MJ.



Composition (wt. %)	Jet A	FT-SPK	HEFA	SIP	ATJ
n-paraffins	21.84	0.31	10.67	0.00	0.00
isoparaffins	30.05	94.83	85.51	99.40	99.62
cycloparaffins	29.99	4.22	3.72	0.54[a]	0.37[b]
alkylbenzenes	12.77	0.46	0.00	0.00	0.00
cycloaromatics	2.92	0.16	0.00	0.00	0.00
naphthalenes	2.21	0.02	0.09	0.06	0.00

[a]approximately 0.03 wt. % of trimethyl-dodecanol; [b]aproximetely 0.32 wt. % of olefins

Table 19.19. Chemical Composition of Jet A and Fuel Blending Components

The SIP fuel consists, except for traces of some alkyl cycloalkanes, almost exclusively of a single compound, namely 2,6,10-trimethyl dodecane – farnesane. In this respect, Farnesane differs fundamentally from most of the other synthetic fuels, which are complex mixtures of iso-alkanes and in part also contain aromatics [72]. Typical hydrocarbon composition of SIP fuel (farnesane) is presented in Table 19.20.

Fuel sample	n-alkane	Iso-alkane	olefin	naphthene	aromatic	Total
SIP (Farnesane)	-	96.4	0.2	1.3	-	97.9

Table 19.20. Typical hydrocarbon composition of SIP fuel

Unlike other synthetic fuels, whose density range is 730 – 770 kg/m^3, SIP has a density of 773.1 kg/m^3 and slightly below the lower limit for blends (775 kg/m^3) (Table 19.21). Depending on conventional jet fuel's density SIP may be easily blended, meeting the requirements of standards.

Property	Units of measurement	Limits ASTM D1655/D7566	Results	
			Jet A-1	SIP
Density at 15 °C	kg/m^3	775.0/840.0	795.0	773.1
Heat of combustion	MJ/kg	Min 42.80	43.39	44.0
Aromatics	% (V/V)	Max 25.0	13.7	0
Smoke point	mm	Max 25.0	26	n/a

Table 19.21. Properties of SIP fuel

Measurements show that there exists a precise linear relationship between density and Farnesane content of the blend (Figure 19.21). The density of Farnesane blends can, therefore, readily be calculated from the values of the neat blend components and the blend ratio. Unlike neat Fischer-Tropsch or HEFA kerosene, whose specified density range is 730 – 770 kg/m³, neat farnesane has a density of 773.1 kg/m³ and therewith slightly below the lower limit for blends (775 kg/m³). Except in the case of an extremely low-density fossil jet fuel, density is no constraint for the maximum blend ratio. For the investigated fuels, blends with Farnesane content up to ca. 90 vol% meet the specification requirement for density.

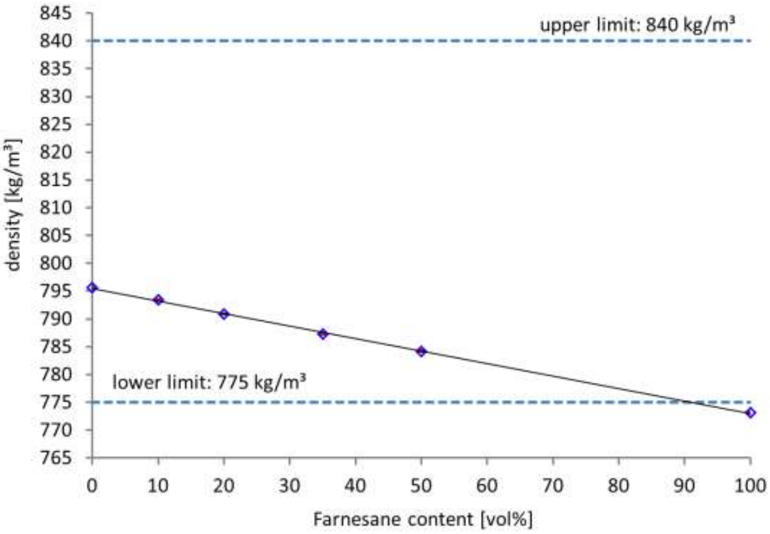


Figure 19.21. Density of fuel 100, Farnesane and blends with 10, 20, 35 and 50 vol% Farnesane

Heat of combustion per unit of mass of SIP is similar or slightly higher compared to fossil jet fuels. However, it has a lower heat of combustion per unit of volume, a decrease in the amount of aromatic compounds, as well as decreasing density, tends to raise the heat of combustion. If the distillation curves are shifted to higher temperatures, the heat of combustion raises, too (Figure 19.22).

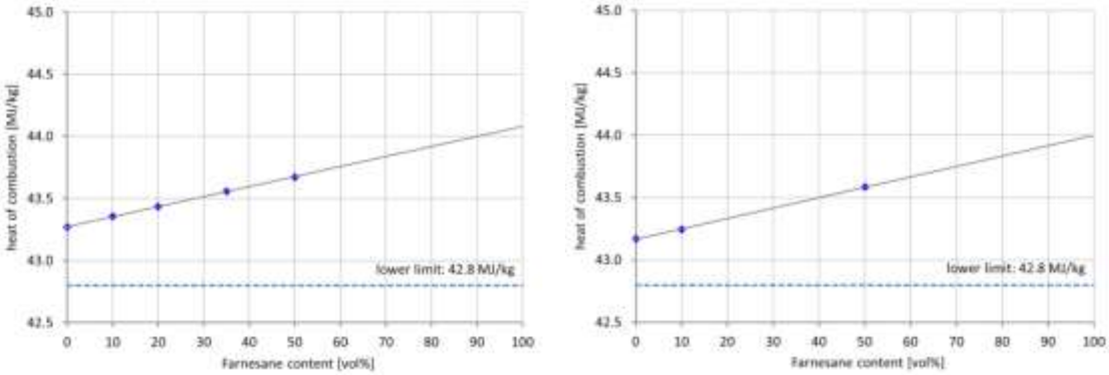


Figure 19.22. Heat of Combustion of Farnesane blends with fuel 1 (left) and fuel 2 (right)

Absence of aromatics in SIP allows blending with conventional jet fuel with consequent reduction of PM emissions in exhaust gases. However, a certain percentage of aromatics is required in jet fuel according to the standard. This is a limiting factor to use SIP fuel for blending with conventional jet fuel. The smoke point of neat Farnesane is too high to be accurately measured. In case of blends with fossil jet fuel an increase and therefore, an improvement of smoke point upon increasing the amount of Farnesane in the blend is observed. Neat farnesane has a boiling point of 247°C which lies close to the final boiling point of the Jet A-1 fuels. Distillation profiles of blended jet fuels with SIP will be shifted to higher temperatures upon increasing the amount of farnesane in the blend. Blending SIP the fuel lowers the vapour pressure of the blend, which is reflected by the increase in boiling temperature. SIP fuel presents a high value of a flashpoint of around 100ºC. This is due to the composition of this fuel, which has basically only one compound, with high boiling point. SIP blends with Jet A-1 will exhibit higher flash points compared to fossil Jet A-1 because the vapour pressure of the mixture will be decreased. This observation agrees nicely with the shift of the entire boiling curves to higher temperatures. Due to the high boiling point of Farnesane, its blends with Jet A-1 exhibit higher flash points compared to neat Jet A-1 because the vapour pressure of the mixture decreases.

The freezing point of Farnesane (< -100°C) is far below the upper limit for both jet fuel and blends (-47°C). Therefore, any specification compliant fossil kerosene blended with farnesane will meet the requirements of ASTM 7566 regardless of the blend ratio. Materials with higher viscosity values present lower freezing points. These two properties are used to characterize jet fuel fluidity. High viscosity values can result in problems with pumping and filter plugging. SIP doesn't comply with the specification for viscosity at -20 ºC, that is a limiting factor for blending with conventional jet fuel. SIP fuels contain a low amount of oxygenated compounds (small amounts of alcohol). Due to this SIP fuel typically has total acid number values lower comparing to conventional jet fuels. At the same time, SIP fuel demonstrates a higher tendency to existent gums formation (10 mg/100 ml) comparing to other synthetic fuels and its blend (below 7 mg/100 ml). At the same time, SIP easily stands test for thermal oxidation stability. The respective values for two fuels are below the detection limit of the method (1 mg/100 ml). The dependency of gum content and blend ratio is – as expected – linear. All measured values of the blends up to 50 vol% lie considerably below the upper limit of 7 mg/100 ml. Blending Jet A-1 fuels with Farnesane improves lubricity.

The value of viscosity is directly related to the number of carbons or to the molecular weight. SIP fuel has a higher value of viscosity (14mm^2/s) comparing to conventional fuel. The higher value of SIP is related to the presence of a single heavy compound (farnesane) in the fuel. This result is consistent with the low freezing point of SIP. The maximum amount of Farnesane in the blend is therefore limited. The respective measurements (Figure 19.23) show, according to the Grunberg-Nissan equation, a logarithmic correlation between viscosity and blend ratio. Thus, at high blend ratios regarding Farnesane, an increase in viscosity is more pronounced than at low ratios. Nevertheless, 50 vol% blends of both fuels meet the requirements according to ASTM D7566.

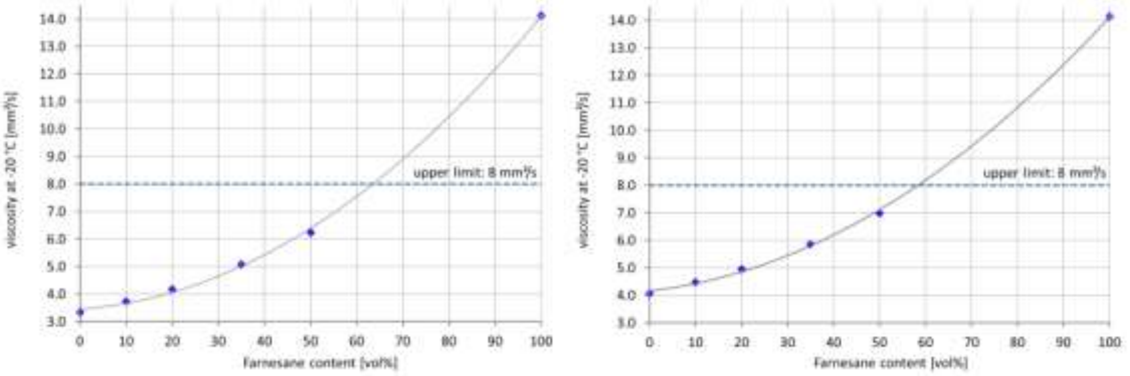


Figure 19.23. Viscosity of fuel blends containing Farnesane and fuel 1 (left) and Farnesane and fuel 2 (right) as well as for the neat blend components.

3.5.5 Cost, maturity, users

The expense of SIP production is largely driven by the economics of sugar conversion, in which large amounts of a relatively expensive feedstock are converted into farnesene at low yields. Even at a relatively optimistic rate of 0.3 ton of farnesene per ton of sugar, at a molasses price of €167/ton and sugar content of approximately 55%, more than €1,000 worth of molasses is required to produce 1 ton of jet fuel, which has a substantially lower value [73].

Mature technology once blended up to 10%.

3.6 ATJ-SPK

3.6.1 Pathway Description

ATJ-SPK stands for Alcohol To Jet Synthesized Paraffinic Kerosene. This acronym specifically refers to Alcohol to Jet fuel not containing aromatics. There is also a production pathway for Alcohol to Jet fuel that does contain aromatics. This pathway is called ATJ-SKA. The ATJ process starts with na alcohol with the general formula ROH, where R represents a saturated alkyl group with the chain length of 2-5 carbon atoms and –OH is a hydroxyl group [96]. There are several sub-pathways expected to be eventually approved by ASTM as ATJ-SPK production pathways, covering conversion of alcohols either as single alcohol or as a mixture. Such alcohols may be linear or branched [97]. The production of ATJ fuel consists of two separate steps: The production of the alcohol, and the conversion of the alcohol to a fuel. These steps are, in principle, independent of each other and can take place at different locations. Although the source of the alcohol can be of decisive importance from a sustainability point of view, it is only the conversion process of the alcohol to a fuel that is of relevance for technical certification. To convert the alcohol to a fuel, it is first dehydrated into the respective alkene product containing the same number of carbon atoms. The product is then separated from liquid water and impurities by fractionation and enters the next process step as a gas. In the next step, the gaseous material is oligomerised into higher molecular weight unsaturated compounds. Unsaturated oligomers that have molecular weight approximately consistent with jet fuel are separated and further processed in the third major step, hydrogenation over a solid-phase catalyst with hydrogen gas. In the final step, the hydrogenated product is distilled to yield the final products of which kerosene is one [98].

The feedstock for the ATJ is the respective alcohol and the feedstock for the alcohol, in turn, is highly variable. A currently popular approach is the fermentation of lignocellulosic residues, but in principle, the feedstock can be all kinds of biomass, or even be inorganic substances – the New Zealand company LanzaTech company has developed a gas fermentation process by which ethanol can be produced from steelwork flue gases as the sole source of carbon and energy [99]. A schematic diagram of the ATJ process is shown in Figure 19.24.

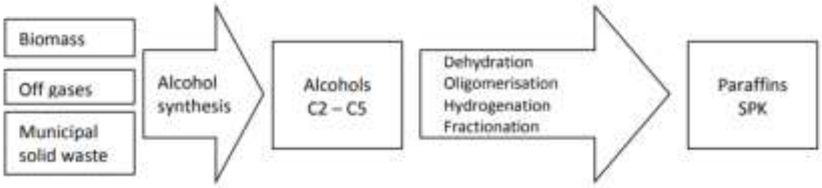


Figure 19.24. Simplified overview diagram of the ATJ-SPK process

3.6.2 Approval Status

In 2011 the companies Cobalt, Gevo, Swedish Biofuels and UOP joined together to create a suitable data set through AFRL and other independent sources and to provide the necessary scientific reports to initiate ASTM certification of ATJ [97]. Certification work has been performed by Gevo on ATJ-SPK from iso-butanol, by Cobalt on ATJ-SPK from butanol, by Swedish Biofuels on ATJ-SPK from ethanol and by UOP on ATJ-SPK from both iso-butanol and various alcohols [98]. The Swedish Biofuels sub-pathway is slightly different from the others in that it is not limited to the conversion of a single alcohol, but can convert all types of alcohols, as single alcohol and or as a mixture of alcohols, including all types of alcohol isomers, both linear (n-) and branched (iso-). Conversions have been demonstrated both from ethanol and from 2,3-butanediol. The aromatics content resulting from this process can be adjusted as required, ranging from next to zero to the maximum permitted. A research report on ATJ-SPK was approved by ASTM in November 2014, with some minor corrections to be included as an annexe [100]. Use of ATJ-SPK blends as aviation kerosene was approved in April 2016 [101] (*Annex A5*) but was limited to ATJ from iso-butanol (the Gevo pathway). This limitation to only one subpathway was contested [102], but was based on the assessment that the other sub-pathways have not yet submitted sufficient documentation for inclusion in the approval.

3.6.3 Availability and compatibility

The main producer of ATJ-SPK is Gevo [103]. ATJ pathway received certification based on Gevo's isobutanol, and there is currently no integrated commercial facility for bio-jet production using this route.25 The EU, under FP7, 26, is supporting the development of two demonstration projects. One will produce bio-jet from ethanol using Swedish Biofuels' technology, and the other will produce bio-jet from the lignin fraction of a cellulosic ethanol plant using Biochemtex' technology. The former will have a capacity of 10 ML/y. of bio-jet, and the latter will be smaller [104].

It can be used in Turbofan powertrain technology.

3.6.4 Chemical properties and risks

Alcohol-to-Jet fuels are produced from C2 to C6 alcohols that are accessible biotechnologically, e.g. by fermentation. After dehydration of the alcohols, the resulting alkenes are oligomerised. These higher olefins are then hydrogenated to produce iso-alkanes. Alcohols used for ATJ-SPK production can be produced from biomass sugars by mature and simple microbial fermentation technologies similar to that used in beer and wine-making. The extraction of sugars from the carbohydrate polymers is relatively easy with edible biomass feedstocks such as sugar cane or corn, in which case a simple treatment in hot water is enough to release the monomers. In the case of non-edible biomass (e.g., lignocellulose), sugar extraction is more problematic and additional (pretreatments are required to break or weaken the lignin structure that surrounds the cellulose and hemicellulose polymers. Alcohols are produced in the biofermenters at low concentrations and near room temperature to allow microorganisms to survive. Ethanol can be readily dehydrated to ethylene over acidic catalysts such as silica-alumina, silicoaluminophosphates, zeolites, and heteropolyacids. Dehydration of C4 alcohols also takes place smoothly over acidic catalysts, although obtaining a single olefin remains challenging. Isobutanol can be readily converted into isobutylene over alumina catalysts. Apart from isobutylene, other C4 linear olefins such as n-butene and 2-butene can be produced in minor amounts. The olefins resulting from the above dehydration processes can be oligomerized to higher olefins by well-known industrial processes using both homogeneous and heterogeneous catalysts. It is possible to produce aromatic compounds from the alkene intermediates, but ATJ-SPK is by specification essentially free of aromatic compounds. In the case of the Gevo fuel produced from isobutanol, ATJ-SPK consists essentially of two iso-alkanes, namely 2,2,4,6,6-pentamethylheptane and 2,2,4,4,6,8,8-heptamethylnonane, where the former is the major compound. Due to the production pathway, iso-alkanes and n-alkanes of kerosene fraction are components of ATJ-SPK. Typical hydrocarbon composition of ATJ-SPK fuel is presented in Table 19.22.

Fuel sample	n-alkane	Iso-alkane	olefin	naphthene	aromatic	Total
ATJ-SPK	-	99.8	-	0.2	-	100

Table 19.22. Typical hydrocarbon composition of ATJ-SPK fuel

Such hydrocarbon composition results in lower density compared to conventional jet fuel (Table 19.23). Some batches of ATJ-SPK can demonstrate density values even lower than required by the standard. ATJ-SPK jet fuel is characterized by higher energy content per unit of mass and lower energy content per unit of volume comparing to conventional jet fuels [72]. For fossil fuel blends with ATJ-SPK, the dependency of density on blend ratio is again strictly linear Since the density of ATJ-SPK (757.1 kg/m³) falls below the lower limit (775 kg/m³), the maximum blend ratio regarding ATJ-SPK is limited; for the fuels included in the study, the limits range from ca. 40 vol% to ca. 70 vol%.

Property	Units of measurement	Limits ASTM D1655/D7566	Results		
			Jet A-1	ATJ-SPK 1	ATJ-SPK 2
Density at 15 °C	kg/m^3	775.0/840.0	795.0	757.1	760
Heat of combustion	MJ/kg	Min 42.80	43.39	44.1	44.0
Aromatics	% (V/V)	Max 25.0	13.7	0	0
Smoke point	mm	Max 25.0	21	27	n/a

Table 19.23. Properties of ATJ-SPK fuel and fossil jet fuel

Blending ATJ-SPK with conventional jet fuels provides improvement of mass-energy content of blends. Absence of aromatics in ATJ-SPK allows blending with conventional jet fuel with consequent reduction of aromatics. However, blending will be limited by the requirement to minimal content of aromatics in jet fuel. Absence of aromatics and high content of alkanes provides higher values of smoke point of ATJ-SPK. ATJ-SPK are generally characterized with higher initial boiling points that can cause concerns concerning high altitude evaporation.

ATJ-SPK possess comparatively higher flashpoint. Thus, blending ATJ-SPK with conventional jet fuels may improve its fire safety. Due to the production pathway, ATJ-SPK doesn't contain chemically unstable hydrocarbons and heterogenic compounds, which results in high chemical and thermal oxidation stability similarly to conventional jet fuels. Absence of sulfur is typical for ATJ-SPK. For ATJ-SPK blends of all fossil fuels included in the study, values for lubricity lie within the interval defined by the neat blend components.

3.6.5 Cost, maturity, users

The cost results for ATJ pathways illustrate that lignocellulosic feedstocks are approximately 40% more expensive to convert into fuel. For corn and sugarcane, the upgrading process represents around 50% of the minimum viable price, whereas, for lignocellulosic ATJ conversion, it only accounts for around 80% of the minimum viable price. A substantial portion of the ATJ production cost for food crop–derived fuels is attributable to ongoing feedstock and energy costs, whereas the largest expense for lignocellulosic ATJ pathways is attributable to the upfront CAPEX costs, which account for approximately 40% of the levelized cost. Sugarcane ATJ (with ethanol as an intermediate product) has yields of approximately 0.45 ton per ton of sugar [73]. A stochastic analysis conducted by Bann et al. (2017) [74] estimated an average baseline value of €1.38 to €2.08 for various ATJ feedstocks. Likewise, a harmonized analysis conducted by de Jong (2018) [75] estimated a levelized cost of around €2.50/liter for ATJ from wheat straw, all on greenfield, Nthof-a-kind facilities.

The LanzaTech company announced in May 2020 the spin-out of LanzaJet, alongside its corporate partners Mitsui, Suncor and All Nippon Airways, to bring sustainable aviation fuel to the commercial market. The new company has launched with commitments from the Japanese trading and investment company, Mitsui & Co. and Canadian oil and gas producer Suncor Energy to invest $85 million to back the first pilot and development-scale facilities that LanzaJet will be constructing [105].

3.7 ATJ-SKA

3.7.1 Pathway Description

ATJ-SKA stands for Alcohol To Jet - Synthesized Kerosene with Aromatics. This acronym refers to Alcohol to Jet fuel containing aromatics. ATJ-SKA produced by Swedish Biofuels is also known by its trade name SB-JP-8 [97]. The principle pathway for ATJ-SKA is the same as the ATJ-SPK pathway, except for an additional aromatization step. Depending on the technological capability of the technology provider, the production of aromatics can be performed as an integrated stream in the overall production process. A schematic diagram of the ATJ-SKA process is shown in Figure 19.25.

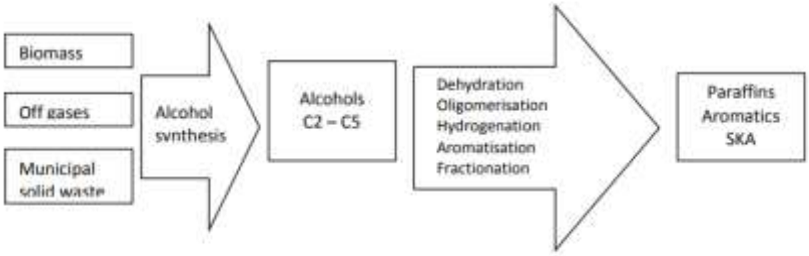


Figure 19.25. Simplified overview diagram of the ATJ-SKA process

As with ATJ-SPK, fractionation is the final step. Byogy production process is made by Swedish Biofuels, and it is available on their website but is extremely limited [106]. However, their process follows the same structure as described above [107]. A competing approach was proposed by the US company Terrabon/Logos. However, available information on that companies' production process is largely limited to the conversion of biomass to alcohols, whereas the conversion step to Jet Fuel is vaguely described as "oligomerization" [108]. Work on this approach was terminated when Terrabon/Logos went bankrupt in 2012.

3.7.2 Approval Status

ATJ-SKA is not yet approved by ASTM. Certification work has been mainly performed by Swedish Biofuels and Byogy. Swedish Biofuels technology was demonstrated using funding from US DARPA. The US Air Force has conducted extensive lab tests on Swedish Biofuels SKA fuel including specification tests (MIL-DTL-

83133), Fit-for-Purpose tests, toxicology assessments, and material compatibility tests. All these tests have been successfully passed, as have a fuel atomizer spray test, APU combustor test and nozzle flow test.

3.7.3 Availability and compatibility

The main producer of ATJ-SKA is Swedish Biofuels [109]. Can be used blended with fossil jet fuel up to 30% v/v [43]. The technology is at an early commercial stage with low availability. It has the same opportunities as SPK, but blend ratio unlikely to be enlarged. The technology is mature once blended up to 30% v and has lower pollutants (PMs up to -60%, and S). Integrated, fuel-centric research is still needed, investigating the effects of fuel composition on operations and emissions, where fuel is varied for otherwise identical conditions, and the effects identified. Such research should include fuels outside the current experience base for fossil fuels, to identify risks and opportunities.

It can be used in Turbofan powertrain technology.

3.7.4 Chemical properties and risks

ATJ-SKA is designed as a fully synthetic fuel, which as a neat fuel meets all the specification requirements for conventional kerosene. It was therefore expected that all blends with conventional kerosene would also meet the specification requirements. ATJ-SKA production pathway results in iso-alkanes, n-alkanes and also some portion of aromatics. Content of aromatics may be regulated during the production process according to the requirements to fuel [72].

ATJ-SKA contains n-alkanes and iso-alkanes, in which those with boiling points close to that of n-undecane ($C_{11}H_{24}$) occur in comparatively high amounts; minor amounts of cycloalkanes can be found as well. The sample has an aromatic content of 15.8 vol%, while the spectrum of aromatic compounds is limited. The aromatics consist mainly of alkylbenzenes, indanes and tetrahydronaphthalenes. The content of naphthalenes (0.080 vol%) is low. Due to the content of aromatics in ATJ-SKA its density is usually similar to the density of conventional jet fuels and within the range of standard requirements (Table 19.24). ATJ-SKA jet fuel is characterized with comparatively equal energy content per unit of mass and energy content per unit of volume as for conventional jet fuels. As it is seen from the experimental data presence of aromatics in ATJ-SKA provides density and energy content similar to conventional jet fuel. Amount of aromatics complies with standard requirements, at the same time presence of aromatics influence on the reduction of ATJ-SKA smoke point.

Property	Units of measurement	Limits ASTM D1655/D7566	Results	
			Jet A-1	ATJ-SKA
Density at 15 °C	kg/m^3	775.0/840.0	795.0	785.9
Heat of combustion	MJ/kg	Min 42.80	43.39	43.4
Aromatics	% (V/V)	Max 25.0	13.7	15.8
Smoke point	mm	Max 25.0	26	23

Table 19.24. Properties of ATJ-SKA and fossil jet flues.

Distillation start and endpoints of ATJ-SKA lie close to those of the fossil fuel. ATJ-SPK possess comparatively higher flashpoint. Thus, blending ATJ-SKA with conventional jet fuels may slightly improve its fire safety. Due to the production pathway, ATJ-SPK doesn't contain chemically unstable hydrocarbons and heterogenic compounds and sulfur-containing compounds, which results in high chemical and thermal oxidation stability similarly to conventional jet fuels. Lubricity of the neat ATJ-SKA (wsd = 0.606 mm) is already quite good and in fact better than that of the fossil fuel (0.728 mm). In this case, the lubricity of all blends lies within the interval of values for the neat blend components. However, improvement of lubricity upon the incorporation of ATJ-SKA becomes evident only at high blend ratios regarding ATJ-SKA. At low blend ratios, the positive influence on lubricity is weak.

3.7.5 Cost, maturity, users

Mature technology once blended up to 30% to fossil fuel.

ATJ-SKA is an alternative biofuel that has a better fuel burn efficiency (greater miles per gallon), reduce greenhouse gases by more than 80% [110], delivers lower engine maintenance costs (negligible n-paraffins), has lower freeze temperature (opening up new flight space) and can adjust aromatics to any level (to adapt to local crude oil specs). In comparison with jet fuels that are composed of a variety of hydrocarbons [111], ATJ is synthetic kerosene with aromatics (SKA), which contain alkanes like those found in petroleum-derived JP-8 [112]. Therefore, ATJ-SKA use is related to a lower engine maintenance cost and higher reliability and a significant beneficial environmental impact [113].

Technical uncertainty is critical to the determination of ATJ fuel pathway's economic performance. In future economic analyses, it is necessary to consider technical uncertainty. The variance in by-product sales plays an important role in profitability [114]. Nevertheless, several different publications have calculated the incentive currently required to make sustainable fuels competitive for aviation costs against conventional fuels. The bulk fell within a range of 39.6 to 53.5 eurocent per litre of jet fuel [115]. Choosing an average of 47 eurocent per litre is calculated using different break scenarios, even for different blend-in ratios (Table 19.25). The increase in ticket prices is also calculated on the assumption that the cost of fuel contributes 30% of the total ticket price.

Blend in ratio	Additional cost [€ per liter]	% of average price[10]	% ticket price increase
2.5 %	0.01	2 %	0.6 %
5 %	0.02	4 %	1.2 %
10 %	0.05	8 %	2.4 %
20 %	0.09	16 %	4.8 %

Table 19.25. Additional fuel and ticket costs if sustainable aviation fuels for different blend-in ratios are introduced [115]

3.8 CH kerosene

3.8.1 Pathway Description

CH stands for Catalytic Hydrothermolysis. The product from the process is also known under the trademarked name "ReadiJet" [116]. As part of the ASTM certification project, the production pathway has been renamed CHJ (for Catalytic Hydrothermolysis Jet). The production pathway of CH fuel (also called hydrothermal liquefaction) consists of three major steps. It starts with Catalytic Hydrothermolysis, where triglyceride oils, other esters or fatty acids are converted into n- and iso-alkanes, cycloalkanes and aromatic compounds. In the next step, the material is mildly hydrotreated to saturate residual olefins and remove residual oxygenates, preserving aromatics and cycloparaffins. In the final step, the output stream is distilled and fractionated into the final products of which kerosene is one [117]. Feedstock for the CH process is similar to that for HEFA, i.e. oils and fats. A variety of edible and non-edible materials have been successfully tested by ARA, with the current focus on oil from Brassica Carinata, a non-edible oil [118]. CH kerosene is a fully synthetic kerosene, including synthetic aromatics. According to ARA, aromatic content can be controlled to between 10% and 20% by controlling processing severity. In figure 26, the pathway for the production of

CHJ is reported. Neat CH kerosene is very similar in composition and properties to fossil kerosene, including in aromatic content [119]. The CH crude oil produced by the CH conversion process contains thousands of isomers distributed over the entire boiling range of jet and diesel fuels. Research has shown that through the CH process, biojet fuels can be produced from a variety of triglyceride-based feedstocks such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil.

The specification defines a jet fuel blending component produced using catalytic hydrothermolysis conversion of lipids. The core technology has been developed by Applied Research Associates (ARA) and utilizes a supercritical water process to perform the conversion of lipids into hydrocarbons that closely resemble crude oil. This crude is then hydrotreated and fractionated to produce renewable diesel, jet, and naphtha. The overall process is branded as Biofuels Isoconversion (BIC), which ARA and Chevron Lummus Global will take to market jointly. Several commercialization entities are already performing engineering activities for the construction of such facilities.

CHJ produces a blending component that is extremely similar in composition to petro-jet. It includes normal-/ iso-paraffins, cycloparaffins, and aromatics (without the naphthalenes that are primary contributors to air quality challenges of jet exhaust). This is the first synthetic fuel pathway to include major amounts of molecules that are not normal- or iso-paraffins, which are critical to normal engine operation. This means that it is likely that this fuel can be used at higher blends in the future, even up to use as a 100% drop-in fuel, after a bit more production monitoring and engine demonstration work. ARA has also developed a front-end hydrothermal cleanup process that will enable broader use of potentially lesser-cost lipids as SAF feedstocks, including raw crush oil from various seeds as well as brown grease.

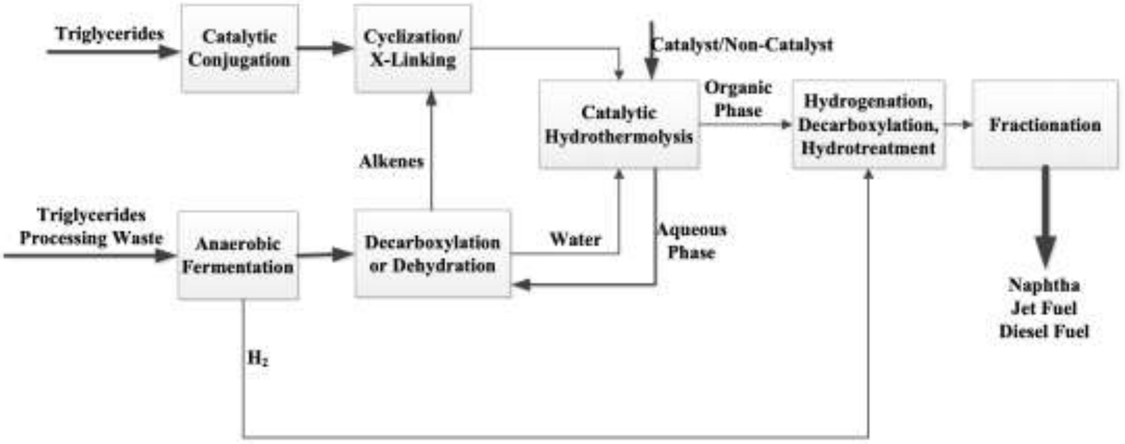


Figure 19.26. Catalytic hydrothermolysis to jet fuel [93]

3.8.2 Approval Status

Extensive tests have been conducted, including a test flight in 2012 [120]. A research report has been finished and submitted for OEM review [116]. Certification work is being performed by ARA, based on fuel produced from its 4 barrel per day pilot and 100 barrel per day demonstration plants [120]. On 3rd February 2020 the publication by ASTM of the new catalytic hydrothermolysis jet fuel (CHJ) pathway specification as *Annex A6* to ASTM D7566, has been announced. Although the CHJ does require blending with petroleum-based jet fuel and has a maximum blend restriction of 50%, CAAFI is highly encouraged by the composition of CHJ.

3.8.3 Availability and compatibility

The only provider of CH kerosene in 2012 was ARA.

No difference was observed in PW615F engine operability for the 50% ARA CH/50% Jet A-1 or the 100% ARA CH biofuel blends compared to the baseline Jet A-1 fuel. No negative impact was observed on SFC, gaseous emissions, smoke number, or PM. Inspection of fuel system components showed no adverse effects from an operation on the CH fuel blend. Metallic debris was found during preservation of the FMU, following the ATP. The source of debris has not been identified, but it is not believed to be CH fuel related. The single nozzle can combustor tests were conducted at Université Laval, under the direction of P&WC. Ground starts at 50, 0, -20, -30, and -40 °F and altitude relights at 15, 20, 25, 30, and 35 kft were performed. No starting differences or altitude relight lean boundary differences were observed. The rich limits were not achieved for the relights, due to rig constraints.

3.8.4 Chemical properties and risks

The CH reaction is conducted at temperatures from 450°C-475°C and pressures of 210 bar in the presence of water with or without a catalyst [121]. The resulting products – including carboxylic acids, oxygenated species, and unsaturated molecules – are sent to decarboxylation and hydrotreating processes for saturation and oxygen removal. The treated products, ranging from 6–28 carbon numbers, contain n-alkanes, iso-alkanes, cyclo-alkanes, and aromatics, which require a fractionation step for separation to naphtha, jet fuel, and diesel fuel. The jet fuel made from the CH process meets ASTM and military (MIL) specifications and has excellent combustion quality, cold flow properties, and stability. Depending on the triglyceride-based feedstock used, biojet fuels have different properties, as shown in Table 19.26.

	JP-8	From Soybean	From Jatropha	From Tung	From Camelina	From Carinata	MIL-DTL-83133H-Spec Requirement
Aromatics	18/8 (vol%)	2.6 (wt%)	10.8 (wt%)	61.7 (wt%)	24.2 (vol%)	16.8 (vol%)	≤25.0
Paraffins (normal+ iso)	N/A	40.0 (vol%)	32.8 (wt%)	16.2 (wt%)	N/A	N/A	N/A
Olefins	0.8 (vol%)	N/A	N/A	N/A	1.3 (vol%)	1.5 (vol%)	≤5.0 (vol%)
Cycloparaffins	N/A	52.0 (vol%)	39.2 (wt%)	16.7 (wt%)	N/A	N/A	N/A
Dicycloparaffins	N/A	5.9 (vol%)	N/A	N/A	N/A	N/A	N/A
Heat of combustion, MJ/kg	43.3	43.4	43.4	42.3	42.9	43.2	≥42.8
Smoke Point, mm	22	>30	28	N/A	22	26	≥19
Freeze Point, mm	-51	<-47	-39	<-66	-54	-57	≤-47
Flash Point, mm	51	>38	45	38	48	46	≥38
Distillation	N/A	pass	195–229	187–252	N/A	N/A	N/A
Density, kg/L	0.804	0.793	0.804	0.839	0.818	0.802	0.775-0.840
Acid Number, mg of KOH/g	0.003	<0.010	<0.010	N/A	0.011	0.012	≤0.015
Hydrogen, wt%	13.8	N/A	14	11.9	13.8	13.8	≥13.4
Viscosity at -40C, cSt	9.9	N/A	N/A	N/A	7.4	6.5	≤12.0
Cetane Index	N/A	N/A	43.9	34.2	N/A	N/A	N/A

Table 19.26. Properties of CH biojet fuels produced from various feedstock

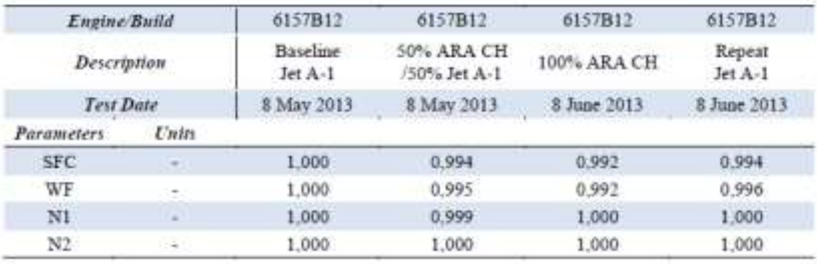
Properties of CH fuel, conventional Jet A-1 and its 50/50 blend are shown in Table 19.27. It can be seen that properties of CH jet fuels are largely close to those of conventional Jet A-1 fuel. CH fuel has slightly higher flashpoint that positively influences fire safety of blended fuels [122]. Higher freezing point is explained by the technological process and maybe regulated during CH fuel production. Some positive effect is connected to sulfur content that is lower compared to conventional fuel. This will result in lower sulfur oxides emission during combustion. The rest of the quality parameters of CH fuel and its blend are very close to conventional fuels.

Property	Units of measurement	Results		
		Jet A-1	100% CH	50/50 Jet A-1/CH
Free water and particulate contamination	-	pass	pass	pass
Acid number	mg KOH/g	0.01	0.01	0.01
Aromatic content	% vol,	18	17	18
Olefins content	% vol	0.8	0.9	0.8
Sulfur content	% mass	0.05	0.03	0.03
Distillation:				
- initial boiling point	C	145	150	148
- 10%		168	165	166
- 20%		176	172	173
- 50%		199	200	200
- 90%		243	249	246
- final boiling point		267	268	266
- residue		1.3	1.2	1.2
- loss	%	0.9	0.9	1.0
Flashpoint	C	37	45	42
Density at 15 °C	kg/m^3	801	804	802
Freezing point	C	-51	-44	-47
Viscosity at -20 °C	mm^2/s	4	4	4
Smoke point	mm	23	24	23
Naphthalene content	% vol	1.1	0.3	0.7
Net heat of combustion,	MJ/kg	43.2	43.3	43.3
Copper strip test	-	1a	1b	1b
Existent gums	mg/100ml	<1	1	<1
Conductivity	pS/m	269	4	115

Table 19.27. Properties of fossil fuel, CH fuel and 50/50 blend

Engine operability test was conducted for Jet A-1 fuel, CH fuel and for the 50 CH fuel / 50% Jet A-1 fuel. The engine operability demonstrated while the engine was powered by the two biofuel blends as compared to the operability demonstrated with the baseline Jet A-1. No significant differences in engine operability were observed that could be attributed to the change in fuel. The parameters time to light (TTL) and time to idle (TTI), as well as the peak inter-turbine temperature (ITT) can be used to evaluate the quality of the engine start with both the baseline Jet A-1 and ARA CH fuel blends. The tests demonstrated that all three fuels demonstrated equivalent engine start characteristics.

Engine performance was evaluated by taking steady-state measurements at six representative power settings: GI, 30%, 50%, 85%, 93% and 100% of rated takeoff thrust. A five minute stabilization time was used prior to taking any performance measurements. The results show that the biofuel blends had no significant impact on SFC, low rotor speed (N1) or high rotor speed (N2). The pre to post-test comparison with the Jet A-1 baseline fuel revealed a small decrease in fuel consumption, but it was determined to be a result of a small error on fuel flow measurement. The biofuel results are compared with the repeat Jet A-1 fuel and presented in Table 19.28.



Engine/Build		6157B12	6157B12	6157B12	6157B12
Description		Baseline Jet A-1	50% ARA CH /50% Jet A-1	100% ARA CH	Repeat Jet A-1
Test Date		8 May 2013	8 May 2013	8 June 2013	8 June 2013
Parameters	*Units*				
SFC	-	1,000	0,994	0,992	0,994
WF	-	1,000	0,995	0,992	0,996
N1	-	1,000	0,999	1,000	1,000
N2	-	1,000	1,000	1,000	1,000

Table 19.28. Performance test main parameters at takeoff thrust of 1460 lbf

Measured SFC for the biofuel blends is 0.1 to 0.8% lower than the baseline Jet A-1. These variations are attributed to a fluctuation in fuel flow measurements. In addition, the remaining performance parameters, N1 and N2, also show negligible deltas with regards to the baseline fuel at constant thrust.

Engine exhaust emissions were measured and processed in accordance with the International Civil Aviation Organization (ICAO) regulations. The smoke analyzer and reflectometer were used together to calculate the smoke number at each condition point. An LII system was used to measure the PM mass and number count. As expected, the smoke number did not significantly change between the various fuels, due to the similar aromatic content. All other engine emissions for the baseline Jet A-1, the 100% CH and the 50% CH/50% Jet A-1 blends were within experimental scatter of those obtained with Jet A-1. Engine emission measurements for each fuel type are summarized in Figure 19.27. Emissions meter readings for each pollutant are plotted against thrust. All the shown results have been normalized.

As is evident in the plots, the CH blends had no impact on UHC, CO, or NOx emissions. Any variation shown is within expected test scatter. Jet A-1 and ARA CH have similar aromatic content, so it is understandable that the Society of Automotive Engineers (SAE) smoke numbers are similar

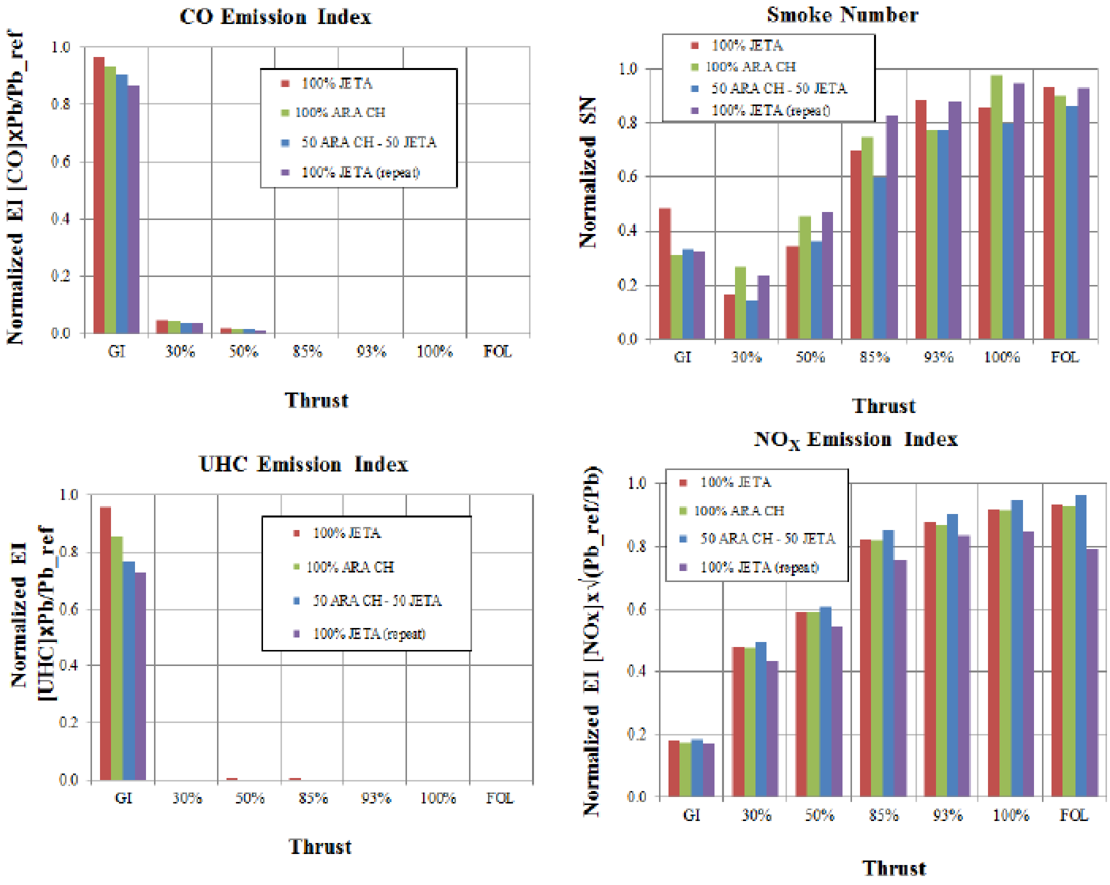


Figure 19.27. Engine emissions comparison of Jet A-1 and ARA CH biofuel blends [122]

3.8.5 Cost, maturity, users

ARA and Chevron Lummus Global (CLG) developed the Biofuels ISOCONVERSION (BIC) process based on ARA's patented, novel Catalytic Hydrothermolysis (CH) process and CLG's market-leading hydroprocessing technology. The BIC process converts any renewable fat, oil, and grease feedstock into high yields of 100% drop-in, pure hydrocarbon fuels that meet petroleum fuels specifications and other valuable chemicals [123].

3.9 HHC-SPK or HC-HEFA-SPK

3.9.1 Pathway Description

Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene was developed by IHI Corporation (HQ: Tokyo, Japan, CEO: Tsugio Mitsuoka, hereinafter referred to as "IHI") and New Energy and Industrial Technology Development Organization ("NEDO"), that carried the project "Development of Production Technologies for Bio jet fuels / Pilot scale test on once-through production process using Hyper-Growth Botryococcus Braun" for stable production of bio-jet fuel from microalgae.

Specifically, the feedstock is bio-derived hydrocarbons, fatty acid esters, and free fatty acids. Recognized sources of bio-derived hydrocarbons at present only include the tri-terpenes produced by the Botryococcus braunii species of algae. Bio-derived hydrocarbons and lipids are converted to hydrocarbons by treating the feedstock with hydrogen to remove oxygen and other less desirable molecules. The hydrocarbons are cracked and isomerized, creating a synthetic jet fuel blending component comprised of paraffins.

3.9.2 Approval Status

In May 2020, a new ASTM D7566 alternative jet fuel production pathway: ASTM D7566 Annex A7 – Hydroprocessed Hydrocarbons (HH-SPK, or HC-HEFA) has been approved. This addition describes the hydroprocessing of bio-derived hydrocarbons (as opposed to simply fatty acids or fatty acid esters entailed in HEFA production), for instance, those obtained directly from oils (triterpenes) produced by the Botryococcus braunii algae. This task force and research activity was led by IHI Corporation using both the FAA Clearinghouse concept as well as the industry's D4054 Fast Track provision. The Clearinghouse is intended to streamline the management of the testing and data review of SAF candidates. The University of Dayton Research Institute (URDI) is the project leader for Clearinghouse activity and is initially funded under ASCENT to support Phase 1 testing and research review. IHI's timely completion of approval indicates both concepts are impactful and enable the qualification process for select new pathways to be completed at reduced cost and timeframe. In line with Fast Track provisions, the HH-SPK will initially have a 10% max blending level. This fuel pathway was the first to receive expedited review under ASTM's "fast track" review process and benefitted from guidance from a special clearinghouse established by the U.S. Federal Aviation Administration (FAA) to help guide SAF producers through the rigorous assessment and approval process.

3.9.3 Availability and compatibility

The technological advancements have brought about a lot of changes in algal biotechnology. It has provided the ability to select and breed the best strains, the ability to monitor and control system inputs, the ability to convert more biomass to fuel, the possibility to harvest easily and extract more oil in a better way. Still commercializing algal biofuel requires a lot of effort and collaboration among the stakeholders [124].

3.9.4 Chemical properties and risks

HC-HEFA-SPK fuel was developed under R&D project "Development of Production Technologies for Bio jet fuels / Pilot scale test on once-through production process" to produce algae-based biofuel, using the hyper-growth *Botryococcus braunii*. *Botryococcus* features an exceptionally high growth rate and high hydrocarbon oil content; IHI's fuel is based on the hydroprocessing of oil from *Botryococcus braunii* (Bb oil). The principal technologic scheme of HC-HEFA-SPK fuel production looks as in Figure 19.28.

Figure 19.28. Scheme of HC-HEFA-SPK fuel production

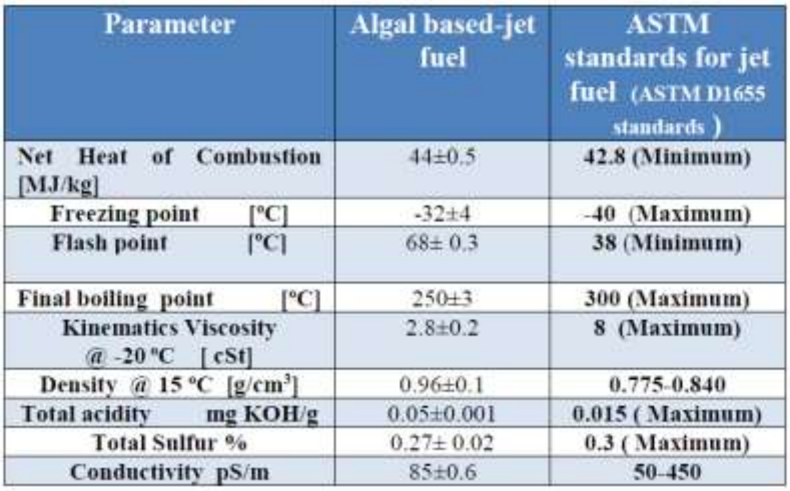
Table 19.29 presents the average for measurements done in triplicate during characterisation. It includes the physicochemical data of both the bio-jet fuel produced in this study and the various conventional jet fuels. The importance of each parameter is explained in terms of the energy needed by the aircraft.

Analysis of data in Table 29 shows that most parameters recorded for algae-based jet fuel comply with the ASTM standards for aviation fuels. The analysis of data for the algae-based jet fuel shows that only density and freezing point needs to be improved. This can be achieved by the use of additives. Bio-jet fuel produced in this study can be blended with Jet A 1, Jet A or Jet B. By blending bio-jet fuel with conventional jet fuel it is possible to reduce the fuel carbon footprint because the refraction index and combustion ability will increase and improve fuel sustainability.

Parameter (Min or Max for ASTM standards)	Algae bio-jet (fuel from this study)	Jet A1 (ASTM D 1655 standards)	Jet A (ASTM standards D 1655)	Jet B (ASTM standards D 1655) :wide cut Kerosene	Importance of the parameter in terms of Energy production
Heating Value [MJ/kg] (Minimum)	44	42.8	42.8	42.8	Represents the total energy released for fuel combustion. It is the energy content of the fuel
Freezing point [°C] (Maximum)	-30	-47	-40	-50	Assists in fuel flow at lower temperatures. Consequently, the level of energy produced will not be affected because the mass of the fuel will not be affected
Flash point [°C] (Minimum)	68	38	38	Not reported	Related to the fuel flammability and ignition
Kinematics Viscosity at -20°C [Cst] (Maximum)	2.8	8	8	Not reported	Influences the capacity of the engine to restart and consume less fuel at higher altitudes.
Density at 15 °C [g/ml]	1.38	0.775-0.840	0.775-0.840	0.751-0.802	Affects the engine performance and fuel consumption because the mass of fuel injected depends upon its density, therefore, the energy to propel the aircraft can be affected
Sulfur (total) [wt %] (Maximum)	0.27	0.30	0.30	0.30	Affects the fuel efficient, therefore, the generated energy can be affected
End point for Distillation [°C] (Maximum)	250	300	300	Not reported	Influences the fuel quality and the energy to be generated by the fuel

Table 19.29. Comparison between conventional jet fuels and bio-jet fuel produced in the current study

Table 19.30 presents the data recorded from the characterization of the algae-based jet fuel generated from the laboratory experiment. The results were recorded in triplicate; they are presented with the average and standard deviations. The analysis of this data shows that most parameters are in accordance with the ASTM standards except the freezing point and specific gravity. However, these two parameters can be improved with the use of relevant additives or processes.



Parameter	Algal based-jet fuel	ASTM standards for jet fuel (ASTM D1655 standards)
Net Heat of Combustion [MJ/kg]	44±0.5	42.8 (Minimum)
Freezing point [°C]	-32±4	-40 (Maximum)
Flash point [°C]	68± 0.3	38 (Minimum)
Final boiling point [°C]	250±3	300 (Maximum)
Kinematics Viscosity @ -20 °C [cSt]	2.8±0.2	8 (Maximum)
Density @ 15 °C [g/cm^3]	0.96±0.1	0.775-0.840
Total acidity mg KOH/g	0.05±0.001	0.015 (Maximum)
Total Sulfur %	0.27± 0.02	0.3 (Maximum)
Conductivity pS/m	85±0.6	50-450

Table 19.30. Characterisation data for Algae-based jet fuel produced from the laboratory process

Heating value, also known as Net Heat of Combustion, represents the amount of energy that can be generated by a jet fuel in order to run an aircraft. It is a very important parameter required for all fuels, including jet fuel. The data in Table 19.30 has recorded a heating value or Net Heat of Combustion of 44 MJ/kg for algae-derived jet fuel which is above the minimum of 42.8 MJ/kg required by ASTM standard for jet fuel [125].

The freezing point is another very important parameter regarding the performance of a jet fuel. It influences jet-fuel fluidity and pumpability at lower temperatures during the flight. At higher altitudes, where temperatures are much lower, the jet fuel will tend to crystallize. It is therefore important to have a jet fuel with the lowest freezing point to avoid the solidification of the fuel at higher altitudes. An ice inhibitor or anti-freezing ingredient can be added to ensure that jet fuel does not solidify. The result, reported in table 11, shows that the freezing point of algae-based jet fuel, which is -32°C is higher than the value of -40°C required by ASTM. In this case, the use of an ice inhibitor or anti-freezing ingredient is therefore recommended to improve the freezing point of algae-based jet fuel.

The flashpoint relates to jet fuel volatility. This can have an impact on combustibility and flammability. It is the main parameter related to fire safety associated with jet-fuel handling at various temperatures. The data reported in Table 19.30 indicate a very high flash point for algae-derived jet fuel. This is an indication that the algae-derived fuel presents lower risks of flammability at lower temperatures and can be handled safely in hot environments. The final boiling point recorded in table 30 is 250°C. A maximum of 300 °C is prescribed by the ASTM standard for jet fuel. This implies that all hydrocarbon fractions needed for jet fuel can be collected at 250°C, reducing the energy demands for the fractionation process.

Viscosity affects the fuel's fluidity and also, to a larger extent the fuel's pumpability over an operating temperature range. The ASTM maximum limit for viscosity at -20°C is 8 cSt. In this study, algae-based jet fuel recorded a value of 2.8 cSt for viscosity at -20°C, as indicated in Table 19.30. This parameter complies with the ASTM standard regarding kinematic viscosity.

Density relates to volatility and specific energy. The recorded density at 15°C for the algae-based jet fuel is equal to 0.96 g/cm$^{3.}$ and it is found beyond the range provided by the ASTM standard for jet fuel, as indicated in Table 19.30. This could be due to the presence of dissolved particulate matter in the algae-based jet fuel. The cleanness of the algae-based jet fuel could be the cause of this situation. It is possible to remedy this situation by using reforming and upgrading processes.

3.9.5 Cost, maturity, users

It is required to be blended with petroleum-based jet fuel, up to a 10% maximum level. As a drop in-fuel, it can be used in the operation of commercial aircraft around the world. According to the Civil Aviation Bureau Circular (National Exchange No. 1718) issued by the Japanese authority, the Ministry of Land, Infrastructure, Transport and Tourism, ASTM D7566 applied fuel is recognized as usable for aircraft in Japan. Based on the results of technological development, IHI Corporation aims to commercialize bio-jet fuel production. In addition, it will continue to study the construction of a supply chain for fuel production and supply. Later in 2020, bio-jet fuel produced by the project is scheduled to be supplied to domestic regular airline routes for commercial demonstration flights. [126]

3.10 HDCJ kerosene

3.10.1 Pathway Description

HDCJ stands for Hydroprocessed Depolymerized Cellulosic Jet. This term encompasses the production pathway better known under the term "pyrolysis", but also includes similar pathways where alternative processes are used for depolymerisation. The production pathway of HDCJ fuel consists of three major steps. It begins with a feedstock of lignocellulosic biomass, which is essentially a combination of lignin, cellulose and hemicellulose, each of which are complex polymers comprised of carbon, hydrogen and oxygen. In the first step, the feedstock is depolymerised, i.e. the polymers are broken down into smaller fragments. In the case of pyrolysis, depolymerisation is conducted by heating the material in an oxygen-free atmosphere. Other possible ways of depolymerisation are hydrothermal or catalytic approaches or combination with pyrolysis. The depolymerised material is then hydroprocessed to remove oxygen, converting the oxygenates to hydrocarbons and to some extent saturating aromatic compounds. In the final step, the hydrocarbon product is distilled to produce the final products of which kerosene is one [127]. Feedstock for the HDCJ process can be a broad variety of lignocellulosic material, like wood, straw, miscanthus, switchgrass or bagasse. The US company KiOR, which has so far produced most of the HDCJ fuel, has used woody biomass as a feedstock.

3.10.2 Approval Status

HDCJ is not yet approved by ASTM. Most of the certification work has so far been performed by KiOR, based on their production pathway where depolymerisation is performed by a combined thermo catalytic process. Some work has also been done by UOP using pyrolysis for depolymerisation, but this process is still being developed. Neat HDCJ has an aromatic content of some 50%, which is above the permissible maximum for jet fuel of 25%. It is therefore inevitable that HDCJ will have to be blended with conventional jet kerosene for the aromatic content to be diluted to specification levels. Approval is currently pursued for a maximum blend ratio of 30%.

Almost all fuel so far used for ASTM certification has been produced by KiOR in their 10 bbl/day demo facility in Pasedena, Texas. Lab tests have been performed on a blend of 70% conventional kerosene and 30% HDCJ, with specification testing, fit-for-purpose testing and materials compatibility testing all passed. In addition, engine and APU rig tests have been successfully performed on various blends of KiOR HDCJ, conventional jet kerosene and FT kerosene. No further tests are currently planned. A research report on the testing performed on HDCJ fuels has been drawn up and distributed to the OEMs in July 2014. Incorporation of OEM feedback into the report was begun,138 but the process was then slowed down by the financial problems of KiOR, which in November 2014 filed for bankruptcy [128].

3.10.3 Availability

The only possible provider of HDCJ kerosene is currently KiOR, however, the KiOR plant has been idle since March 2014 [129], and no fuel was available.

3.11 HDO-SK

3.11.1 Pathway Description

HDO-SK stands for Hydrodeoxygenated Synthesized Kerosene. This is the term used by the US company Virent to refer to a product from its "BioForming" process. Whereas "BioForming" is registered as a Trademark and describes a process resulting in various product streams, HDO-SK is specific to one product stream and is intended as a generic term for purposes of ASTM certification. The production pathway of HDO-SK fuel consists of four major steps. In the first step, plant-derived oxygenated compounds are hydrodeoxygenated, resulting in intermediate products like alcohols, ketones and other oxygenates with limited reactivity. This is a thermochemical process using metal catalyst. In the next step, the resulting intermediate products are dehydrated, oligomerised and hydrogenated to produce a mixture of normal paraffins, iso-paraffins, cycloparaffins and aromatics. This is a single catalytic step during which several types of reactions occur. The resulting components are all hydrocarbon types also found in fuel derived from fossil sources. The final two steps are essentially the same as in conventional refining, with the material being first hydrotreated, and then distilled into the final products of which HDO-SK is one [130]. Feedstock for the production of HDO-SK fuel can be a broad variety of both cellulosic material (like wood or straw) and commercial sugars. Actual production so far has essentially been from corn syrup.

3.11.2 Approval Status

HDO-SK is not yet approved by ASTM. Certification work is being performed by Virent in cooperation with Shell. Neat HDO-SK has a cycloparaffin content of 80% and only minor aromatics content. It is therefore inevitable that HDO-SK will have to be blended with conventional jet kerosene, to achieve the required minimum aromatics content and dilute the cycloparaffins. No blend ratios have as yet been formally proposed, but testing of blends has so far concentrated on a 50% blend. Certification testing of HDO-SK has so far been limited to lab tests. Specification testing and fit-for-purpose testing are essentially finished, with no issues identified, but only preliminary materials compatibility tests have been performed. Work on rig and engine tests is still pending. HDO-SK, therefore, is still some time away from ASTM certification.

3.11.3 Availability

The only producer of HDO-SK kerosene is currently Virent [131].

3.12 HDO-SKA

3.12.1 Pathway Description

HDO-SKA stands for Hydrodeoxygenated Synthesized Aromatic Kerosene. Like HDO-SK described in section 3.8, this term is used by the US company Virent to refer to one of the products from its "BioForming" process. In the case of HDO-SKA this is a product stream consisting almost solely of aromatics. The production pathway of HDO-SKA fuel consists of three major steps. As with HDO-SK in the first step, plant-derived oxygenated compounds are catalytically hydrodeoxygenated, resulting in intermediate products like alcohols, ketones and other oxygenates with limited reactivity. The resulting intermediate products are then condensed as a second step to form longer carbon chains through C-C bond forming reactions. This is a single catalytic step during which several types of reactions occur. In this step, the oxygenates are converted to olefin intermediates, which react to produce aromatics resembling those typically found in jet fuel, together with low levels of n-paraffins, iso-paraffins, and cycloparaffins. In the final step, the material is distilled into the final products, of which HDO-SKA is one [132]. As is the case for HDO-SK, feedstock for the production of HDO-SKA fuel can be a broad variety of both cellulosic material (like wood or straw) and commercial sugars.

3.12.2 Approval Status

HDO-SKA is not yet approved by ASTM. Certification work is being performed by Virent in cooperation with Shell.

Neat HDO-SKA consists solely of aromatics, the other components having been removed by distillation. This composition gives the neat fuel poor thermostability and an off-spec smoke point and anyway is way above the maximum permissible aromatics content of 25%. It is therefore unsuitable for use as a neat fuel and is not intended to be used as such. Rather, approval is pursued for use as a blend component where appropriate and advantageous. A prospective use could be for blending with synthetic fuels not containing aromatics, like FT or HEFA, as a balancing blend component in a 50/50 blend with conventional jet fuel. No maximum blend ratios for HDO-SKA have been proposed, but the maximum aromatics content of 25% constitutes a natural upper limit. Certification testing of HDO-SKA has so far been limited to lab tests. Specification testing, fit-for-purpose testing and toxicity testing are essentially finished, with no issues identified, but only preliminary materials compatibility tests have been performed. Work on rig and engine tests, including emissions performance, is planned but is still pending. HDO-SKA therefore is still some time away from ASTM certification.

3.12.3 Availability

The only producer of HDO-SKA kerosene is currently Virent.

3.13 HEFA+

HEFA+, commonly called “green diesel” or high-freeze-point HEFA (HfP-HEFA), is a synthetic hydrocarbon typically made from bio-feedstocks such as vegetable oil or waste fats. HEFA+’s primary competitive advantage stems from its similarity to renewable diesel, a biofuel already produced at commercial scale for the road sector. It is an upgrading from the conventional Green Diesel (HVO) to the aviation quality standards (cold temperature properties, density) [43]. Existing production of renewable diesel for the road sector dwarfs the scale of production of other potential alternative jet fuels (AJFs). Production could theoretically ramp up quickly at existing facilities. If HEFA+ were to be certified as an AJF, it would therefore immediately have a market advantage relative to other AJFs that are further from commercialization. Proponents of HEFA+, such as Neste Corporation, tout the high technological readiness and relatively low price of HEFA+ relative to other AJFs. This suggests that once certified, substantial volumes of HEFA+ could be used in the aviation sector in the near term.

3.13.1 Approval Status

In 2018 HEFA+ was undergoing a rigorous research process to acquire the ASTM certification D4054 “Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives.” The certification process will be lengthy, as it requires consensus from all original equipment manufacturers (OEMs) that produce airframes or engines before moving to the next stage of approval. From 2014, as part of data collection, Boeing, in collaboration with the U.S. Federal Aviation Administration (FAA) and engine manufacturers, has started flight tests using its ecoDemonstrator 757 and 787 flight test airplanes, using a blend of 15% green diesel and 85% petroleum jet fuel in one engine. The final blending allowance for HEFA+

in the ASTM standard will be determined through further testing. If approved, HEFA+ would be included as an annexe of ASTM D7566. Once the certification process would complete, the blended fuel would be ready for use on commercial flights and could easily be integrated into common fuel delivery systems at airports.

3.13.2 Availability and compatibility

Currently, it is uncertain when HEFA+ will be available for airlines. Past reports indicate a typical timeline of 3 to 5 years for certification (more or less, between 2016 and 2021). Although the process to certify HEFA+ has been ongoing for several years, it is difficult to predict when it will be completed. However, the large similarities of HEFA+ to renewable diesel will enable the current production potential to be used to produce HEFA+. In the case of a renewable diesel, the global production capacity is approximately 6 billion litters (4.7 million tonnes) as of 2017, with the majority (4.5 billion litters) located in the EU. Existing renewable diesel production in North America would displace only 2% of U.S. and Canadian jet fuel demand (approximately 72 million litters in 2017). In the EU, the majority of renewable diesel production comes from waste feedstocks such as used cooking oil and animal fats, as the industry transitions away from palm oil because of environmental concerns. Neste, a leading proponent of HEFA+ and Europe's largest producer of renewable diesel, generated about 80% of its renewable diesel from waste fats and oils and the remain-der from crude palm oil. In North America, Diamond Green Diesel and AltAir, the two largest renewable diesel producers, primarily make use of waste feedstocks such as animal fats and used cooking oil. Although much-existing pro-duction of renewable diesel comes from wastes and by-products, this does not guarantee that future production in response to increased demand would come from those sources. There is limited potential for expanding the production of HEFA+ by diverting waste oils and fats from other uses. The supply of waste feedstocks such as used cooking oil, animal fats, tall oil, and PFADs is fixed and will not increase with the demand for these wastes. Diverting 100% of waste and residual fats and oils to biofuel production would be neither practical nor environmentally beneficial. Drastically increasing the demand for these materials would sharply increase their prices, which would lead to substantially higher overall costs for HEFA+.

3.13.3 Chemical properties and risks

It has higher energy content per volume, lower per weight. This variant would have physical properties closer to those of conventional renewable diesel but would be limited to only a 10% blend rate in jet fuel [133]. HEFA+, commonly called "green diesel" or high-freeze-point HEFA (HfP-HEFA), is a synthetic hydrocarbon typically made from bio-feedstocks such as vegetable oil or waste fats. HEFA+'s primary competitive advantage stems from its similarity to renewable diesel [also known as hydrogenated vegetable oil (HVO) or hydrogenation derived renewable diesel (HDRD)], a biofuel already produced at commercial scale for the road sector. HEFA+ production resembles the production of renewable diesel for the road sector, a process wherein vegetable oils, waste oils, and fats are processed into hydrocarbons. Renewable diesel chemically different from traditional biodiesels produced for the road sector, which are produced via trans-esterification to generate fatty acid methyl esters (FAME).

HEFA+ production process converts bio-oils into a chemical form more similar to fossil fuels, thus facilitating higher blending with petroleum-based diesel. The first step in renewable diesel production is bio-oil treatment with hydrogen gas and a catalyst in order to remove oxygen (i.e., hydrotreatment). Once the oxygen is removed, the remaining hydrocarbon chains are then hydroisomerized to break down the long chains and improve the cold flow properties of the finished fuel. The end product generally contains hydrocarbon lengths in the diesel range, although further hydroisomerization can break down the chains of carbon even further, thereby increasing the share of bio-kerosene.

Producing traditional HEFA fuels requires additional hydroisomerization beyond that needed to produce renewable diesel, as kerosene has a shorter chain length than diesel. As the chains shorten, the process also creates low-value light compounds such as naphtha and propane. These light compounds cannot be included in a finished jet or road fuel, so reducing their share of the product stream raises the overall value of fuel production by increasing the yield of transport fuel relative to lower-value materials. To produce HEFA+, manufacturers can instead alter the HEFA process to reduce the intensity of the hydroisomerization stage of hydroprocessing, leaving longer hydrocarbon chains more similar to diesel than to kerosene.

Decreasing the yields of light compounds reduces the cold flow properties of the finished fuel relative to traditional HEFA. The reduced low-temperature performance for HEFA+ is a limiting factor for using it in aviation, where jet fuel specifications for Jet A and Jet A-1 require a maximum freezing point of –40°C and -47°C, respectively. The unblended or "neat" HEFA+ has a higher freezing point than traditional HEFA fuels, thus requiring a greater share of petroleum-derived fuel in order to meet the specifications. Therefore, HEFA+ testing has occurred at blend rates of 15%—substantially less than the 50% blends allowed for traditional HEFA fuel in road transport

The heat of combustion per unit of mass of HEFA+ is higher comparing to fossil jet fuel (about 44 MJ/kg), and heat of combustion per unit of volume is lower (about 34 MJ/l). The main concern for HEFA+ fuel it low-temperature properties, which are more similar to diesel fuel rather than for jet fuel. Having diesel-like hydrocarbon composition HEFA+ respectively has heavier fractional composition. Respectively, blending HEFA+ with conventional jet fuel will reduce its evaporability. At the same time, HEFA+ will possess higher flash point and, thus, improved fire safety.

3.13.4 Cost, maturity and users

Fuel technology is mature and ensures lower pollutants (PMs and S). Though, research is needed to better understand the blend limits and the properties for production and distribution, together with an integrated, fuel-centric research, investigating the effects of fuel composition on operations and emissions, where fuel is varied for otherwise identical conditions, and the effects identified. Such research should include fuels outside the current experience base for fossil fuels, to identify risks and opportunities.

Hydroprocessed Esters and Fatty Acids (HEFA) and HEFA+ scenario's production costs will be driven by feedstock costs of around 60-80%. The conversion efficiency of energy in feedstock biofuels in the range of 50-70% is projected to be higher than the other scenarios [134].

The manufacturing technology is less complicated than in the following two examples, and it is anticipated that both investment and operating costs will be correspondingly lower. The total cost per litre of HEFA jet fuel derived from oil crops and waste oils was investigated many times in the literature, with estimates typically in the range of EUR0.8-1.5/l, although such estimates are again highly dependent on the cost of feedstock [134]. For HEFA+, the price of fossil jet fuel will be forced further down the bottom end of the range and closer to market-competitive levels.

3.14 Liquefied Natural Gas (LNG)

Liquefied Natural Gas (LNG) is not used. It is not drop-in, requires a radical change of airframe and combination with electricity still not in the market. Possibilities of using LNG as jet fuel are being explored, but non-drop-in is not feasible in the time frame for a real implementation, but it could be a solution for the future.

It is not drop-in, volume/weight/energy ratio requires different aircrafts, logistics facilities. Increased water vapour emission by 40% (potential climate impact).

Decrease of CO2 by 25% and of NOx by 80%. Furthermore, Zero PM emissions and better thermal efficiency.

3.15 Environmental, managing and ethical aspects

The current demand for feedstock for biofuel production is significant [135]. Concerns about the sustainability of feedstocks used for biofuels have arisen in the RED [136] where the EU re-thought its biofuel policy and defined a set of criteria aimed at ensuring the sustainable use of biofuels (transport) and bioliquids (used for electricity and heating). Outside Europe, international aviation has recently agreed on a set of criteria for defining an alternative fuel as sustainable. Within the ICAO CORSIA scheme, the life-cycle emissions of alternative jet fuels have to demonstrate a minimum GHG saving of 10% - encompassing direct and indirect (ILUC) emissions, according to CORSIA methodology - compared to fossil kerosene. Moreover, sustainable biofuels should not be produced from biomass obtained from land converted after 2009 [137]. Defining feedstock sustainability is certainly debatable, as many different aspects can be taken into consideration and no overarching agreement on a definition exists neither at scientific nor political levels. At an international level, the definition of what constitutes a sustainable aviation biofuel has been significantly simplified, certainly in comparison to Europe and the discussion of biofuels sustainability in the current RED Recast, as well as the surrounding safeguards provided by the broader regulatory context. Moreover, several feedstocks are perceived as having a better sustainability performance than others; feedstock suitable for aviation has been considered the non-food oil crops, waste cooking oil and other lipidic residues. Feedstock sourcing and processing are ongoing challenges for the industry, as their composition is strongly variable, requiring constant plant adaptation. In order to mitigate this issue, practically all the industrial players of the sector have announced the installation of pre-treatment units for their plants [138].

Lipid feedstocks used for the production of HEFA aviation biofuels are today mainly based on palm oil and palm industry co-products (e.g. Palm Fatty Acid Distillate (PFAD), Palm Kernel Oil (PKO), etc.), nevertheless their sustainability is widely debated, and their importance is expected to reduce in medium term. Among oil-bearing crops that are alternative to traditional varieties used for human and animal food, several options have been explored in recent years, but most of them with low market impacts: i.e. Jatropha, cotton oil soapstock [139], tobacco oil [140], etc. An interesting work has been carried out in the framework of the FP7 EU supported project ITAKA [141, 142] on Camelina oil (Camelina sativa L. Crantz). New projects are trying to demonstrate these potentials by means of a larger production, i.e. BIO4A [143]. For HEFA-kerosene, the production of the feedstock is based on fallow land rotation, no demand for additional land or substitution of crops. Lower nvPM as much as related with a relatively lower aromatics and S content. GHG savings estimated to potential achieve 66%, RSB certification for the CCE camelina oil plantations-CO is slightly reduced. UHC no change / slight reduction. NOx remains approximately constant. CO2 is linearly reduced. H20 is linearly increased. Particulate matter characterization: A pronounced and linear reduction in SAE smoke number. A significant reduction in nvPM mass & number emissions is accompanied by a move to smaller size.

Used Cooking Oil (UCO) is also widely considered a promising feedstock for aviation biofuels production. An accurate estimation of the UCO potential in the EU is complicated both by a shortage of available data and by the reliability of reported numbers, where ranges are considerable. Available volumes in EU are predominantly estimates based on volumes collected from the commercial sector, as the collection of UCO is regulated by EU law; the potential resources of used cooking oil collected per capita varies considerably between countries. By 2017, the volume of UCO collected from households in the EU was estimated to have grown to just under 48 kt y−1, while the total possible UCO volume theoretically available from households was estimated as being 854 kt y−1 [144]; USDA [145] reports a total use (including imports) for 2018 of about 2.8 Mt y−1 in EU.

Animal fat (or tallow), is one of the two main products from rendering animal by-products (ABPs); the other being solid protein. Tallow is a potential feedstock for aviation biofuels production although almost all the volumes of this material – at least in the EU - are already in use. Just under 2.8 Mt of tallow was produced in the EU in 2016, according to the European Fat Processors and Renderers Association (EFPRA) [42]. The EU categorizes ABPs as Cat 1, 2 or 3 depending on the risk they pose to public and animal health (Regulation (EC)

1069/2009); with Cat 1 material having the highest risk. Tallows have varying existing uses depending on the category they belong to, in 2016 approximately 620 kt of Cat 1 and 2 fats and 500 kt of Cat 3 fats were used as fuels (principally for biodiesel manufacture and a smaller fraction used for direct combustion) with the rest mainly being used by the animal feed and oleo-chemical industries [146].

Aviation fuel could also be made from the estimated annual EU crude tall oil (CTO) resource of 650 kt, or more likely distilled tall oil fraction of CTO, as crude tall oil is said to contain impurities which damage the hydrotreating catalysts [147]. Tall oil was described as a 'biomass fraction of wastes and residues from forestry and forest-based industries' and was added in 2015 to the list of materials from which biofuels could be made and which would 'count double' towards a Member State renewable energy target; however real availability of this feedstock is debated [148].

The price volatility of the lipid feedstock is a quite relevant issue for the industry, for instance, animal fat (cat 1 and 3) and palm oil had, in 2016, an average price increase of 30%–40% [138]. In 2017, the average price for UCO changed from 560 € CIF Europe to 615 € t-1 and Tallow Methyl Ester (TME) from 886 to 915 € t-1 FOB ARA.

Lipid feedstock are not the only option for the sector, technologies like FT can be supplied by lignocellulosic materials; US DOE reported that the USA produces 1.18 Gt of dry lignocellulosic biomass per year [149], with 933 million tonnes y−1 of agricultural residues and 368 Mt y−1 of forestry residues [45,46]. However, questions remain whether lignocellulosic biomass could be available in sufficient quantities to cover the demand for materials, animal feed, and other applications such as biofuel production and bio-based chemicals [150]. After a study lasting two years, JRC presented the results on biomass flow, supply and demand on a long-term basis for the European context [151]. Total EU28 domestic biomass production from land-based sectors (agriculture and forestry) in 2013 accounted for 1.4 Gt of above-ground dry matter, with agriculture the biggest supply sector providing 65% of the total, followed by forestry with 34%. In agriculture, the crop economic production is almost entirely harvested and marketed (514 Mt y−1), while the residues that amount to 442 Mt y−1 are used only used at a rate of 23%. Part of the uncollected potential could be removed to produce bio-based materials and energy, while the other part should be left to preserve the soil structure and fertility and maintain ecosystem services including soil organic carbon levels or preventing soil erosion. The study also investigated the EU28 wood potential, estimating an average annual harvest level of 271 Mt y−1 (of which 224 Mt y−1 are removed from forests); similarly to the agricultural sector, part of the residue potential could be removed for bio-energy or bio-based materials. At EU level, reported data to indicate that energy accounts for nearly half (48%) of the total use of woody biomass, the remaining 52% being material uses. JRC also reported that, as a whole, the EU28 uses more than 1 Gt of biomass dry matter, with more than 60% used in the feed and food sector, followed by bioenergy (19.1%) and biomaterials (18.8%). This figure is quite close to the overall production potential, thus suggesting that with the current market and price structure only a minor share of residual biomass potential is available for new uses (e.g. biofuels for aviation), with competition among sectors likely to occur in an increased demand scenario.

Apart from feedstock specifically produced for biofuels, the utilization of the organic part of municipal solid wastes for the production of biofuels is considered as an interesting approach for improving EU's energy security, limiting the pollution associated with waste production, thus allowing societal improvements [152]. Two main companies are working at commercial scale for producing biofuels from MSW: Enerkem [50] and Fulcrum [51], with an announced capacity of 100 kt y−1 and 175 kt y−1 of input respectively. The benefits of shifting municipal waste in the hierarchy of waste management is not limited to better resource use but also offers a way to positively impact the sector's GHG balance. In 2014, the total waste generated in the EU28, by all economic activities and households, amounted to 2.5 Gt y−1 and, excluding major mineral wastes, to 891 Mt y−1 [153]. The amount of collected recyclables and bio-waste materials varies widely across European countries, and significant differences are also a function of the collection system used (e.g. door-to-door, civic amenity sites, etc.). Only the 19% of generated municipal waste is collected separately in large cities in the EU28 [154] and it explains the reason behind considering MSW as a potential feedstock of specific interest for biofuel production.

The S2Biom project estimated a European bio-waste potential based on the definition of the Waste Framework Directive (which excludes paper waste), of 89 Mt y−1 (dry basis) by 2030 [155]. Searle and Malins [156] assumed a biogenic fraction of household waste of 63%, estimating a sustainable EU potential of 63 Mt y−1 on a dry basis.

For ATJ-SPK, lower nvPM as much as related with a relatively lower aromatics and S content. In Figure 19.29 there is the Carbon Footprint of Gevo's Individual Farmers. The CO2 emission are already lower than the US average by 50%. Precision agriculture is carried, with low till or even no-till planting, that is an agricultural technique for growing crops or pasture without disturbing the soil through tillage. The farmers are also moving to manure-based fertilizer [157].

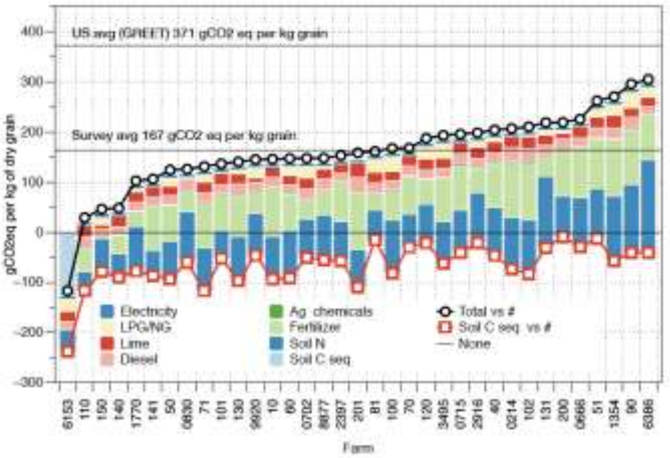


Figure 19.29. Carbon Footprint of Gevo's Individual Farmers

Using advanced biofuel is a significant objective for decreasing GHG emissions. Despite there are designated objectives on sustainability in aviation and EU support for alternative jet fuels [158], environmental, managerial, and ethical problems should be considered by countries and supranational organizations while fulfilling these objectives. Therefore, environmental, managing and ethical aspects of advanced biofuels are considered in this report with four subheadings as technical risks, supply chain risks, impact on biodiversity and ecosystem, and security considerations.

3.15.1 Technical Risks of Aviation Biofuels

The performance characteristics of aviation biofuels in turbine engines are nearly related to their chemical composition. Generally, biofuels have less complicated chemical composition than conventional jet fuels that contain a wide range of hydrocarbons. FT-SPK, HEFA and ATJ-SPK consist of n-, iso- and cyclo paraffins, and SIP mainly iso-paraffins. FT-SPK, HEFA, ATJ-SPK and SIP contain low/negligible amount of aromatics, but FT-SPK/A is made up of a maximum 20 wt% of alkylated aromatics.

Westhuizen et al. [159] analyzed that the chemical compositions of FT-SPK and conventional jet fuel were similar by two-dimensional gas chromatography, except for alkyl benzene content 2.73 wt% and 14.05 wt% respectively. After 2009, FT-SPK was approved as a blending component up to 50% in volume for conventional aviation fuel, HEFA was accepted as another blending component on ASTM D7566 in 2011. The chemical composition and carbon range of HEFA are generally similar to FT-SPK. The standard specifications of FT-SPK/A are also similar to FT-SPK and HEFA, but for aromatics content, FT-SPK/A contains less than 20wt% of aromatics. As for SIP, the standard specifications are mostly different from FT-SPK, HEFA and FT-SPK/A, because of its chemical composition and long carbon chains, which result in high viscosity and weak combustion performance in turbine engines. Therefore, SIP is permitted to blend with conventional jet fuels, max. 10 vol% [160, 161]. ATJ-SPK was approved of blending component (max. 50 vol%) for fossil jet fuels. Despite its production processes, dehydration, oligomerization, hydrogenation and fractionation, the chemical compositions of ATJ-SPK are infrequently available.

The performance characteristics of aviation advanced biofuels are crucially important to ensure fuel safety and reliability. These were classified into low-temperature fluidity, thermal oxidation stability, combustion property, fuel volatility, and fuel metering and aircraft range.

One of the most important characteristics is low-temperature fluidity defined by a freezing point and kinematic viscosity. These properties of bio-jet fuel must be sufficiently low to ensure suitable fuel fluidity in turbine engine as the temperature of an aircraft fuel tank is immensely low at high altitudes. For FT-SPK, HEFA, FT-SPK/A and ATJ-SPK, the freezing point was max. -40ºC and -60ºC for SIP. The low freezing point of bio-jet fuels is strongly associated with the high iso-paraffins, alkylated aromatics content and short carbon chain. Another parameter is the kinematic viscosity is not limited in ASTM D7566, but it must be less than 8mm2/s at -20ºC for blended jet fuels not to cause pumping difficulties, poor atomization and incomplete combustion [162]. Most bio-jet fuels had adequate kinetic viscosities and so favourable fuel low-temperature fluidity. On the other hand, SIP tended to exhibit high viscosity due to its extremely high content of long-chain farnesane (C15).

The thermal oxidation stability of aviation advanced biofuels can be categorized into thermal stability and oxidation stability. The thermal stability is related to the amount of deposits formed in the engine fuel system at the operating condition. Fossil jet fuel contains 10–20 wt% of aromatics, but bio-jet fuel is generally free of aromatics and primarily consisted of n-, iso- and cyclo-paraffins. These compounds of biofuels are known to display a weaker tendency to form a deposit at high temperature. Hence, aviation biofuels have better thermal stability than conventional jet fuels. The fuel oxidative stability is measured the fuel resistance to oxidation at moderate temperature (100-160°C) and in the presence of oxygen. The oxidative stability of aviation biofuels was weaker than conventional jet fuels mainly due to the absence of aromatics/antioxidants [163].

The combustion characteristics of aviation biofuel have major importance, particularly in GHG emissions and climate change. These properties can be classified into a smoke point, the emissions of particulate matter (PM), monoxide (CO) and carbon dioxide (CO2), and derived cetane number (DCN) which define fuel ignition feature. The smoke point requires a minimum of 25mm height of flame without smoking. However, it is not limited in ASTM D7566. A high smoke point shows that fuel has a low smoke-producing tendency. Corporan et al. [164] informed that the smoke point of FT-SPK and HEFA was larger than 40 mm, displaying their noticeable combustion performance. The smoke point of 100% synjet fuel (FT-SPK) was found higher than 50mm, yet fossil jet fuel's smoke point value was 25mm. This difference is because of the aromatic contents of conventional jet fuels. The emission of PM can contribute to haze and smog formation, and can be harmful if inhaled. Moreover, the particle size of PM formed from aviation biofuels was generally 35% smaller than conventional jet fuels, owing to the absence of aromatics. Corporan et al. [165] reported different results that the emissions of NOx and CO2 from FT-SPK and HEFA were both similar to fossil jet fuel, but CO and UHC emissions were 10–25% less than conventional jet fuel. In general, the gaseous emissions from aviation biofuels are lower than fossil jet fuels depending on the gas species and engine operating conditions, due to the lack of stable aromatics [166]. Although DCN is not specified in ASTM D7566, it is an important characteristic of fuel ignition. A higher DCN means shorter ignition delay time, which permits fuels to combust more completely. As a result, better combustion performance with more power and fewer harmful emissions could be achieved. Hui et al. studied the ignition property of FT-SPK, HEFA and conventional jet fuel, and they informed that fossil jet fuel had a DCN of 49.35, which was much lower than that of aviation biofuels (DCN > 60), because of the bonding in benzene ring in stable aromatic compounds.

The fuel volatility of aviation biofuels indicates the tendency of the fuel to vaporize, which can be described by the distillation property and flashpoint. The distillation property is critical for process controllability, energy integration and product optimization [167, 168]. For FT-SPK, HEFA, FT-SPK/A and ATJ-SPK, it is specified in ASTM D7566-18 that 10% recovery must be reached at 205ºC, but for SIP at 250ºC. The flashpoint is an important parameter that is commonly used to evaluate the all flammability hazard during storage and shipping. In ASTM D7566-18, flashpoint for FT-SPK, HEFA, FT-SPK/A and ATJ-SPK is specified as a minimum 38ºC. Nevertheless, SIP has a minimum flash point of 100oC, due to containing long-chain farnesane (C15). Buffi et al. [169] reported that the flashpoint was 42ºC for HEFA produced from used cooking oil. For FT-SPK and ATJ-SPK, the flashpoint was reported 46ºC and 47.5ºC, respectively [170].

More heat energy can be acquired from jet fuels that have higher density and net heat of combustion. FT-SPK, HEFA and ATJ-SPK generally have a lower density than SIP, FT-SPK/A and conventional jet fuels, owing to the lack of aromatics (Corporan et al., 2011; Scheurermann et al., 2017). The net heat of combustion should be higher than 42.8 MJ/kg for blend fuels/conventional jet fuels, but no limit is stated in ASTM D7566-18, except for SIP fuel (a minimum of 43.5 MJ/kg). The net heat of combustion is related to the ratio of hydrogen to carbon (H/C ratio), and aromatics comprise low H/C ratio because of the presence of double bonds. Consequently, blending FT-SPK with conventional jet fuel reduced the net heat of combustion as compared to pure FT-SPK. Though the being of aromatics has a harmful impact on the combustion property, their existence is necessary for aviation biofuel to acquire compatibility with current fueling system. As a result, ASTM D7566-18 maintain a minimum of 8 wt% of aromatics in the blended jet fuels to balance suitable fuel properties and finally provide an all fuel performance in aviation activities [171].

3.15.2 Supply Chain Risks of Biofuels

While systematically understand the risks, it should be better to understand the biofuel supply chains. It is well known that transport fuel industry is capital intensive and this may be one of the main obstacles on the commercialization of advanced biofuels. Therefore, understanding the biofuel supply chain is important to consider cost optimizations.

First of all, costs may be reviewed based on the findings of Pavlenko's report. They find that Alcohol-to-Jet Fuel (AJF) technologies have various figures on production costs and carbon reduction rates. AJF production costs can vary substantially, ranging from €0.88 per litre for hydro-processed fuels made from waste fats and oils to €3.44 per litre for the direct conversion of sugar jet fuel which is two to eight times higher than the price of petroleum jet fuel. Moreover, they also find that the most cost effective fuel for reducing carbon emission is cooking oil-derived HEFA for the near term at approximately €200 per tonne of CO_2 equivalents. The next most effective options are the gasification of municipal solid waste and lignocellulosic feedstocks, which have a cost of approximately €400 to €500 per tonne of CO_2e reduced. They propose that while planning for policy incentives carbon emission rates should be considered. In line with this study, Neuling and Kaltschmitt [172] analyze aviation biofuels with a comparative perspective by considering techno-economic and environmental aspects. They find that in terms of energy efficiency, the HEFA processes seem to have the best performance characteristics. Moreover, using palm oil results in comparatively low production costs (890 €/t) and relatively low GHG emissions of 52.0 $g_{CO2}eq/MJ_{Kerosene}$. Furthermore, they find that lignocellulosic biomass demonstrates good results from a GHG-reduction point of view (30.4 to 38.2 $g_{CO2}eq/MJ_{Kerosene}$). From an economic point of view, ATJ using wheat grain feedstock seems to be the best option, resulting in biokerosene production costs of 827 €/t with higher GHG emission figures.

Based on Riviere and Marlair [173] the main subsystems of the biofuel chains are:

- the transport and storage of raw materials;
- the conversion processes to final biofuel. This subsystem includes the transport and the storage of materials necessary to processes;
- the transport of biofuel to filling stations;

- and the final use of biofuel in vehicles.

In this supply chain system, it can be assessed that risk assessment in biofuel supply chain may be classified two as transportation risks and storage risks because the biofuel chains include the transport of chemicals, by-products and biomass towards the plant, and the transport of biofuel from the plant towards the stations. The transportation can be done by using railroad tanker, by road tanker, by boat or by pipeline. An option would be to also consider transport issues of effluents where pertinent. From the storage side, it can be said that the same products need to be stored in a large amount.

The biofuel chains include the storage and use of chemicals (acid, alkali, solvent, catalyst.), of biofuel, of biomass and of by-products or effluents. These materials are stored in a large amount. There are several risks identified as (1) the risk of self-heating; (2) the risk of dusts explosion; (3) the risk of spill materials. These can be interpreted as supply risks and eventually affect the aviation fuel system.

From a modelling perspective, Debnath [174] asserts that if the initial biorefineries are located in regions with less biomass yield variability, then the *n*th biorefinery may be located in a region with more yield variability and greater feedstock cost. His model is applied for switchgrass and miscanthus and propose that these models can even be used for short rotations of woody crop operations too. The value of strategically selecting land to contract will vary across regions and across species. These models are significant for survivability of the biorefinery firms. If there will not be optimized solutions, biorefineries cannot operate and produce biofuels, and it will risk aviation fuel supply.

3.15.3 Impact on Biodiversity and Ecosystem

Beyond supply chain risks, there are some other risks concerning the production of biofuels. Correa et al. [175] summarized the impacts of biofuel production on biodiversity and ecosystem services with six main categories. First one is competing for the land-use category, and this category consists of how much GHG will be emitted and how much biodiversity will be lost after the replacement of original systems by biofuel production systems. The transformation of native ecosystems leads to fragmentation, habitat losses, and large CO2 emissions arising from losses in biomass and soil carbon contents. The competition with agricultural lands increases the potential for indirect land-use changes, leading to increases in CO2 emissions, further biodiversity losses and environmental degradation outside biofuel cultivation areas.

The second category is spatial configurations of cultivation landscapes, and in this category, a combination of intensive production areas, agroforestry systems, and forest patches (i.e., land-sparing) has been proposed as a way to maintain regional biodiversity and ecosystem services for oil palm cultivation. Alternatively, biofuel cultivation areas could be managed to promote higher biodiversity (i.e., land-sharing). Therefore, biofuel cultivation and conversion technologies should be considered based on the saving rate of GHGs in the production process when compared to fossil fuels and other alternatives. Then, soil disturbance should be considered as another performance factor. Finally, the effects on local and regional persistence of native species should be considered.

In this sense, it has been reported [176] that microalgae biofuels have several advantages over traditional agricultural biofuels by yielding more oil per hectare of land, producing higher-quality fuel, and not require arable land or freshwater. Moreover, in this production process, besides fuel, animal feed, biopolymers, or nutritional oils can be produced too. However, despite these advantages, there is some uncertainty about the carbon impact of microalgae biofuels when the involvement of higher energy use, greenhouse-gas emissions, and water use considered [177].

However, a different perspective on microalgae biofuels [178] hypotheses that GM microalgae can easily invade ecosystems due to their small size, rapid growth, and enormous number. The main environmental concerns relate to competition between the introduced microalgae and native species, changes in natural habitats, horizontal gene transfer, and toxicity. Mainly, the risk posed by GM microalgae mainly depends on their persistence against biotic and abiotic stresses in the presence of native species. The risks of GM Algae are summarized as human health (Allergies, Antibiotic resistance, Carcinogens, Pathogenicity or toxicity) or environment (Change or depletion of the environment, competition with native species, horizontal gene transfer, pathogenicity or toxicity).

3.15.4 Security Considerations

Security of alternative aviation biofuels may be considered from the agrobioterrorism window, i.e. as the use of pathogens or toxins against agricultural products or facilities. Bioterrorists favoured these attacks, because the used material do not affect humans, the difficulty of distinguishing it from a natural outbreak, using vast and unsecured area, and finally low biotechnical and operational barriers compared to human targeted biological war [179]. It has been proposed that there may be some counterstrategies for agrobioterrorism as using effective detection systems, genetic engineering and advanced agricultural techniques, and effective cooperation between countries.

Ratner et al. [180] noted that the impact assessments of traditional aircraft are more accurate since they also take into account the impact of the airport infrastructure. The use of electricity as a fuel, on the one hand, simplifies the infrastructure (storage and transportation of kerosene is not required), and on the other hand, complicates it (chargers are needed for batteries, containers for loading and placing them in the aircraft, modifying loading mechanisms). The use of hydrogen fuel significantly changes the infrastructure. It is not yet clear what contribution these changes have to the overall environmental load across the entire life cycle and across all categories of impact.

4 Electrofuels

Electrofuels are those that use renewable energy for fuel synthesis and that is carbon-neutral with respect to greenhouse gas emission. Some potential electrofuels respect to the potential application as aviation fuels are n-octane, methanol, methane, hydrogen and ammonia. The physical and combustion properties significantly differ from jet fuel, except for n-octane. Different electrofuels perform differently with respect to important aspects such as fuel and air mass flow rates.

Electrofuels can generally substitute conventional kerosene-based fuels but have some downsides in the form of higher structural loads and potentially lower efficiencies. Synthetically-produced n-octane is a potential candidate for a future electrofuel where even a drop-in capability is given. For the other fuels, more issues need further research to allow the application as electrofuels in aviation. Specifically interesting could be the combination of hydrogen with ammonia in the far future; however, the research is just at the beginning stage [181].

European green transport group Transport and Environment (T&E) found that replacing fossil fuels in planes with "electrofuels" is the "only technically viable solution that would allow aviation to exist in a world that avoids catastrophic climate change". This will present a challenge to consumers as well as the industry, as the expense of these fuels means the cost of a plane ticket is projected to rise 58% if they replace kerosene in all aircraft.

Electrofuels are produced by combining hydrogen with carbon extracted from CO_2, as schematically depicted in Figure 19.30. Ideally, the hydrogen would be produced by electrolysis using renewable electricity to obtain it from water, and this would be combined with CO_2 sucked from the atmosphere to make a drop-in fuel. If such a process was implemented on a large scale, it would be effectively carbon neutral – but it with present time technology would cost up to six times more than jet fuel [182].

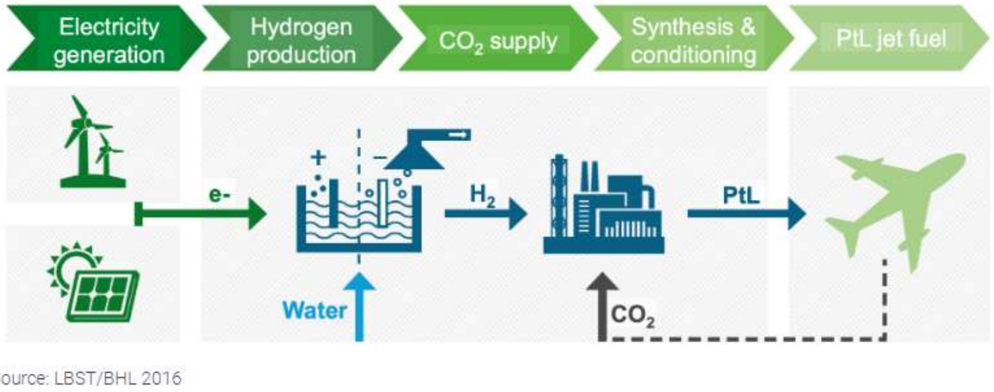


Figure 19.30. Possible electrofuel pathway [183]

4.1 Power-To-X

Due to the obstacles in using hydrogen as a fuel, molecular hydrogen is generally used as a chemical intermediate for the production of easily manageable liquid or gaseous fuels, such as methane ("power-to-gas") and longer chained hydrocarbons ("power-to-liquid") from carbon dioxide (Synfuels), or for the production of ammonia from nitrogen ("power-to-ammonia"). All three conventional "power-to-X" technologies (Figure 19.31) share the combination of the electrolytic hydrogen synthesis and subsequent catalytic conversion of the hydrogen gas with carbon dioxide or nitrogen.

- The power-to-gas process usually involves the methanation of hydrogen and carbon dioxide (by the exothermic Sabatier process). Methane is much easier to transport and to store than hydrogen. Based on its availability from fossil resources (natural gas), methane is already a well-established fuel for ground transportation. Infrastructure and motor optimizations are at a high level compared to other novel fuels, which represents a major advantage. Methane can be used either as compressed gas (compression of 200-250 bar) or in liquefied form (boiling point of 161.5°C).
- The synthesis of longer chained hydrocarbons is achieved via the power-to-liquid process. In the first step, a fraction of the electrolytic hydrogen is required to reduce carbon dioxide to carbon monoxide. Mixed with further hydrogen, the latter forms syngas: the precursor for the subsequent Fischer–Tropsch synthesis. Depending on the operational conditions such as syngas composition, pressure and temperature, as well as the catalyst system, fuels with desired properties can be synthesized. Synthetic fuels produced from renewable electricity, CO and water via Power-to-Liquid (PtL) processes may offer an alternative fuel source for aviation in the long term [85].
- The power-to-ammonia approach provides the opportunity for a completely carbon-free fuel and for using one of the most abundant elements of our atmosphere, nitrogen, as a hydrogen carrier. Currently, the well-known Haber–Bosch process is the standard technology for ammonia production. The Haber–Bosch-process has an energy efficiency of around 60%, assuming the hydrogen is produced via steam reforming from fossil fuels. Another way is the electrochemical reduction of molecular nitrogen to ammonia via the comparatively new solid-state ammonia synthesis (SSAS). Due to the high activation barrier, elevated reaction temperatures in the range between 80 and 650°C seem to be necessary. The overall energy efficiency of the SSAS process can be as high as 66% [184]. The storage of ammonia is considerably easier compared to hydrogen. Liquefaction is achieved already at a pressure of 10.3 bar [185]. Utilization of ammonia by combustion is a rather weakly-researched area. Major disadvantages of ammonia as a fuel are:
    - its low energy density, which, even in the liquid state, reaches only one-third of regular gasoline/kerosene
    - its corrosive chemical nature, which requires new materials for storage tanks and fuel lines
    - its toxicity.
- The all electrochemical synthesis entails the hydrogenation of target molecules, such as carbon dioxide, biogenic oxygenates or nitrogen. It is achieved using protic solvents (preferably water), as a proton source, and electrons, delivered by the cathode of the electrolyzer. The direct electrochemical reduction of carbon dioxide, e.g., to methane, ethane or methanol, has been the subject of recent research with incremental progress [186, 187, 188, 189, 190, 191].

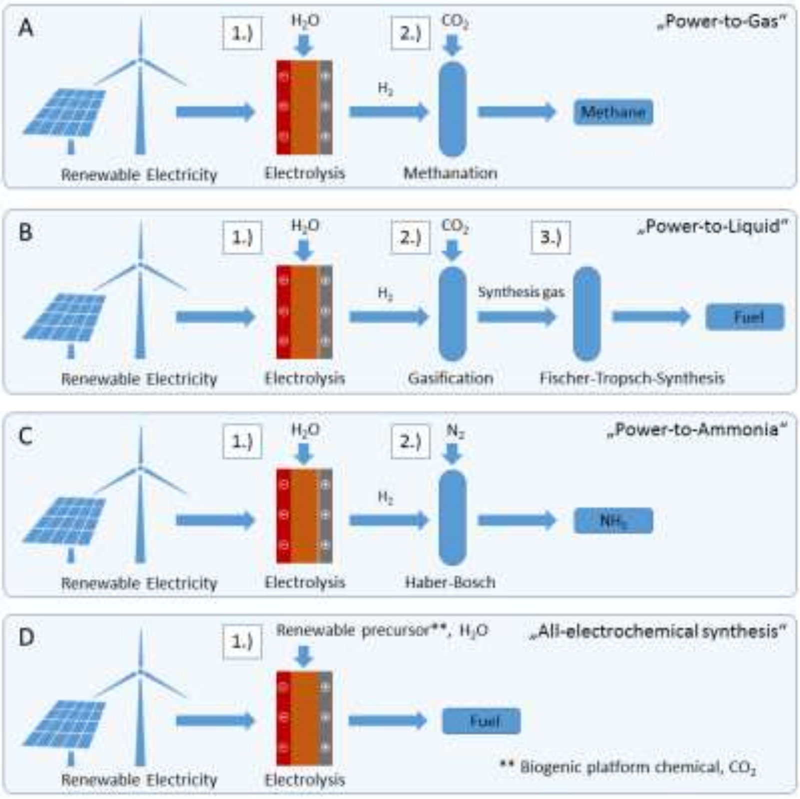
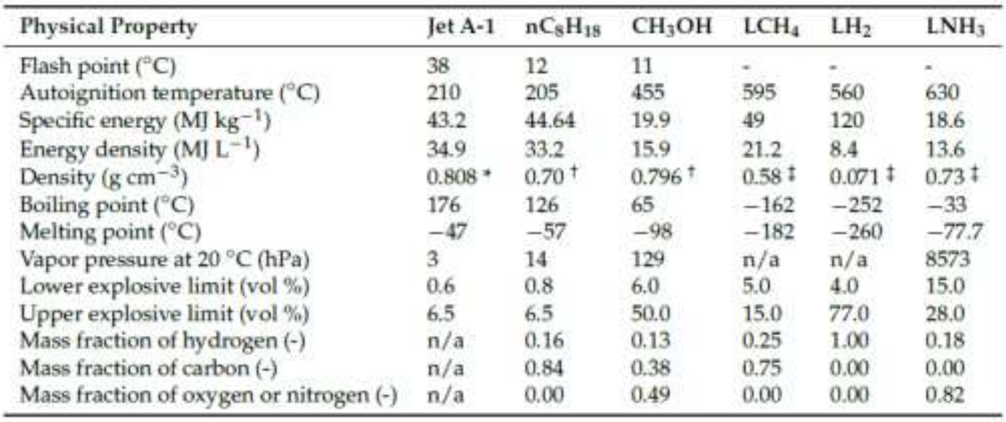


Figure 19.31. Schematic illustration of the described "power-to-X" technologies: (A) Power-to-Gas; (B) Power-to-Liquid; (C) Power-to-Ammonia; (D) All-electrochemical synthesis [181].

New one-step reactions are needed to bypass the production and the storage of hydrogen to raise energy efficiency further. Electrochemical pathways can be, given the appropriate technology readiness, more efficient than conventional processes and are needed to steer the demand of electricity in a way that new regenerative energies can handle. All electrochemical pathways are, in terms of technology readiness, far behind, but have the potential for the creation of tailor-made emission-free aviation fuels with renewable energies.

4.1.1 Comparison of Physico-Chemical Fuel Properties

Based on the discussed synthesis processes, five representative electrofuels are reported: n-octane, methanol, methane, hydrogen, ammonia. They are compared with conventional jet fuel (Jet A-1) regarding some selected properties of importance for the utilization as potential sustainable aviation fuels; see Table 19.31.



Physical Property	Jet A-1	nC_8H_{18}	CH_3OH	LCH_4	LH_2	LNH_3
Flash point (°C)	38	12	11	-	-	-
Autoignition temperature (°C)	210	205	455	595	560	630
Specific energy (MJ kg^{-1})	43.2	44.64	19.9	49	120	18.6
Energy density (MJ L^{-1})	34.9	33.2	15.9	21.2	8.4	13.6
Density (g cm^{-3})	0.808 *	0.70 †	0.796 †	0.58 ‡	0.071 ‡	0.73 ‡
Boiling point (°C)	176	126	65	−162	−252	−33
Melting point (°C)	−47	−57	−98	−182	−260	−77.7
Vapor pressure at 20 °C (hPa)	3	14	129	n/a	n/a	8573
Lower explosive limit (vol %)	0.6	0.8	6.0	5.0	4.0	15.0
Upper explosive limit (vol %)	6.5	6.5	50.0	15.0	77.0	28.0
Mass fraction of hydrogen (-)	n/a	0.16	0.13	0.25	1.00	0.18
Mass fraction of carbon (-)	n/a	0.84	0.38	0.75	0.00	0.00
Mass fraction of oxygen or nitrogen (-)	n/a	0.00	0.49	0.00	0.00	0.82

*Table 19.31. Comparison of physical and chemical properties of Jet A-1 and different potential electrofuels (L = liquified; * at 15°C; † at 20°C; ‡ at boiling point) [192].*

4.1.2 Combustion Characteristics

All investigated electrofuels, except n-octane, differ significantly from jet fuel regarding their combustion properties. For a combustion chamber case under typical aviation conditions, several important parameters are calculated for a constant cruise operating point. The mass flows of air for combustion and cooling the burned hot gases are nearly the same, whereas the mass flow of fuel differs due to the specific energy Figure 19.32.

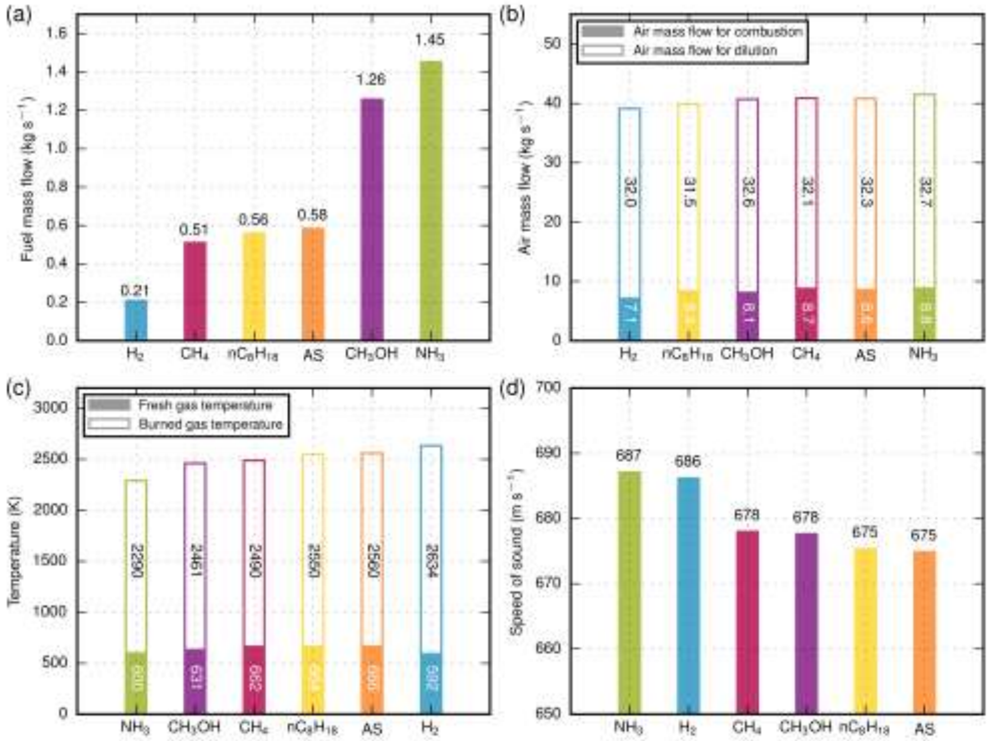


Figure 19.32. Inlet and outlet parameters of the schematic combustion chamber: (a) Fuel mass flows; (b) Air mass flows; (c) Temperatures; (d) Speed of sounds [181].

Mixture approaches (ammonia/hydrogen mixture) might be of special interest, where more research is needed. The design of combustors has to be adapted to the fuels, requiring basic research on flame stabilization and emission. Although this process will need great effort, it provides the chance to reduce the emission of soot and nitrogen oxide, if the combustion were based on more advanced approaches, like lean premixed or partially-premixed combustion.

4.1.3 Turbine Performance

The fuel choice has an influence on turbine performance. As a consequence of the reduced mass flow and the reduced engine speed remaining constant, absolute mass flow decreased, and absolute rotational speed increased. Higher power output and higher shaft speed is observed for all fuels presented. The alternative electrofuels considered may be used in current turbine designs without major performance impacts. With regard to the aerothermodynamics of the hot gas path, they can even be used with current designs. With regard to the turbomachinery design, however, the increase in rotor speed changes the mechanical loads and thus requires modifications in the mechanical design. The fuels, therefore, are not drop-in options, but appear to be alternatives worth further evaluation with regard to the upstream fuel supply chain and, if that turns out promising, with regard to a more detailed component design for the compressor, the combustor and the turbine of the aeroengine.

4.1.4 Availability and Impacts

We only consider drop-in electrofuels - i.e. electrofuels which can be used by aircraft through combustion in a jet turbine, with minimal or no modifications to the aircraft, engines or ground refuelling infrastructure. This draws a line with other types of fuel, such as hydrogen, which requires completely new aircraft designs and new airport refuelling infrastructure. A hydrogen scenario has similar, though slightly lower, implications to synthetic fuels in terms of costs and additional electricity needs.

The emission reductions resulting from the use of electrofuels depend mainly on what electricity is used to produce the hydrogen, and the choice of the source of CO_2 leads to different impacts. Using CO_2 from a fossil carbon origin, such as the one being emitted in a steel or a power plant, means the fuel is not carbon circular because the CO_2 ends up in the atmosphere anyway. Designing a synthetic fuel production chain around carbon capture risks locking-in one sector to decarbonise the other, creating a disincentive to move towards full decarbonisation. In a 2050 timeframe, the alternative is to use CO_2 captured directly from the atmosphere - a more expensive process, but one which ensures the electrofuels is fully circular. Despite these cost impacts, as fuel efficiency improvements will not decarbonise aviation, and with advanced sustainable biofuels unable to meet all of aviation fuel demand in 2050, if the sector wishes to decarbonise, it must steadily and in a sustainable manner increase electrofuels production to meet the remainder of its fuel demand. At least until more radical technology breakthroughs become available [19].

However, the cost implications of electrofuels will remain substantial. Direct air capture costs are falling but will remain considerable for some time. While renewable electricity costs are falling, and in some cases reaching parity or falling below non-renewable electricity costs, the fact that electrofuels production requires enormous quantities of electricity means that its cost will likely exceed that of untaxed kerosene. It is unlikely that, even with carbon pricing, electrofuels will reach cost parity with kerosene. As a result, policies will need to be put in place to ensure the uptake of electrofuels. These policies are detailed below, but any policy which requires airlines to purchase a more expensive fuel will result in an overall increase in operational costs. At least some of that increase can be expected to be passed onto consumers, increasing the price of tickets, and thereby reducing demand. In available forecasts, the impact that this reduced demand will have on air traffic and thus the overall demand for fuels is taken into account.

It is worth noting the impact that electrofuels uptake will have on overall electricity demand: meeting aviation fuel demand with electrofuels will require 912 TWh. This amount is equivalent to 28.2% of Europe's total electricity generation of 3234 TWh in 2015, or 94.4% of the 966 TWh of renewables generation (Figure 19.33). Note that this electricity used in the production of electrofuels will have to be renewable and additional for the resulting fuel to be considered zero carbon. Also, other sectors, such as industry, are expecting to use some types of electrofuels as a way to decarbonise. Such demand will have a considerable impact on broader efforts to decarbonise the European economy - it could mean that additional renewable electricity is used to create electrofuels, when it could have been used in a more efficient manner by other sectors of the economy.

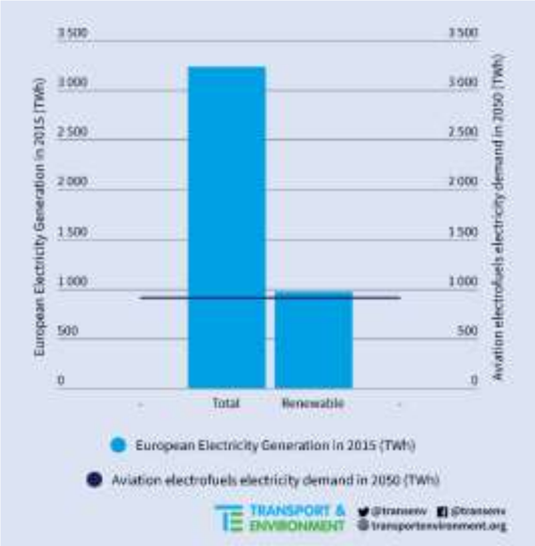


Figure 19.33. Electricity required to produce electrofuels for EU aviation in 2050

These competing demands for additional renewable electricity need to be taken into account to assess the realistic amounts of electrofuels which could be used in aviation. In the production of electrofuels only a portion will be suitable for use in the aviation sector (for example 80% - a very optimistic assessment). As with advanced sustainable fuels, there is a risk of some residual emissions from electrofuels. And as stated above, the zero-carbon status of these fuels is dependent on their potential displacement impacts, the manner of their production and therefore on the broader decarbonisation of the economy.

In the proposed scenario electrofuels are produced from 100% additional renewable electricity using direct air capture CO_2. With a cost of 2,100 Euro per ton in 2050, electrofuel uptake will increase ticket prices a further 23% compared to a ticket price with a 150 Euro/ton CO_2 equivalent price, resulting in a 28% reduction in projected passenger demand compared to a business-as-usual scenario. Safeguards are essential in order to ensure that electrofuels results in actual emission reductions, without negative side effects on other sectors. As discussed above, the two areas of concern are the supply of electricity and the supply of CO_2. Renewable electrofuels have an expanded role in the regulatory framework proposed for the RED II (Renewable Energy – Recast to 2030) [193].

4.1.5 Power to Liquid production in Europe

On June 2020, an industrial consortium (main partners: German PtL technology provider Sunfire, Swiss-based CO_2 air capture technology specialist Climeworks, Luxembourg-headquartered international engineering company Paul Worth SMS Group and Valinor, a Norwegian family-owned green investment company) is planning Europe's first power-to-liquid (PtL) plant that will produce hydrogen-based renewable aviation fuel in Norway. The Norsk e-Fuel consortium is initially looking to build a demonstration plant at the Herøya Industry Park in Porsgrunn, near Oslo, capable of producing 10 million litres of fuel a year before scaling up the facility to commercially produce 100 million litres by 2026. The output of the full-scale plant would save an estimated 250,000 tonnes of CO_2 emissions annually and fuel the five most frequently serviced domestic routes in Norway with a 50% blend. The renewable fuel would be generated from CO_2 and water using 100% renewable electricity. The demo plant would cost €90 million. Using a single-step co-electrolysis process, Sunfire and Climeworks technologies convert renewable electricity, water and CO_2 captured from ambient air and unavoidable CO_2 sources into syngas, which is then converted through the established Fischer-Tropsch process into renewable fuels. For a commercial-scale plant to produce 100 million litres of jet fuel annually would require a renewable electricity demand of roughly 200 megawatts. A flight between Berlin and Beijing using a 10% PtL blend would increase the ticket cost by around 50 euros. To fulfil a quarter of European aviation's annual demand for jet fuel by 2040 from renewable sources would require around 20 billion litres. Prices for the PtL fuel from the demo plant will be higher initially than for biofuel alternatives, but in the long run, having industrialised plants with cheaper electricity resources will enable us to push production prices down to between €1 and €1.50 per litre, depending mainly on electricity prices [194].

5 New propulsion technologies: Liquid Hydrogen

5.1 Hydrogen from Water Electrolysis

The electrolysis of water to produce hydrogen has been well known since the end of the 18th Century [195]. The energy efficiency of the water electrolysis is already high (70–80% [196]). Hydrogen is an almost ideal electrofuel and has been, for a long time, considered as the core energy carrier of future energy systems [197]. Hydrogen possesses the highest gravimetric energy density of all fuels. However, hydrogen has a very low volumetric energy density and a high diffusion coefficient, which makes hydrogen difficult to store. Compression and liquefaction are the main ways to store hydrogen effectively, but hydrogen compression consumes 15.5% of the hydrogen's inner energy content and liquefaction up to 45% [198]. The use of hydrogen in a combustion engine or its oxidation in a fuel cell ("cold combustion") currently yields efficiencies from 40% (combustion) up to 55% (fuel cell). Well-to-wheel efficiency would be, given the data above, between 15.4 and 37.2%.

5.2 Hydrogen for propulsion

A new independent study, commissioned by Clean Sky 2 and Fuel Cells & Hydrogen 2 Joint Undertakings on hydrogen's potential for use in aviation found that hydrogen, as a primary energy source for propulsion, either for fuel cells, direct burn-in thermal (gas turbine) engines or as a building block for synthetic liquid fuels, could feasibly power aircraft with entry into service by 2035 for short-range aircraft (Figure 19.34).

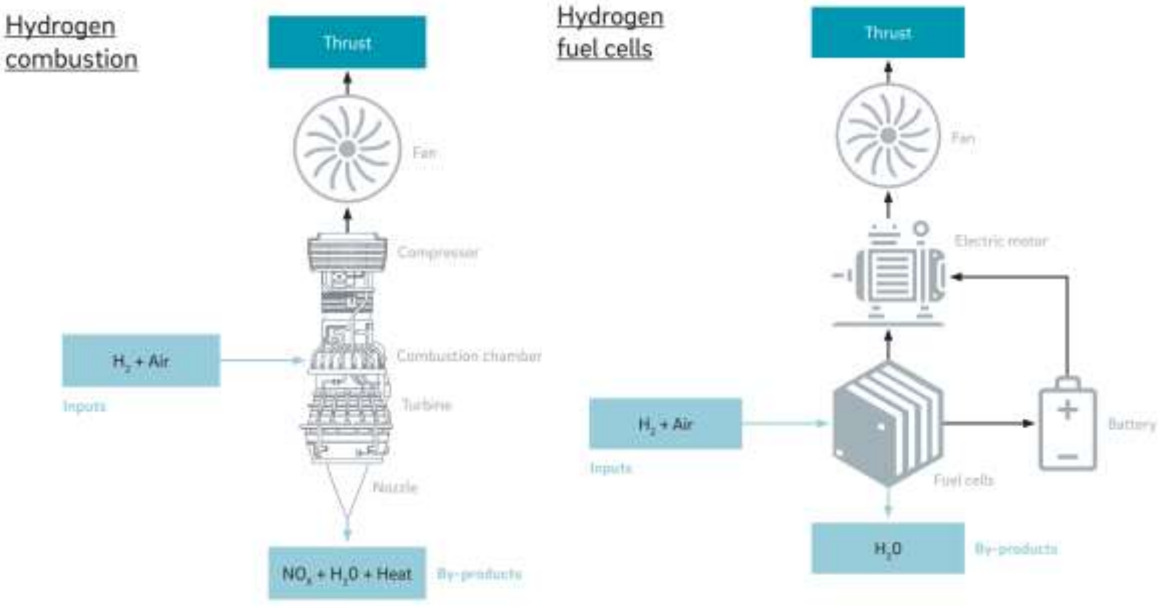


Figure 19.34. Possible uses of hydrogen in aircrafts [199]

Costing less than €18 [$20] extra per person on a short-range flight, and reducing climate impact by 50 to 90%, hydrogen could play a central role in the future mix of aircraft and propulsion technologies. Such disruptive innovation will require significant aircraft research and development, further development of fuel cell technology and liquid hydrogen tanks, and also an investment into fleet and hydrogen infrastructure and accompanying regulations and certification standards to ensure safe, reliable and economic hydrogen-powered aircraft can take to the skies. Industry experts anticipate that it will take 10 to 15 years to make these important advancements, and consequently, the research needs to start now. The study estimated that the first short-range hydrogen-powered demonstrator could be developed by 2028 if sufficient investments into R&I are made. The technical challenges and unique characteristics of hydrogen as an on-board energy source make it best suited to commuter, regional, short-range and medium-range aircraft. For the next decades, longhaul air travel is likely to be based on liquid hydrocarbon fuels; but increasingly these too will need to be sustainable, and these 'drop-in' fuels will also rely on hydrogen for their production [200].

Hydrogen can be used as a fuel for aircraft when it is combusted in an H_2 burning engine or reacted in a fuel cell powering electric motors. Despite the three times higher gravimetric energy density compared to kerosene, hydrogen's relatively higher volume requires larger volume, which requires larger tanks on-board the aircraft and adjusted aircraft designs. The size and weight of H_2 tanks pose major limitations for high energy demand on long-range flights [15, 14]. From a fuel-supply perspective, hydrogen has other advantages: it can be produced directly from renewable energy and its synergies with other hydrogen-dependent sectors can be realized[4]. A ramp-up in hydrogen demand across sectors would unlock scale effects that would at least partially mitigate the initial cost disadvantages.

Hydrogen propulsion is projected to be two to three times more effective than synthetic fuels in reducing aviation's climate impact. Even at this early stage, the rough order of climate impact can be: Aircraft using fuel cell systems can reduce climate impact the most, by an estimated 75 to 90 %. H_2 combustion aircraft are the next best alternative, with 50 to 75 % reduction. Synfuels using CO_2 from direct air capture land at 30 to 60 % reduction, while reduction potential from synfuels utilizing CO_2 from industrial processes depends on the accounting of CO_2 emissions. Hydrogen as a fuel does not contain carbon; thus, its combustion does not cause CO_2 emissions in flight. Reducing NOx comes with a trade-off since it increases fuel burn, raising CO_2 emissions. Initial studies of H_2-powered aircraft show that NOx emissions can be reduced by 50 to 80 % with lean-mixture technology without large reductions in efficiency [201, 202]. Further research and development are required to realize these advantages. When a fuel-cell propulsion system is used, no NOx emissions arise in the reaction of hydrogen [203].

5.2.1 Technical feasibility

Hydrogen and fuel cell technology has undergone significant development in the last decades. Based on an extensive literature review, industry perspectives on technology development, and expert interviews, this study built what experts considered an "optimistic and achievable" projection of the performance of H_2 propulsion components for the next 5 to 10 years.

The most important components in a hydrogen aircraft are [203]:

- Hydrogen tanks: Hydrogen can be stored as pressurized gas or in liquid form. While gaseous storage can be suitable for shorter flights and is commercially available, this study focuses on liquid hydrogen (LH2) storage tanks as they require roughly half as much volume and consequently, they are significantly lighter than tanks for gaseous hydrogen. This is especially important for short- to long-range segments, where aircraft will carry several tons of hydrogen per flight. Compared to kerosene, LH2 tanks are still about four times as big. Since LH2 needs to remain cold and heat transfer must be minimized to avoid vaporization of hydrogen, spherical or cylindrical tanks are required to keep losses low [204, 205, 206, 207]. To efficiently integrate the tanks into the aircraft's fuselage, the airframe will need to be extended, which increases the aircraft's operating empty weight[5].
- A LH2 fuel system for the distribution, vaporization, and feeding of LH2 to the fuel cells or turbines: LH2 requires cryogenic cooling down to 20 degrees Kelvin. These temperatures must be handled by

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[4] Only difference for other industries is that additional liquefaction capacity will be needed

[5] For aircraft below the short-range segment, storing the hydrogen in pods below the wing could also be an option since the performance is not decreased too much but maintenance, safety, and modularity aspects are much easier to cope with.

pipes, valves, and compressors; boil-off needs to be kept low; and leakage and embrittlement of material avoided.

- Fuel cells (for fuel cell-powered aircraft): In a fuel-cell-powered aircraft hydrogen is converted into electricity that then drives an electric motor and a fan or propeller. Most advanced and suitable for aviation today are low-temperature proton-exchange membrane (PEM) fuel cells. Adding an energy storage such as a battery to this system helps ensure fast load following and power peak shaving to optimize the sizing of the fuel cell system[6].
- Hydrogen direct-burning turbines (for H2 combustion): In H2 combustion airplanes LH2 is directly burned in a turbine, much like kerosene, to create thrust [208] [209].24 The use of cryogenic cooling of the fuel is expected to slightly increase efficiency (40 to 50% lower heating value [LHV]) compared to conventional engines. This study also considers a hybrid system of H2 turbines and fuel cell systems. Such a system could optimize the higher power densities of turbines with the higher power densities of turbines the higher efficiencies and lower climate impact of fuel cell systems.

The most important technology developments required for H2-powered aircraft are [203]:

- LH2 tank mass needs to be reduced by 50% compared to current prototypes. There are various levers to reduce the required tank mass, including boil-off requirements on the ground, which are set by safety regulations; scaling effects for larger volumes; advanced tank designs that integrate into the aircraft fuselage; and the use of lightweight material for double-insulated tank walls and insulation. The tank mass is expressed by the gravimetric index and is defined as the weight of the LH2 fuel mass in relation to the full weight of the LH2 tank filled with maximum LH2 fuel. The latest concepts for commuter aircraft have a gravimetric index of up to 20% [210]. For short-range aircraft, an index of 35% needs to be achieved, for long-range aircraft 38%. Any improvement in this area lowers the weight and volume of the aircraft, which reduces energy demand and therefore improves the economics of building and operating the airplane.
- Safe and reliable fuel distribution and components are critical in H2-powered aviation. Safe and reliable systems that also optimize heat management do not exist today and need to be developed, extensively tested, and certified for commercial aviation.
- LH2 propulsion systems have to be developed for safe operation over a long lifetime. H2 turbines need to be optimized for climate impact with very low NOx emissions at the same time they are highly efficient in creating thrust. The new fuel cell system technology will need to achieve up to two to three times more system power density than current fuel cell systems, with an improved density of 1.5-2 kilowatts per kilogram (kW/kg). This new design for the fuel cell system is projected to operate with efficiencies of up to 55 to 60% (LHV). For higher power ratings in the megawatt-classes, the cooling of fuel cell systems requires volumetric optimized heat exchangers.

While these advancements are ambitious, projections of technology development and experts considered them achievable within 5 to 10 years.

5.2.2 Economics (total cost of ownership) of H2 aircraft

Comparing the costs of aircraft [203], the total costs of ownership (TCO) of an aircraft need to be considered. Compared to kerosene aircraft, H2 aircraft have different costs for fuel and related infrastructure, the aircraft itself, and operations. The comparison for synfuels is simpler, as only fuel and related supply infrastructure costs differ from conventional aircraft. In our analysis, fuel costs encapsulate all costs for the production of the fuel and the required infrastructure for distributing, storing, and refueling the airplanes. They do not include indirect second-order effects that are uncertain and difficult to estimate today, such as the potential need to adapt airport gate box sizes to accommodate longer aircraft.

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[6] The potential use of supercapacitors and other storage solutions was not investigated in this study.

For a short-range aircraft in 2035, costs (Figure 19.35) increase by around 25% compared to a 2035-technology adjusted kerosene aircraft. The main cost differences come from higher energy costs, which affect the TCO by 9%, higher capital expenditure (CAPEX) for the aircraft (7%), and maintenance costs (6%) and other costs (3%).

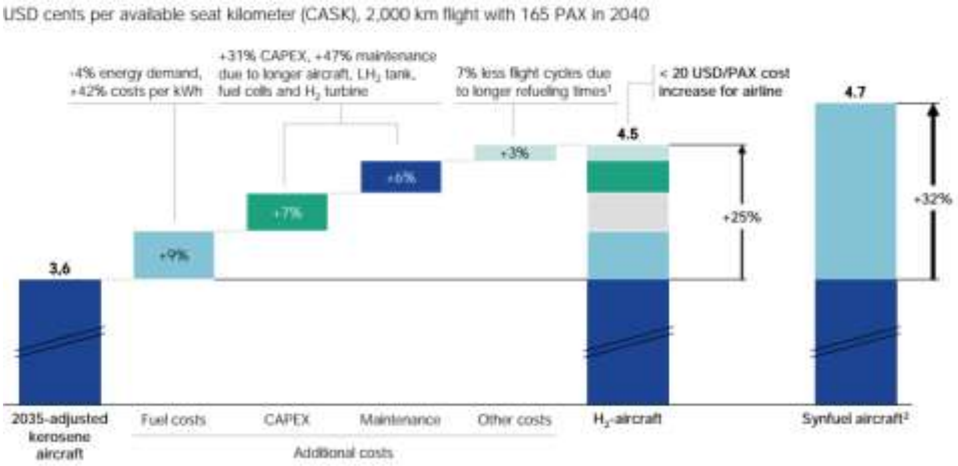

Figure 19.35. Cost comparison of H2 short-range aircraft versus kerosene and synfuel aircraft [203]

Energy costs depend on the cost of fuel and the required energy to propel the aircraft. Hydrogen aircraft are typically somewhat heavier and/or bulkier, requiring more energy to propel. Hydrogen is also more expensive in its production compared to kerosene, although its cost is expected to decrease rapidly. Due to the higher energy costs for synfuels from direct air capture, the TCO increase is higher than with the H2-powered aircraft. In 2050, LH2 fuel prices are expected to approach those of kerosene[7]26 because of the higher demand for LH2 and associated production cost improvements. While synfuel costs will also drop over time, they will remain structurally more expensive than hydrogen costs as they require an additional process step. Fuel costs will also depend on the changing energy demand for H2-powered aircraft compared to conventional reference aircraft. Aircraft CAPEX and maintenance costs. CAPEX for H2 aircraft is expected to be higher than for conventional aircraft. This is mainly due to the costs for the LH2 tank structure that is integrated into the fuselage, the increased complexity of the fuel distribution, increased costs for propulsion, and the increased aircraft size. Total maintenance costs for H2 aircraft might rise due to the larger airframe and the LH2 tanks that could require more checks – especially in the first years of introducing LH2 aircraft. In the long term, maintenance costs for the propulsion system might decrease.

Current assessments show that refueling times for H2 aircraft might be longer than those of conventional aircraft. Turnaround times would then increase and around 5 to 10% fewer flight cycles could be flown with the same aircraft. This would have a particularly pronounced effect on the aircraft CAPEX costs and on personnel (i.e., crew) costs, which could increase as H2 aircraft potentially fly 5 to 10% fewer flights per year. Airport and air traffic control fees mostly depend on the maximum take-off weight (MTOW) of an aircraft. For LH2 aircraft the MTOW will be higher and fees are expected to be marginally higher. However, this assumes that there are no fee subsidies for H2 aircraft and that landing fees will still mainly depend on MTOW in the future. This might be changed in the short-term to encourage the development of more climate-friendly technologies but would be adjusted in the long term once the roll-out of more decarbonized aviation is more broadly adopted.

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[7] Depends on the volatility of kerosene prices – current EIA projections, U.S. Energy Information Administration (2019)

5.2.3 Commercialization readiness

It is crucial to optimize time to market for new H2 aircraft given the objective of reducing the climate impact of aircraft by 2050 and the long ramp-up time from entry-into-service (EIS) of a widespread aircraft rollout. Conventional aircraft development cycles occur about every 15-20 years until a new aircraft platform is introduced. For short-range aircraft, which make up the bulk of emissions, the next window of opportunity is expected to be around 2030-2035. This would be the major chance to introduce new designs in short-range aircraft in order to have an impact on the climate before 2050 [203].

In general, aircraft commercialization starts with an ideation and concept phase, then development, certification, and aircraft handover. For H2 aircraft it will be critical to reaching a component technology readiness status of TRL6 as soon as possible to then build a fully functional prototype or representational model. During the same time, all components and the overall aircraft must be certified. Two concept design options, evolutionary and revolutionary, are possible during commercialization; they offer different pros and cons [203].

- Evolutionary aircraft designs will be characterized by the tube-and-wing design of current commercial aircraft. However, this approach would allow for a slightly adapted fuselage and airframe to accommodate the LH2 tanks. It would offer a faster entry-into-service for H2 aircraft and could employ conventional manufacturing and certification techniques. Although less efficient than a fully revolutionary aircraft, the evolutionary aircraft option appears a pragmatic low-carbon one given the short time frame.
- Revolutionary aircraft designs would allow new aerodynamic concepts and better integration of the LH2 storage (e.g., with a blended-wing-body design). One concept that is well suited for smaller aircraft is distributed propulsion. Several propellers on the wing and an adjusted wing layout lead to highly efficient wing aerodynamics [211, 212]. An option for medium- and long-range aircraft with a longer fuselage length could deliver thrust with an aft fuselage fan. The effect of boundary layer ingestion in this approach increases propulsive efficiency. The disadvantage of all radically new aircraft concepts is that they have a long, unpredictable commercialization process with extended development to ensure the aircraft's aerodynamic stability in all flight phases and to optimize cabin design, manufacturing, and operations.

H2-powered commuter, regional, and short-range aircraft could be commercially available in the next 10-15 years. Detailed analysis was done on potential hydrogen-powered aircraft designs for each segment. Together with industry and research partners, the most promising propulsion technologies were defined for each segment after analyzing each propulsion component and its performance.

Based on these most promising designs, detailed aircraft design studies were conducted for hydrogen-powered short-range and long-range aircraft. The aircraft concepts were designed using multidisciplinary, iterative sizing processes with several specialized semi-empirical and physics-based models. The design philosophy followed a stepwise approach to capture most of the phenomena that produce differences in performance. Starting from an existing aircraft, requirements and technologies are then gradually changed, which allows a seamless interpretation of the final results. For instance, conventional aircraft references (Airbus A320neo and Airbus A350-900) were adjusted, so they reflected similar conditions such as the technology in 2035 projections, shorter ranges, or lower speeds. The results of the simulation were used to create potential concept designs for medium-range aircraft. An assumption-based approach was chosen for commuter and regional aircraft; several expert discussions and a high-level calculation of H2 propulsion systems and components guided this analysis. The simulations yielded, for each aircraft design, the resulting energy demand and key technological parameters. These were then used to project total costs of ownership for each segment and compared to the reference aircraft powered by synfuel [203].

5.2.4 Airport refueling infrastructure and operations

While supply-side challenges will be significant in 2050 [203], they will not be unique in a future energy system that partially relies on hydrogen. (By some estimates, hydrogen could play a role in about 18% of final energy demand, with 24% in Europe by 2050.39) The challenges affecting the airport refueling infrastructure and operations are unique, however, and will require significant development and planning to overcome. They include searching for scalable refueling technology, optimizing refueling practices, and re-configuring airport infrastructure to introduce parallel fuel systems.

The first challenge is developing scalable refueling technologies. In many large airports today, hydrant pipelines are used to refuel aircraft, by 2040 cryogenic hydrant refueling systems for LH2 seem to be cost-technically infeasible, as their cost may be as much as five times the cost of conventional hydrant systems. Given this fact, the most viable near-term LH2 refueling technology seems to be the LH2 refueling truck. These trucks work well at smaller airports, where kerosene refueling trucks are used today, but at larger airports they could greatly increase ground traffic and pose logistical challenges.

For now, the optimal solution is unclear. Larger mobile refueling platforms or even refueling station lots away from boarding gates may be an option. The latter may sound cost-technically infeasible given today's required turnaround times, but considering the lengthier refueling times needed for medium- and long-range LH2 aircraft discussed below, an economic case could be made for refueling station lots if they greatly optimize refueling times. In the longer term, LH2 hydrant pipeline systems may become a viable solution. Refueling practices and operations will also need to be reviewed.

5.3 Energy efficiency

Throughout the value chain, it is possible to evaluate the Energy efficiency. The hydrogen value chain has energy losses from energy input in the production phase to the efficiency of the powertrain onboard the end user. From literature data, it has been estimated the energy efficiency from production to propeller for both electrolysis and gas reformation with carbon capture. According to IRENAs latest report, an alkaline electrolyser today has an energy use of 51 kWh/kg gaseous hydrogen, giving it an efficiency of 65%. A liquefaction plant-like Lindes Leuna facility with an energy use of 11.9 kWh/kg LH_2 has an efficiency of about 74%, where the efficiency is defined as LH_2 LHV / (LH_2 LHV + Liquefaction Energy). With a total energy input of 63 kWh/LH2 and a lower heating value of 33.3 kWh/kg LH2, the energy efficiency to produce 1 kg LH2 is 52%. When produced through gas reformation, the estimated energy needed to produce 1 kg of gaseous hydrogen with carbon capture is 48 kWh/kg, with 11.9 kWh/kg for liquefaction. Thus, the energy efficiency of the production phase is 55.5%, slightly better than by electrolysis.

During storage and distribution, multiple sources estimate a boil-off between 0.2 and 0.5% per day. IEA report a boil-off stream of 0.3% for liquid tankers for hydrogen delivery, while US Drive estimate 0.5% for liquid distribution tankers and a very low evaporation rate for large storage. The NASA LH2 tank at Cape Carnaval has a reported evaporation loss of 0.03% per day for storage over multiple years. US Drive also reports a loss of up to 5% when unloading the LH2 to vessel/local storage [213, 214]. This is higher than what has been reported by developers/suppliers during the work of this report, which indicate that bunkering with a minimum of losses, towards 1% is plausible. As a conservative measure, we have used the 0.3% loss for storage/distribution and 5 % in the bunkering phase. Boil-off during storage onboard the vessel is also a potential loss, but according to Air Liquide there are several options to permanently re-use boil of gas and thus eliminate the loss [215] or technology that increases the maximum holding time without boil-off [216]. Lastly, with an estimated efficiency of 50% for the fuel cell about 16 kWh of the input energy reach the propeller – thus the complete energy efficiency of the value chain is around 25% when produced by electrolysis and 26.5% when produced by gas reformation and carbon capture, see appendix for calculations. The energy losses in kWh are visualized in Figure 19.36 and Figure 19.37.

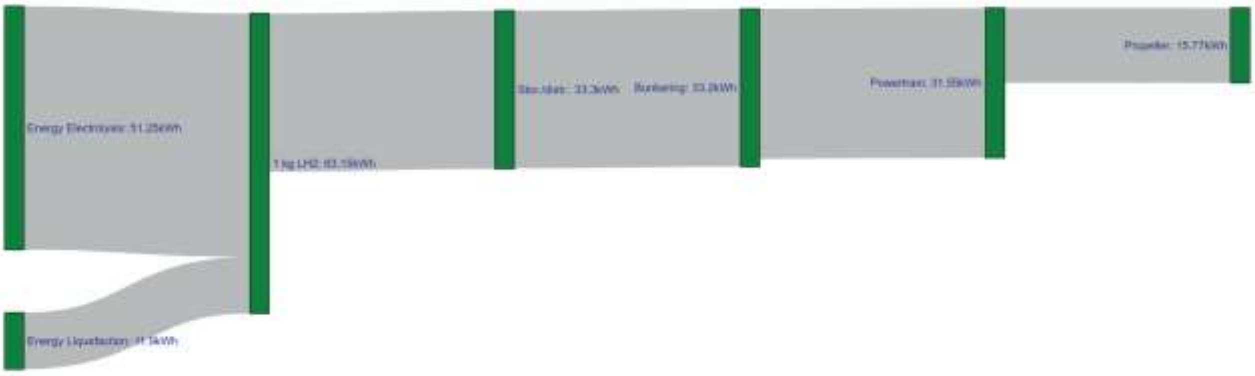


Figure 19.36. Energy losses from production to propeller – Electrolysis

Figure 19.37. Energy losses from production to propeller – Gas reformation with Carbon Capture

6 Concentrated Solar Power (CSP)

In June 2019, the ETH Zurich announced that it had pioneered a new kerosene alternative since it had been able to turn concentrated sunlight into liquid hydrocarbon fuels. The technology works by carbon capture. The process extracts CO2 from the atmosphere and mixes it with water and concentrated sunlight, also known as Concentrated Solar Power (CSP). This produces synthesis gas that can then be converted into jet fuel. The process involves solar thermochemistry, since large solar fields of mirrors are used to concentrate the sun's rays to very high temperatures in a solar reactor to catalyze the rearrangement of molecules of CO2 and H2O into synthetic hydrocarbons to ultimately manufacture aviation fuel (Figure 19.38).

Figure 19.38. IMAGE@Synhelion – A solar field of mirrors and tower for solar jet fuel production would look like today's tower CSP projects

Based on this technology, the Swiss startup Synhelion is working on commercializing two routes to solar jet fuel with the help of Italy's Eni, the 10th-largest oil company in the world [217]:

1. Long-term 100% solar fuel technology developed out of solar fuels research at ETH Zurich in Switzerland to manufacture jet fuel (kerosene) from carbon dioxide and water captured from the air, and is based on solar thermochemistry using heat as the energy input for producing the syngas, which is subsequently converted into liquid fuels.
2. A simpler solar reforming-based route that is more efficient than the pure water and carbon dioxide splitting process and based on existing industrial technology.

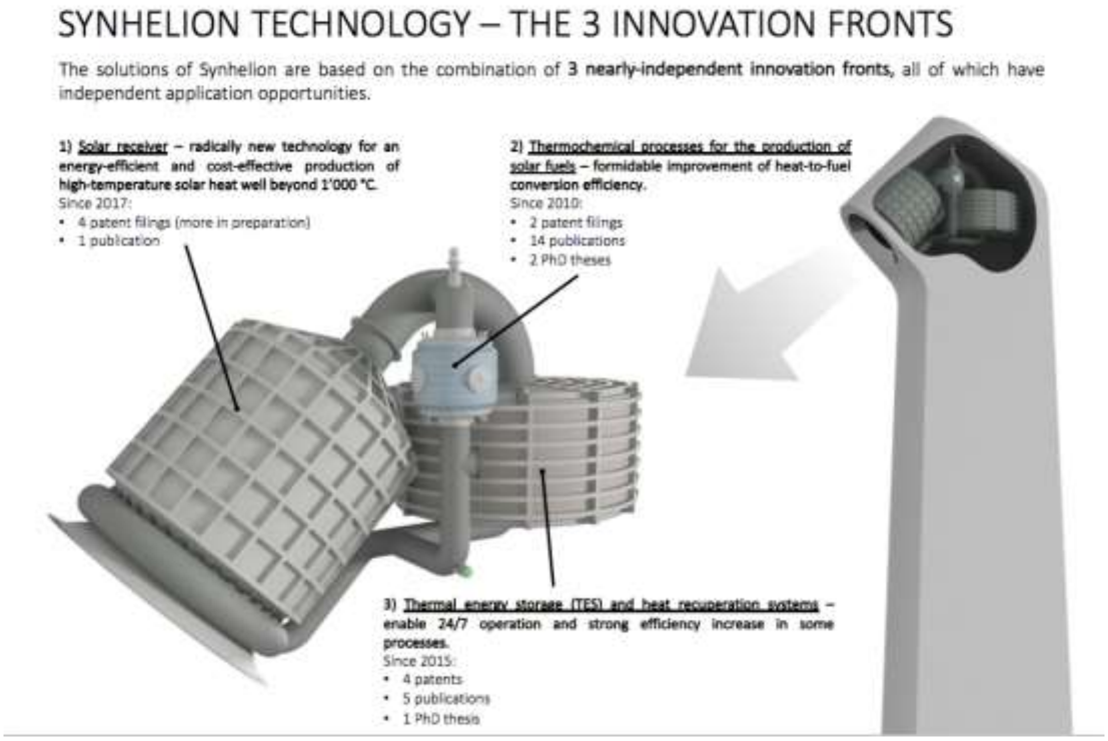
The two routes have essentially three steps; Step one; capture the ingredients. Step two; rearrange them into syngas. Step three; convert syngas into kerosene; aviation fuel (or other liquid hydrocarbons).

For the solar reforming route, for step one, they can get CO2 and water either from a point source like methane or from direct air capture.

Synhelion (Figure 19.39) will perform step two, delivering 800°C to 1100°C of heat from a solar field of mirrors to the reactor to perform the thermochemistry to produce syngas. The syngas will then be converted to liquid fuels, via standard industrial technology, such as Fischer-Tropsch synthesis, to produce the commercial aviation fuel. Jet fuel made through a solar reforming-based approach would be commercially viable in the short term and cost little more than today's jet fuel because reforming is a mature, standard technology. Solar reforming of a methane source uses the same technology as current reforming, except heat from a solar receiver is substituted instead of heat from burning natural gas. The fuel has about 50% lower

CO2 emissions at a similar price to fossil fuels can be produced. The solar reforming fuels would be commercialized by 2022.

For the jet fuel from air route; for step one, Synhelion is partnering with a company such as ETH Zurich spinoff Climeworks that captures CO_2 and H_2O directly from air (Figure 19.40). Synhelion will perform step two, delivering 1500 °C of heat from a solar field of mirrors to the reactor to perform the thermochemistry to turn these hydrocarbons into syngas. In step three, the syngas is converted to commercial aviation fuel, the same way as it is done today by large oil and gas companies. Synhelion can reach beyond the 20% reactor efficiency needed to make the jet fuel reasonably economical. However, larger-scale is needed to test. The start-up plans to scale-up the technology step-by-step to industrial size over several years. The goal is to enter the market with 100% solar jet fuel from the air by 2030.



SYNHELION TECHNOLOGY – THE 3 INNOVATION FRONTS

The solutions of Synhelion are based on the combination of **3 nearly-independent innovation fronts,** all of which have independent application opportunities.

1) Solar receiver – radically new technology for an energy-efficient and cost-effective production of high-temperature solar heat well beyond 1'000 °C.
Since 2017:
- 4 patent filings (more in preparation)
- 1 publication

2) Thermochemical processes for the production of solar fuels – formidable improvement of heat-to-fuel conversion efficiency.
Since 2010:
- 2 patent filings
- 14 publications
- 2 PhD theses

3) Thermal energy storage (TES) and heat recuperation systems – enable 24/7 operation and strong efficiency increase in some processes.
Since 2015:
- 4 patents
- 5 publications
- 1 PhD thesis

Figure 19.39. IMAGE@Synhelion: Tower schematic for Synhelion solar jet fuel production

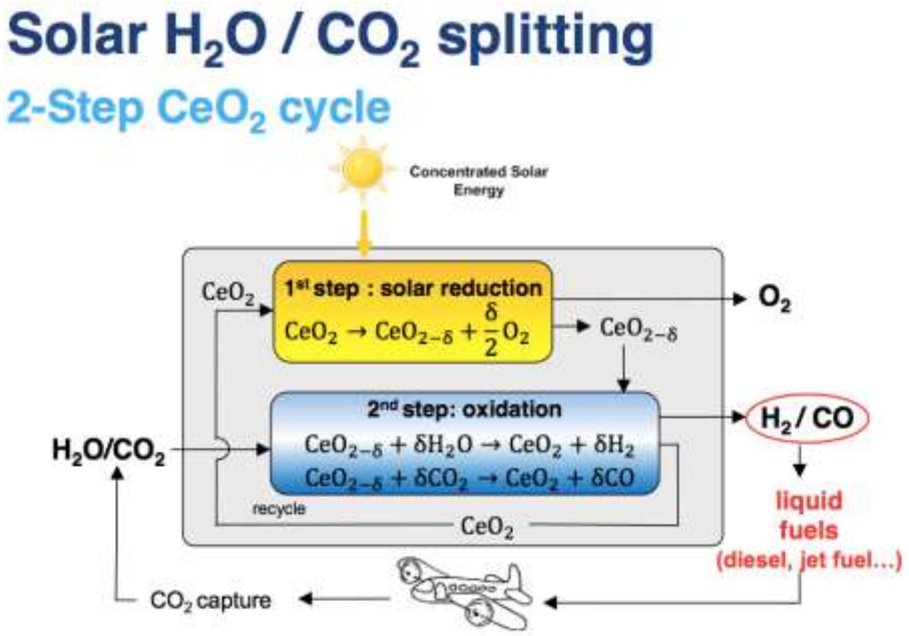


Figure 19.40. Philipp Furler Diagram of the jet fuel from air process

Despite the cost, this sunlight fuel is a lot more promising than other methods of producing clean aviation fuel. For example, the production of some biofuels can be taxing on other essential processes. The production of crops for fuel, as happens with some biofuels, is a direct competitor for the food market. Producing crops for fuel, at a large scale, impacts how much food we can grow and, subsequently, how many people get fed.

On 15th May 2020, the Lufthansa Group announced that it had partnered with Synhelion and Climeworks to bring concentrated sunlight fuel to the mass market.

7 Conclusions

In order to reach climate-neutral aviation, new architectures, product development and certification, deployment in the market are urgent. In particular, the transition to new sources of sustainable energy and aviation fuels is needed in much shorter timescales than anticipated to date. Exceptional research and technology efforts are required to reduce fuel consumption while ensuring safety and competitiveness. For this reason, research, development and deployment of sustainable aviation fuels by the relevant actors and proactive policies for wide-scale and economically viable use is a preeminent priority within the next decade [1].

There is still a significant price gap between sustainable and conventional jet fuels which is primarily because of the high production cost of SAF. However, SAF still has the potential to make an important contribution to mitigating the environmental impacts of aviation, and recent policy and industry initiatives are likely to have a positive impact on the development [218].

Seven biofuels for aviation production pathways have been certified (up to July 2020), and other pathways are in the qualification process. There is an increased interest in electro fuels which is introduced as zero-emission aviation fuel. However, high production cost is a big barrier, and there are only a few demonstration facilities.

Hydrogen propulsion has significant, so far underestimated potential to reduce the climate impact of aviation and contribute to decarbonization objectives. To initiate a path towards decarbonization through hydrogen, the industry needs to change trajectory today, as commercialization and certification of aircraft can take more than 10 years, and substantial fleet replacement another 10 years. To transition to a new propulsion technology, a sector roadmap to reduce climate impact, a step-up in Research & Innovation (R&I) activity and funding, and a long-term policy framework will be required [203].

Transforming aviation towards climate neutrality will require an integrated approach spanning technology providers and innovators, manufacturers and operators, public sector authorities and travellers. It will involve re-inventing innovation, product development and fleet replacement cycles needed to introduce a new breed of aircraft with decisive steps in aircraft technology. It will require infrastructure to make new fuels and energy sources available, climate-optimised networks and operations, and innovative public policy and regulation. The partnership can support the implementation of the right public policies needed to deliver the necessary impact in the aviation system and within the timeframes required [219].

8 References

[1] Long-term aviation fuel decarbonization: Progress, roadblocks, and policy opportunities, ICCT briefing 15.01.2019.

[2] «IATA. (2018). Aircraft Technology Roadmap to 2050. Retrieved from https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/technology20roadmap20to20205020no20foreword.pdf».

[3] «CAO. (2019). Electric, Hybrid, and Hydrogen Aircraft – State of Play. Retrieved from https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg124-130.pdf».

[4] «Synder et al. (2009). Propulsion Investigation for Zero and Near-Zero Emissions Aircraft. Retrieved from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090023315.pdf».

[5] «Hepperle, M. (2012). Electric Flight – Potential and Limitations. Retrieved from https://elib.dlr.de/78726/1/MP-AVT-209-09.pdf».

[6] «Misra, A. (2017). Technical Challenges and Barriers Affecting Turbo-electric and Hybrid Electric Aircraft Propulsion. Retrieved from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180004252.pdf».

[7] «Seitz, A., Schmitz, O., Isikveren, A.T., Hornung, M. (2012). Electrically Powered Propulsion: Comparison and Contrast to Gas Turbines. Retrieved from https://www.dglr.de/publikationen/2012/281358.pdf».

[8] «Scott W. Ashcraft, Andres S. Padron, Kyle A. Pascioni, Gary W. Stout, Jr. Dennis L. Huff, Review of Propulsion Technologies for N+3 Subsonic Vehicle Concepts, October 2011».

[9] «Comincini, D. (2018). Modular approach to hydrogen hybrid-electric aircraft design. Retrieved from http://hdl.handle.net/10589/143966».

[10] «IRENA. (2014). Global Bioenergy Supply and Demand Projections: A working paper for REmap 2030. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf».

[11] «Albrecht, U., Schmidt, P., Weindorf, W., Wurster, R., Zittel, W. (2013). Zukünftige Kraftstoffe für Verbrennungsmotoren und Gasturbinen. Retrieved https://www.fvv-net.de/fileadmin/user_upload/medien/materialien/FVV-Kraftstoffstudie_LBST_2013-10-30.pdf».

[12] «Brynolf, S., Taljegard, M., Grahn, M., Hansson, J. (2018). Electrofuels for the transport sector: A review of production costs. Renewable and Sustainable Energy Reviews,81(2), 1887-1905. https://doi.org/10.1016/j.rser.2017.05.288».

[13] «Fasihi, M., Bogdanov, D., Breyer, C. (2016). Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants. Energy Procedia,99, 243-268. https://doi.org/10.1016/j.egypro.2016.10.115».

[14] «Baharozu, E., Soykan, G., Ozerdem, M.B. (2017). Future aircraft concept in terms of energy efficiency and environmental factors. Energy,140(2), 1368-1377. https://doi.org/10.1016/j.energy.2017.09.007».

[15] «Brewer, G.D., (1991). Hydrogen Aircraft Technology. CRC Press.».

[16] The European Green Deal, COM (2019) 640.

[17] A New Industrial Strategy for Europe COM(2020) 102 final.

[18] Strategic research and innovation agenda- The proposed European Partnership on Clean Aviation, DLR, May 2020.

[19] Roadmap to decarbonizing European aviation, October 2018, Transport & Environment.

[20] Advanced Aviation Biofuels: ready for take-off?, Dolf Gielen, Sakari Oksanen, May 2019, energypost.eu/advanced-aviation-biofuels-ready-for-take-off/.

[21] UK Aviation Forecasts Moving Britain Ahead. (2017) Department for Transport. assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/674749/uk-aviation-forecasts-2017.pdf.

[22] Mallins (2017) What role is there for electrofuel carbon future?.

[23] Schmidt, P., & Weindorf, W. (2016). Power-to-Liquids. Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel. Dessau-Roßlau. Mallins (2017) What role is there for electrofuel technologies in European.

[24] Jim Lane Biofuels Digest, 2012.

[25] Shell Aviation, World Energy to supply sustainable aviation fuel to Lufthansa at SFO; ink multi-year collaboration BiofuelsDigest January 7, 2020 | Helena Tavares Kennedy.

[26] https://skynrg.com/press-releases/klm-skynrg-and-shv-energy-announce-project-first-european-plant-for-sustainable-aviation-fuel/.

[27] https://www.biofuelsdigest.com/bdigest/2019/08/19/british-airways-and-shell-to-build-velocys-aviation-biofuel-plant-in-the-uk/.

[28] https://www.avfuel.com/Details-Page/ArticleID/541/Avfuel-Delivers-First-Sustainable-Aviation-Fuel-Shipment-to-Bombardier%E2%80%99s-Facility-in-Canada.

[29] https://gardn.org/industry-led-partnership-to-advance-the-availability-of-sustainable-aviation-fuel-in-canada/.

[30] https://edition.cnn.com/2019/11/19/business/easyjet-flights-carbon-neutral/index.html.

[31] https://www.atn.aero/#/article.html?id=74275.

[32] "Virgin Australia's sustainable aviation fuel flies one million kilometres" (in Dutch). Retrieved 2019-06-19..

[33] Kerry Reals (Apr 26, 2019). "Biofuel Market Is Nearing A Tipping Point". Aviation Week & Space Technology..

[34] https://www.icao.int/environmental-protection/GFAAF/Pages/default.aspx.

[35] Bruno Silva, Environment Officer, ICAO, Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and Sustainable Aviation Fuels, Sustainable aviation fuels at ISCC meetings and conferences (2019).

[36] BiofuelsDigest, 2012, Jim Lane.

[37] https://simpleflying.com/sustainable-aviation-fuel/.

[38] Maniatis, K. EU Transport & Renewable Energy policies: The role of Advanced Biofuels in Decarbonising Transport. EU-India Conference on Advanced Biofuels, 6-8 March 2018, New Delhi. Available at https://ec.europa.eu/energy/en/content/conference-presentati.

[39] http://www.bio4a.eu/.

[40] http://www.besustainablemagazine.com/cms2/flexjet-project-converts-organic-waste-into-sustainable-aviation-fuel/.

[41] Sustainable Aviation Fuels Guide, ICAO-UNDP-GEF assistance project, 2018.

[42] AirBP, https://www.bp.com/en/global/air-bp/news-and-views/sterling-card-newsletters/what-is-sustainable-aviation-fuel-saf-and-why-is-it-important.html.

[43] ASTM (2016) "ASTM D7566-16, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons". Available at: http://www.astm.org/Standards/D7566.htm.

[44] Steve Csonka (2016) "CAAFI – CORE-JetFuel Cooperation Workshop". Available at: www.core-jetfuel.eu.

[45] http://www.caafi.org/focus_areas/fuel_qualification.html.

[46] https://ec.europa.eu/jrc/en; Analysis of current aviation biofuel technical production potential in EU28, M. Prussia, A. O'Connella, L. Lonza, Biomass and Bioenergy 130 (2019) 105371.

[47] E4tech, Review of the potential for biofules in aviation, E4tech, London, 2009..

[48] European Commission, Carbon accounting for forest bioenergy, 2014..

[49] S. de Jong, K. Antonissen, R. Hoefnagels, L. Lonza, M. Wang and A. Faaij, Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production, Biotechnology and Biofuels, vol. 10, no. 64, 2017..

[50] CAAFI, Fuel Readiness Level (FRL), CAAFI, 2010..

[51] Hui, X., K. Kumar, C.-J. Sung, T. Edwards and D. Gardner (2012). "Experimental studies on the combustion characteristics of alternative jet fuels." Fuel 98(0): 176-182;.

[52] Kumar, K. and C.-J. Sung (2010). "A comparative experimental study of the autoignition characteristics of alternative and conventional jet fuel/oxidizer mixtures." Fuel 89(10): 2853-2863.

[53] Kumar, K. and C.-J. Sung (2010). "Flame Propagation and Extinction Characteristics of Neat Surrogate Fuel Components." Energy & Fuels 24(7): 3840-3849.

[54] Wang, H. and M. A. Oehlschlaeger (2012). "Autoignition studies of conventional and Fischer–Tropsch jet fuels." Fuel 98(0): 249-258.

[55] Allen, C., D. Valco, E. Toulson, T. Edwards and T. Lee (2013). "Ignition behavior and surrogate modeling of JP-8 and of camelia and tallow hydrotreaeted renewable jet fuels at low temperaturews." Combustion and Flame 160: 232-239..

[56] Quintero, S. A. A., M. Ricklick and J. Kapat (2012). Synthetic Jet Fuels and their Impact in Aircraft Performance and Elastomer Materials. 48th AIAA/ASME/SAE/ASEE Join Propulsion Conference & Exhibit, Atlanta, Georgia..

[57] T. F. J. D. K. T. M. H. G. C. G. F. L. G. P. Z. Y. A. D. M. L. C. L. J. A. J. M. G. A. K. R. R. J. R. H. M. J. M. a. A. G. B. Rahmes, «Sustainable Bio-derived Synthetic Paraffinic Kerosene (Bio-SPK) Jet Fuel Flight and Engine Tests Program Results,» in *9th AIAA Aviation TEchnology, Integration and Operations Conference, Hilton Head, SC*, 2009.

[58] «ITAKA project (2016) "Press release. ITAKA provides sustainable fuel for worldwide's first biojet supply via hydrant system at Oslo Airport". http://www.itaka-project.eu/Shared%20Documents/20160122_ITAKA_airportusage_start.pdf».

[59] «Greenaironline (2016) "United begins regular use of commercial-scale volumes of AltAir's renewable jet biofuel on flights from LAX". Available at: http://www.greenaironline.com/news.php?viewStory=2208».

[60] «Deutsche Lufthansa AG: Abschlussbericht zu dem Vorhaben Projekt burnFAIR, Arbeitspakete 1.1 bis 1.4, Frankfurt am Main, June 2014».

[61] «Weissermel, K., Arpe H.-J., Industrielle Organische Chemie, fünfte Auflage, Wiley-VCH, Weinheim 1998, p.16 onw.».

[62] «ASTM 7566, issue 14a, Table 1 Part 2».

[63] «ASTM D7566 15c».

[64] «Clifford A. Moses: Evaluation of Synthesized Aromatics Co-Produced with Iso-Paraffinic Kerosene for the Production of Semi-Synthetic Jet Fuel, New Braunfels July 2013».

[65] «Zennaro, Roberto: Fischer-Tropsch Process Economics, p.155; in: Peter M. Maitlis and Arno de Klerk (eds.): Greener Fischer-Tropsch Processes for Fuels and Feedstocks, Weinheim 2013».

[66] «Solena Group, Inc: "BioEnergy platforms: A vision for the future", p.6».

[67] «"GreenSky project prepares to land in Thurrock"; British airways press release, 16. April 2014».

[68] «Meghan Sapp: British Airways drops Solena project after failure to raise funds to build plant, 27.11.2015».

[69] «Jim Lane: United Airlines invests $30M in Fulcrum BioEnergy; inks $1.5B+ in aviation biofuels contracts; in: Biofuels Digest 30.6.2015».

[70] «Ecofys (2016) "Accounting methods for biojet fuel. Final report". Available at: http://www.ecofys.com/files/files/ecofys-2015-accounting-methods-for-biojet-fuel.pdf».

[71] «L. S. Yanovskii, N. I. Varlamova, I. M. Popov, A. L. Maksimov, Manufacturing of Coal-Based Synthetic Jet Fuels Interchangeable with JET A-1 and T-8B Petroleum Fuels. Petroleum Chemistry. 60(1):92-103. DOI:10.1134/S0965544120010168».

[72] «A. Zschocke, S. Scheuermann, J. Ortner. High Biofuel Blends in Aviation (HBBA) ENER/C2/2012/ 420-1 Final Report\».

[73] «The cost of supporting alternative jet fuels in the European Union, Nikita Pavlenko, Stephanie Searle, and Adam Christensen, ICCT working paper 2019».

[74] S. M. R. S. M. D. S. P. P. M. T. W. E. H. J. I. &. B. S. Bann, «The costs of production of alternative jet fuel: A harmonized stochastic assessment, doi:10.1016/j.biortech.2016.12.032,» *Bioresource Technology*, vol. 227, p. 179–187, 2017.

[75] «de Jong, S. (2018). Green Horizons: On the Production Costs, Climate Impact and Future Supply of Renewable Jet Fuels (master's thesis, Utrecht University); http://skynrg.com/ wp-content/uploads/2018/06/dJong.pdf.».

[76] «Yee Chow, Lead Manager Procurement, Cathay Pacific Airways, Implementation of Low Carbon Fuels in International Aviation, in Sustainable aviation fuels at ISCC meetings and conferences (2019)».

[77] «Yakovlieva, A.V., Boichenko, S.V., Leida, K., Vovk, O.A., Kuzhevskii, Kh. (2017). Influence of Rapeseed Oil Ester Additives on Fuel Quality Index for Air Jet Engines. Chemistry and Technology of Fuels and Oils, 53, 3, 308–317».

[78] «"Neste Oil produced enough renewable fuel from waste and residues last year to power over 1 million cars" , Neste press release 4.2.2014».

[79] «Neste Corporation Interim Report January – September 2016, p.10».

[80] «ASTM D7566, issue 14a, paragraph 6.1.2».

[81] «http://swiftfuels.com».

[82] «http://2013.nesteoil.com/business/renewable-fuels/».

[83] «"KLM plans drive-down of jet biofuel price premium as it starts regular series of biofuel transatlantic flights", GreenAir online 18. March 2013».

[84] «United Airlines Makes History with Launch of Regularly Scheduled Flights Using Sustainable Biofuel; United Airlines press release 11. March 2016».

[85] «Are aviation biofuels ready for take off? – Analysis – IEA, https://www.iea.org/commentaries/are-aviation-biofuels-ready-for-take-off».

[86] «L. Starck, L. Pidol, N. Jeuland, T. Chapus, P. Bogers, J. Bauldreay. Production of Hydroprocessed Esters and Fatty Acids (HEFA) – Optimisation of Process Yield. Oil & Gas Science and Technology – Rev. IFP Energies nouvelles,2014 DOI: 10.2516/ogst/2014007».

[87] «A. P. P. Pires, Y. Han, J. Kramlich, M. Garcia-Perez. Alternative jet fuel properties, BioResources, 2018. 13(2), 2632-2657.».

[88] «(S&T)2 Consultants Inc. (2018). Description and Data Collection on Biofuel Technologies. Prepared for the Danish Energy Agency.».

[89] «Jonas Rorarius, Head of Supply Chain Compliance, Neste, Deployment of Sustainable Aviation Fuels, Sustainable aviation fuels at ISCC meetings and conferences (2019)».

[90] «Total, Amyris, USAFRL: Evaluation of Synthesized Iso-Paraffins produced from Hydroprocessed Fermented Sugars (SIP Fuels), February 2014, p. 15 – 21; personal communication».

[91] «http://www.amyris.com/Company/151/BusinessStrategy,, called up 15.8.2014».

[92] «ASTM D7566 14a, paragraph 6.1.3».

[93] «Wei-Cheng Wang, Ling Tao, Jennifer Markham, Yanan Zhang, Eric Tan, Liaw Batan, Ethan Warner, and Mary Biddy Review of Biojet Fuel Conversion Technologies. Technical report. National Renewable Energy Laboratory. July 2016 http:/www.osti.gov/scitech».

[94] R. L. T. C. S. E. C. D. T. J. R. J. L. a. D. S. Davis, «Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Catalytic Conversion of Sugars to Hydrocarbons,» *National Renewable Energy Laboratory, Golden, CO, USA.*, 2015.

[95] «Virent. (2015). "Bioforming." Retrieved Oct. 13, 2015, from http://www.virent.com/technology/bioforming/.».

[96] «Subcommittee J on Aviation Fuels: Evaluation of Bio-Derived Alcohol to Jet Synthetic Paraffinic Kerosenes, Version 4, 12. March 2014, P.21».

[97] «Swedish Biofuels communication».

[98] «Subcommittee J on Aviation Fuels 12. March 2012».

[99] «"LanzaTech and Baosteel's 100,000 gallon/year waste-gas-to-ethanol pre-commercial facility exceeds productivity expectations and hits major milestones in advance of commercialization", LanzaTech press release 3. December 2012».

[100] «"Alcohol To Jet Synthesized Paraffinic Kerosene (AT-SPK) Task Force Report – D02.J6", presentation at ASTM D02 Committee week – San Diego, 9th December 2014, slides 8/9; oral presentations at meeting».

[101] «ASTM D7566 -16».

[102] «Wright. Michael: ATJ-SPK Annex Options, presentation at ASTM D02 Committee week – San Diego, 9th December 2014».

[103] «https://gevo.com/».

[104] «IRENA (2017), Biofuels for aviation: Technology brief, International Renewable Energy Agency, Abu Dhabi».

[105] «https://techcrunch.com/2020/06/02/lanzajet-launches-to-make-renewable-jet-fuel-a-reality/».

[106] «http://www.byogy.com/technology/index.html, researched 18.9.2014».

[107] «Byogy communication».

[108] «Hartmut Pflaum: Qualitätssicherung und Nachhaltigkeit bei der Bereitstellung von Biokraftstoffen für die Luftfahrt – Schlussbericht Fraunhofer UMSICHT, Juni 2014, p.17».

[109] «http://www.swedishbiofuels.se/».

[110] «WEISS, K. (2016), "Renewable Fuels For All Modes Of Transport" (online: https://www.energy.gov/sites/prod/files/2016/09/f33/weiss_alternative_aviation_fuels_workshop.pdf)».

[111] «HILEMAN, J. (2019), "Fuel Approval Process & Status" (online: https://www.icao.int/Meetings/SAFStocktaking/Documents/ICAO%20SAF%20Stocktaking%202019%20-%20AI1-1%20Jim%20Hileman.pdf)».

[112] «STERNER, T.; WONG, B; MUMY, K.; MATTIE, D. (2016), "HUMAN HEALTH ASSESSMENT OF ALCOHOL-TO-JET (ATJ) SYNTHETIC KEROSENES" (online: https://apps.dtic.mil/dtic/tr/fulltext/u2/1028990.pdf)».

[113] «BYOGY RENEWABLES. (2014), "Alcohol To Jet – SKA Full Replacement Bio-Jet Fuel" (online: http://www.ascension-publishing.com/ABLC-2014/Weiss-Byogy.pdf)».

[114] «YAO, G.; STAPLES, M.; MALINA, R.; TYNER, W. (2017), "Stochastic techno-economic analysis of alcohol-to-jet fuel production" (online: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5244559/)».

[115] «WORMSLEV, E.; TANG, C.; ERIKSEN, C. (2017), "Sustainable Fuels For Aviation: An Analysis Of Danish Achievements And Opportunities" (online: http://d34t8abwyt4kba.cloudfront.net/2017/06/sustainable-fuels-for-aviation-danish-aviation-1.pdf)».

[116] «Edward N. Coppola: Evaluation of Hydroprocessed Esters and Fatty Acids (HEFA) Synthetic Kerosene containing Aromatics (SKA) Readijet Renewable Jet Fuel, June 2014, p.1».

[117] «Red, Chuck: ReadiDiesel ReadiJet next Generation alternative Fuels, presentation, June 2012, p.3».

[118] «http://www.ara.com/fuels/Feedstocks-evaluated-CH-process.html, , researched 28. August 2014».

[119] «http://www.ara.com/fuels/Readi-Jet-Diesel-Specs.html, researched 28. August 2014».

[120] «http://www.ara.com/fuels/CH-Technology-Status.html, researched 28. August 2014».

[121] E. C. J. R. J. L. M. a. D. W. Lixiong Li, «Catalytic Hydrothermal Conversion of Triglycerides to Non-ester Biofuels,» *Energy & Fuels,* vol. 24, n. 2, pp. 1305-1315, 2010.

[122] F. O. o. E. a. Energy, «Evaluation of ARA Catalytic Hydrothermolysis (CH) Fuel,» *Pratt & Whitney ,* 2014.

[123] «https://www.ara.com/products/biofuels-isoconversion».

[124] R. Olaganathan, «Algal biofuel: the future of green jet fuel in air,» *Journal of Applied Biotechnology & Bioengineering,* vol. 5, n. 2, 2018.

[125] A. A. C. T. Joseph K Bwapwa, «Jet fuel blend from Algal Jet Fuel and Jet A1 in 50/50 volume ratio,» *nternational Journal of Low-Carbon Technologies,* vol. 14, n. 2, p. 234–240, 2019.

[126] «https://www.ihi.co.jp/en/all_news/2020/other/1196667_2042.html».

[127] «Edwards, Tim/ Trewella, Jeff/Sanchez, Vicente/Leisenring, Roger jr.: Evaluation of Hydroprocessed Depolymerized Cellulosic Jet (HDCJ) Fuels and Blends; April 2014, p.8-10».

[128] «Biofuelsdigest.com: KiOR seeks Chapter 11 reorganisation after asset bid received, Meldung vom 11.11.2014».

[129] «E4tech (UK) Ltd.: Sustainable Aviation Fuels - Potential for the UK industry, July 2014, p.8».

[130] «Dally Brice, Ginestra Cynthia, Edwards Tim, Heminghaus Gregory: Evaluation of Hydrodexygenated Synthesized Kerosene (HDO-SK) and Blends, March 2014, p. 11-14; Pflaum, p. 18/19».

[131] «https://www.virent.com/».

[132] «Dally Brice, Ginestra Cynthia, Heminghaus Gregory: Evaluation of Hydrodexygenated Synthesized Aromatic Kerosene (HDO-SKA) and Blends, May 2014, p. 11-14».

[133] «Pavlenko, N., & Kharina, A. (2018). Policy and Environmental Applications of Using HEFA+ for Aviation. International Council on Clean Transportation; www.theicct.org/sites/default/files/publications/Green-Diesel-Aviation_ICCTWorking-Paper_20180321_vF.pdf.».

[134] «WORMSLEY, E. (2016), Sustainable jet fuel for aviation: Nordic perpectives on the use of advanced sustainable jet fuel for aviation. Copenhague, Dinamarca. Ed.: Nordic Council of Ministers.».

[135] «M.Prussia A.O'Connella L.Lonzab, Analysis of current aviation biofuel technical production potential in EU28, Biomass and Bioenergy Volume 130, November 2019, 105371».

[136] «RED II (proposal), Annexes to the - proposal for a directive of the european parliament and the council on the promotion of the use of energy from renewable sources (Recast)».

[137] «ICAO, https://www.icao.int/environmental-protection/GFAAF/Pages/FAQs.aspx (2017, 11)».

[138] «GREENEA-a, www.greenea.com/publication/new-players-join-the-hvo-game».

[139] M. G. D. A. K. A. A. Keskin, «Using of cotton oil soapstock biodiesel–diesel fuel blends as an alternative diesel fuel,» *Renew. Energy*, vol. 33, pp. 553-557, 2008.

[140] R. P. P. R. S. C. F. V. F. d. L. F. P. S. Grisan, «Alternative use of tobacco as a sustainable crop for seed oil, biofuel, and biomass,» *Agron. Sustain. Dev.*, vol. 36, n. 4, p. 55, 2016.

[141] «ITAKA cordis.europa.eu/result/rcn/199638_en.html (2017, 11)».

[142] C. E. M. C. M. K. D. R. E. A. A. M. F. Zanetti, «Agronomic performance and seed quality attributes of Camelina (Camelina sativa L. crantz) in multi-environment trials across Europe and Canada,» *Ind. Crops Prod.*, , vol. 107, pp. 602-608, 2017.

[143] «BIO4A, www.cordis.europa.eu/project/rcn/216261_en.html (05, 2018)».

[144] «wGREENEA-b, ww.greenea.com/publication/and-do-you-recycle-your-used-cooking-oil-at-home/ (2017, 12)».

[145] «USDA, EU-28 Biofuels Annual Report (2018), www.fas.usda.gov/data/eu-28-biofuels-annual-0».

[146] «D. Dobbelaere, Statistical Overview of the Animal By-Products Industry in the EU in 2016. European Fat Processors and Renders Association».

[147] K. V. G. R. D. B. J. L. A. L. J. R. A. H. J. L. J. M Anthonykutty, «Value added hydrocarbons from distilled tall oil via hydrotreating over a commercial NiMo catalyst,» *Ind. Eng. Chem. Res.*, vol. 52 , pp. 10114-10125, 2013.

[148] K. B. A. K. D. M. M. F. B. V.K. Rajendran, «Analysis of the European Crude Tall Oil Industry – Environmental Impact, Socio-Economic Value & Downstream Potentia, Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT (2016)».

[149] «US Dept of Energy, Alternative Aviation Fuels: Overview of Challenges, Opportunities, and Next Steps, (2017)».

[150] «G. De Bhowmick, A.K. Sarmah, R. Sen, Lignocellulosic biorefinery as a model for sustainable development of biofuels and value added products, Bioresour. Technol., 247 (2018), pp. 1144-1154».

[151] N. R. R. J. R. P. S. G.-C. R. L.-L. M. v. d. V. T. R. P. G. R. M. S. T. G. F. R. A. N. H. L. M. J. G. A. Camia, «Biomass Production, Supply, Uses and Flows in the European Union. First Results from an Integrated Assessment. Science for Policy Report by the Joint Research Centre (JRC), the European Commission's Science and Knowledge Service (2018)».

[152] «J.L. Stephen, B. Periyasamy, Innovative developments in biofuels production from organic waste materials: a review, Fuel, 214 (2018), pp. 623-633».

[153] «EUROSTAT, ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics (2016)».

[154] «EC – DG ENV, Assessment of Separate Collection Schemes in the 28 Capitals of the EU (2015), 070201/ENV/2014/691401/SFRA/A2».

[155] «S2BIOM, www.s2biom.eu (2016)».

[156] «S.Y. Searle, C.J. Malins, Waste and residue availability for advanced biofuel production in EU Member States, Biomass Bioenergy, 89 (2016), pp. 2-10».

[157] «Karen O' Brien, Process Engineer, Gevo, Sustainable Aviation Fuel and the Circular EconomySustainable aviation fuels at ISCC meetings and conferences (2019)».

[158] «Pavlenko, N., Searle, S., & Christensen, A. (2019). The cost of supporting alternative jet fuels in the European Union. Working Paper, http://www.indiaenvironmentportal.org.in/files/file/Alternative_jet_fuels_cost_EU.pdf Accessed at: 01.02.2020».

[159] «Van der Westhuizen R., Ajam M., De Coning P., Beens J., de Villiers A., Sandra P.; "Comprehensive two-dimensional gas chromatography for the analysis of synthetic and crude-derived jet fuels"; J Chromatogr A 2011; 1218: 4478–4486.».

[160] «Asakuma Y., Maeda K., Kuramochi H., Fukui K.; "Theoretical study of the transesterification of triglycerides to biodiesel fuel"; Fuel 2009; 88: 786–791».

[161] «Knothe G., Dunn R.O.; "Dependence of oil stability index of fatty compounds on their structure and concentration and presence of metals"; J Am Oil Chem Soc 2003; 80: 1021–1026».

[162] «Chuck C.J., Donnelly J.; "The compatibility of potential bioderived fuels with Jet A-1 aviation kerosene"; Appl Energy 2014; 118: 83–91.».

[163] «Amara A.B., Kaoubi S., Starck L.; "Toward an optimal formulation of alternative jet fuels: enhanced oxidation and thermal stability by the addition of cyclic molecules"; Fuel 2016; 173: 98–105.».

[164] «Corporan E., DeWitt M.J., Belovich V., Pawlik R., Lynch A.C., Gord J.R., et al.; "Emissions characteristics of a turbine engine and research combustor burning a Fischer-Tropsch jet fuel"; Energy Fuels 2007; 21: 2615–2626.».

[165] «Corporan E., Edwards T., Shafer L., DeWitt M.J., Klingshirn C., Zabarnick S., et al.; "Chemical, thermal stability, seal swell, and emissions studies of alternative jet fuels"; Energy Fuels 2011; 25: 955–66.».

[166] «Gaspar R.M.P., Sousa J.M.M; "Impact of alternative fuels on the operational and environmental performance of a small turbofan engine"; Energy Convers Manage 2016; 130: 81–90.».

[167] G.-F. O. R.-M. C. G.-C. F. S.-H. J. H. S. e. a. Acosta-Solórzano A.D.A., «"Controllability analysis of distillation sequences for the separation of bio-jet fuel and green diesel fractions"; Chem Eng Technol 2016; 39: 2273–2283».

[168] «Gutiérrez-Antonio C., Romero-Izquierdo A.G., Israel Gómez-Castro F., Hernández S.; "Energy integration of a hydrotreatment process for sustainable biojet fuel production"; Ind Eng Chem Res 2016; 55: 8165–8175.».

[169] «Buffi M., Valera-Medina A., Marsh R., Pugh D., Giles A., Runyon J., et al.; "Emissions characterization tests for hydrotreated renewable jet fuel from used cooking oil and its blends"; Appl Energy 2017; 201: 84–93.».

[170] «Scheuermann S.S., Forster S., Eibl S.; "In-depth interpretation of mid-infrared spectra of various synthetic fuels for the chemometric prediction of aviation fuel blend properties"; Energy Fuels 2017; 31: 2934–2943.».

[171] «Yang J., Xin Z., He Q.S., Corscadden K., Niu H.; "An overview on performance characteristics of bio-jet fuels"; Fuel 2019; 237: 916-936.».

[172] «Neuling, U., & Kaltschmitt, M. (2018). Techno-economic and environmental analysis of aviation biofuels. Fuel Processing Technology, 171, 54-69.».

[173] «Riviere, C., & Marlair, G. (2009). BIOSAFUEL®, a pre-diagnosis tool of risks pertaining to biofuels chains. Journal of Loss Prevention in the Process Industries, 22(2), 228-236.».

[174] «Debnath, D. (2019). Advanced biofuels: Supply chain management. In Biofuels, Bioenergy and Food Security (pp. 231-246). Academic Press.».

[175] «Correa, D. F., Beyer, H. L., Fargione, J. E., Hill, J. D., Possingham, H. P., Thomas-Hall, S. R., & Schenk, P. M. (2019). Towards the implementation of sustainable biofuel production systems. Renewable and Sustainable Energy Reviews, 107, 250-263.».

[176] «Ouagrham-Gormley, Sonia Ben & Fye-Marnien, Shannon (2018) The bright side of synthetic biology and Crispr, Bulletin of the Atomic Scientists, 74:1, 19-26, DOI: 10.1080/00963402.2017.1413056».

[177] «Clarens, A. F., E. P. Resurreccion, M. A. White, and L. M. Colosi. 2010. "Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstocks." Environmental Science & Technology 44(5): 1813–1819. doi:10.1021/es902838n.».

[178] «Abdullah, B., Muhammad, S. A. F. A. S., Shokravi, Z., Ismail, S., Kassim, K. A., Mahmood, A. N., & Aziz, M. M. A. (2019). Fourth generation biofuel: A review on risks and mitigation strategies. Renewable and sustainable energy reviews, 107, 37-50.».

[179] «Ban J. Agricultural biological warfare: an overview, vol. 9. Alexandria: Chemical and Biological Arms Control Institute; 2000. p. 1–8.».

[180] «Ratner, S. V., Yuri, C., & Hien, N. H. (2019). Prospects of Transition of Air Transportation to Clean Fuels: Economic and Environmental Management Aspects. International Energy Journal, 19(1).».

[181] «A Study on Electrofuels in Aviation, Andreas Goldmann, Waldemar Sauter, Marcel Oettinger, Tim Kluge, Uwe Schröder, Joerg R. Seume, Jens Friedrichs, Friedrich Dinkelacker, Energies 2018, 10, 392; doi:10.3390/en11020392».

[182] «Electrofuels' that increase plane ticket price by 60% only way to clean up air travel, report finds, Josh Gabbatiss October 2018, The Indipendent».

[183] «https://www.flightnook.com/4th-generation-cleaner-fuels-from-carbon-in-the-air».

[184] R. Caulfield, S. Willis, B. Grimm, P. Box, P. Townsend, P. Address e O. Street, «Solid State Ammonia Synthesis (SSAS) Pilot Plant Demonstration System for Renewable Energy (RE) Firming Storage, Transmission, and Export,» *Alaska Applied Sciences, Inc.: Juneau, AK, USA,* p. 1–5., 2011.

[185] «Zacharakis-Jutz, G.E.; Kong, S.C. Performance Characteristics of Ammonia Engines Using Direct Injection Strategies. Ph.D. Thesis, Iowa State University, Ames, IA, USA, 2013.».

[186] «Amar, I.A.; Lan, R.; Petit, C.T.; Tao, S. Solid-state electrochemical synthesis of ammonia: A review. J. Solid State Electrochem. 2011, 15, 1845–1860; 42.».

[187] «Liu, Y.; Zhang, Y.; Chen, K.; Quan, X.; Fan, X.; Su, Y.; Chen, S.; Zhao, H.; Zhang, Y.; Yu, H.; Hoffmann, M.R. Selective electrochemical reduction of CO2 to ethanol on B and N codoped nanodiamond. Angew. Chem. Int. Ed. 2017, 56, 15607–15611».

[188] «Kuhl, K.P.; Hatsukade, T.; Cave, E.R.; Abram, D.N.; Kibsgaard, J.; Jaramillo, T.F. Electrocatalytic conversion of carbon dioxide to methane and methanol on transition metal surfaces. J. Am. Chem. Soc. 2014, 136, 14107–14113».

[189] «Yuan, J.; Liu, L.; Guo, R.R.; Zeng, S.; Wang, H.; Lu, J.X. Electroreduction of CO2 into Ethanol over an Active Catalyst: Copper Supported on Titania. Catalysts 2017, 7, 220».

[190] «Studt, F.; Sharafutdinov, I.; Abild-Pedersen, F.; Elkjær, C.F.; Hummelshøj, J.S.; Dahl, S.; Chorkendorff, I.; Nørskov, J.K. Discovery of a Ni-Ga catalyst for carbon dioxide reduction to methanol. Nat. Chem. 2014, 6, 320–324».

[191] «Gattrell, M.; Gupta, N.; Co, A. A review of the aqueous electrochemical reduction of CO2 to hydrocarbons at copper. J. Electroanal. Chem. 2006, 594, 1–19».

[192] «IFA. Gefahrstoffe—Datenbanken (GESTIS). Available online: http://www.dguv.de/ifa/gestis/index.jsp».

[193] «https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii».

[194] «Europe's first power-to-liquid demo plant in Norway plans renewable aviation fuel production in 2023, https://www.greenaironline.com/news.php?viewStory=2711».

[195] «Salem, R.R. The electrolysis of water. J. Electroanal. Chem. 1999, 476, 92–93.».

[196] «Gülker, F. Production of hydrogen (Herstellung vonWasserstoff). Patent DE446488 (GB), July 1927.».

[197] «Crabtree, G.W.; Dresselhaus, M.S.; Buchanan, M.V. The Hydrogen Economy. Phys. Today 2004, 57, 39–45.».

[198] «Sap, K.A.; Demmers, J.A.A.; Nimit Patel, G.R.The energy efficiency of onboard hydrogen storage. Intech 2012, 6, 111–133.».

[199] «Robert Thomson, Uwe Weichenhain, Nikhil Sachdeva, Markus Kaufmann, Focus, Hydrogen - A Future Fuel for Aviation? Roland Berger GMBH. https://www.rolandberger.com/en/Publications/Hydrogen-A-future-fuel-of-aviation.html».

[200] «Press Release cleansky2, HYDROGEN-POWERED AVIATION: PREPARING FOR TAKE-OFF Online, 22 June 2020».

[201] A. R. G. Perpignan, «Effect of dilution in an inter-turbine Flameless combustor. Retrieved from https://repository.tudelft.nl/islandora/object/uuid:29a0701e-b692-4d52-83de-1b8a4d07a18b?collection=research,» 2016.

[202] B. K. A. S. P. S. V. S. R. Khandelwal, «The future of air transport. Progress in Aerospace Sciences. https://doi.org/10.1016/j.paerosci.2012.12.002,» vol. 60, pp. 45-59, 2013.

[203] «Hydrogen-powered aviation. A fact-based study of hydrogen technology, economics, and climate impact by 2050, May 2020. Publications Office of the European Union, 2020, ISBN 978-92-9246-341-0, doi:10.2843/766989, EG-04-20-214-EN-C».

[204] S. S. R. G. A. Rondinelli, «Challenges and Benefits offered by Liquid Hydrogen Fuels in Commercial Aviation. https://doi.org/10.13140/2.1.2658.9764,» 2014.

[205] S. B. B. C. C. Y. P. Arnold, «Spherical Cryogenic Hydrogen Tank Preliminary Design Trade Studies. Retrieved from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa. gov/20070030205.pdf,» 2007.

[206] D. H. P. P. P. R. K. Verstraete, «Hydrogen fuel tanks for subsonic transport aircraft.,» *International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2010.06.060,* vol. 35, n. 20, pp. 11085-11098, 2010.

[207] A. S. H. Gomez, «Liquid hydrogen fuel tanks for commercial aviation: Structural sizing and stress analysis. https://doi.org/10.1016/j.ast.2019.105438,» *Aerospace Science and Technology,* vol. 95, 2019.

[208] G. M. J. Corchero, «An approach to the use of hydrogen for commercial aircraft engines.,» *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. https://doi.org/10.1243%2F095441005X9139,* vol. 219, n. 1, p. 35–44, 2005.

[209] G. S. F. Dahl, «Engine control and low-NOx combustion for hydrogen fuelled aircraft gas turbines.,» *International Journal of Hydrogen Energy. https://doi.org/10.1016/S0360-3199(97)00115-8,* vol. 23, n. 8, pp. 695-704, 1998.

[210] «Crespi, P. (2017, October). Liquid Hydrogen: A Clean Energy for Future Aircrafts. Presentation at the E2Flight Symposium, Stuttgart, Germany».

[211] «Borer, N.K., Geuther, S.C., Litherland, B.L., Kohlmann, L. (2019). Design and Performance of a Hybrid-Electric Fuel Cell Flight Demonstration Concept. Retrieved from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190033418.pdf».

[212] «ONERA. (2017). AMPERE The distributed electric propulsion challenge. Retrieved from https://www.onera.fr/sites/default/files/actualites/breves/Fiche_AMPERE_VA.pdf».

[213] «IEA (2015) Technology Roadmap Hydrogen and Fuel Cells, https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHydrogenandFuelCells.pdf, US Drive (2013) Hydrogen Delivery Technical Team Roadmap».

[214] «https://www.energy.gov/sites/prod/files/2014/02/f8/hdtt_roadmap_june2013.pdf».

[215] «Air Liquide (2015) Hydrogen Storage on board aeronef and ground infrastructure, presentation given under FCH-JU Workshop on aeronautical applications of fuel cell and hydrogen technologies, https://www.fch.europa.eu/sites/default/files/12.%20Bensadoun%20%».

[216] «Linde (2014) The Cleanest energy carrier ever – hydrogen solutions from Linde, https://www.the-linde-group.com/en/images/HydrogenBrochure_EN_tcm14-10196.pdf».

[217] «https://www.solarpaces.org/at-synhelion-solar-jet-fuels-get-ready-for-take-off/».

[218] «Sustainable Jet Fuel for Aviation Nordic perspectives on the use of advanced sustainable jet fuel for aviation - Update 2019 NORDIC ENERGY RESEARCH JANUARY 2020».

[219] «Clean_Aviation_SRIA_R1_for_public__consultation, http://www.clean-aviation.eu».