

Use of Sustainable Fuels in Aviation—A Review

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Abstract: As the push for carbon-neutral transport continues, the aviation sector is facing increasing pressure to reduce its carbon footprint. Furthermore, commercial air traffic is expected to resume the continuous growth experienced until the pandemic, highlighting the need for reduced emissions. The use of alternative fuels plays a key role in achieving future emission goals, while also lowering the dependency on fossil fuels. The so-called sustainable aviation fuels (SAF), which encompass bio and synthetic fuels, are currently the most viable option, but hydrogen is also being considered as a long-term solution. The present paper reviews the production methods, logistical and technological barriers, and potential for future mass implementation of these alternative fuels. In general, biofuels currently present higher technological readiness levels than other alternatives. Sustainable mass production faces critical feedstock-related challenges that synthetic fuels, together with other solutions, can overcome. All conventional fuel replacements, though with different scopes, will be important in meeting long-term goals. Government support will play an important role in accelerating and facilitating the transition towards sustainable aviation.



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1. Introduction

Aviation holds a delicate position in the grand scheme of the fight against climate change. Data from 2018 indicates that the sector is responsible for around 2.5% of global carbon dioxide emissions, and 3.5% of global warming if non-CO₂ contributions are also accounted for [1]. In 2019, emissions from jet kerosene combustion reached a new historic high of 1027 MtCO₂ [2], and though these numbers represent only 12% of CO₂ emissions for the combined transport industry [3], aviation is widely seen as the hardest sector to decarbonize, whether it is looked at from a technological or an economical standpoint [4].

The Paris Agreement, resulting from the 2015 United Nations Climate Change Conference (COP 21), set the target of limiting the increase in the global average temperature to “well below 2 °C above pre-industrial levels” and aiming for 1.5 °C [5]. Since then, governments have increased efforts in developing their own plans to contribute towards the common goal, while most current targets are generally not being fulfilled, transportation is still further behind when compared with other sectors that are progressing with a higher pace in their decarbonization efforts, with EU numbers showing it to be especially off course in achieving the proposed climate targets [6]. This has put aviation under the spotlight, with some of the industry’s short-term future objectives to reduce its carbon footprint facing strong criticism for being far too insufficient amidst the current climate crisis [7]. In addition to national pledges, the member states of the International Civil Aviation Organization (ICAO) adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), a market-based mechanism developed in 2016 and that intends to achieve net-zero growth of international aviation from 2020 onward [8]. More recently, the International Air Transport Association (IATA) passed a resolution in which its member airlines commit to working towards net-zero carbon emissions by 2050 [9].

As the climate crisis deepened since the signing of the Paris Agreement, numerous other proposals and plans were developed by other organizations.

Though the consensus regarding the need for both short- and long-term reduction in the carbon footprint remains unchanged [10], most of these plans and schemes were conceived based on models that predicted a continuous growth in commercial air traffic [11], and did not account for the abrupt halt in flights caused by the ongoing COVID-19 pandemic, which brought the biggest drop in global air passengers in history, as Figure 1 shows.

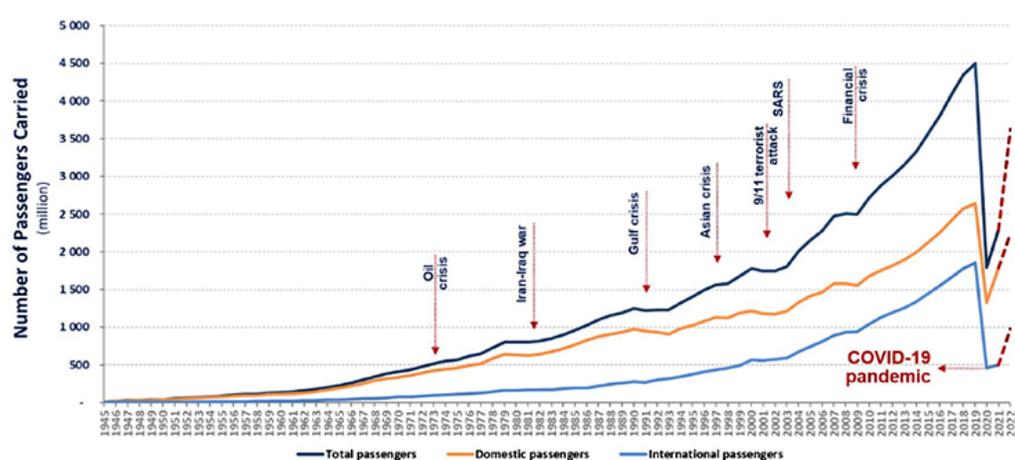


Figure 1. Global passengers carried from 1945 until 2022 projections. Adapted from [12].

During the most intense period of lockdowns in 2020, two thirds of the global commercial aircraft fleet were stationary [13], and though there was a noticeable recovery in the number of flights in 2021, fueled mainly by the air cargo industry, revenue passenger kilometers were still less than half of 2019 values [14,15]. Still, despite the slower than initially predicted recovery, the decline in air traffic is considered to be only temporary [16], as illustrated in Figure 2. Although it is not expected that 2022 numbers will reach those of 2019 [14], and recent long-term projections actually predict an 8% reduction in air passenger traffic for the year 2050 when compared with similar pre-pandemic studies [17], this is not enough to remove the need for mitigation measures [2], even though the pandemic's impact also forced some of the current carbon schemes to have their objectives adjusted [18,19].

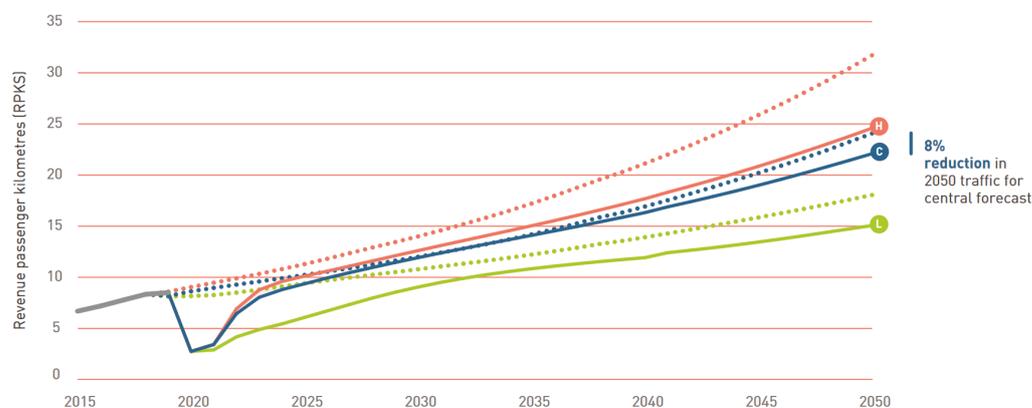


Figure 2. Air Transport Action Group's pre- (dotted) and post-Covid (solid) predictions for revenue passenger kilometres until 2050, for high (H in red), central (C in blue), and low (L in green) traffic forecasts. Adapted from [17].

There are several different areas of focus allowing to reduce the industry's GHG output, but each have different current levels of potential. Optimizing flight routes for minimum emissions rather than cost, improving maintenance schedules and other operational measures, as well as introducing further advancements in weight reduction materials and related technologies [2,20], bring important contributions to decrease emissions and should not be neglected, but are clearly insufficient. Gains in fuel efficiency amount to the most significant improvement in recent decades, with the current generation of aircraft being 20% more efficient than the previous generation, and 85% more than those of the 1960s [2]. However, the rate of improvement is progressively slowing down [21], and future progress is not expected to match the projected increase in air traffic, hence will therefore be insufficient, as Figure 3 indicates. Research has also been conducted in enabling a reduction in emissions in specific stages. Naturally, flight emissions are higher at take-off and climb stages [22], but engine start-up and warm-up emissions are also of particular importance, as the inefficiency associated with cold-starts [23] originates high emissions and energy losses. Furthermore, the GHG reduction since the beginning of the pandemic also empowered movements which contend that the best course of action would be to prevent further growth in the industry, rather than put all hope on future scientific breakthroughs [24]. Nevertheless, given the competitive nature of the market, this option appears to be unfeasible. It is therefore clear that, in order to accomplish the required results, it becomes necessary to lower and eventually end the dependency of commercial aviation on fossil fuels.

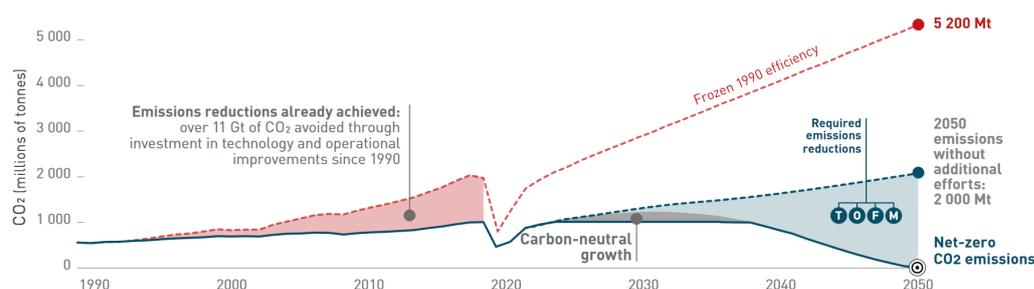


Figure 3. Predictions of CO₂ emissions until 2050 without additional efforts, compared to the 2050 net-zero goal and to the 1990 efficiency trend. Required emissions reductions are obtained through technology developments (T), operations and infrastructure improvements (O), use of sustainable aviation fuels (F), and offsets and other carbon mitigation options (M). Adapted from [17].

Hydrogen- and battery-powered aircraft, as alternatives, are sustained on eventual breakthroughs that can overcome the current technological barriers, but even overlooking that these options would require major design changes in aircraft, and given the slow fleet renewal cycles [11], as well as the fact that new aircraft deliveries were hindered in the last 2 years [14], the short-term implementation level required would be too costly for companies. Thus, these technologies are only viable as long-term solutions. “Drop-in” alternatives to conventional jet kerosene emerge as the best short- and medium-term choice, with different pathways for production of sustainable aviation fuels already being certified for commercial use up to specific blend levels. Currently, biogenic feedstocks are most used, but sustainability poses as a major obstacle to larger-scale applications, and so power-to-liquids (PtL) options could present themselves as a better solution. However, the latter are currently too expensive in comparison with the former, and other methods, such as using solar energy, are still in the early development phases.

Against this background, this paper seeks to further analyze the current state of alternative aviation fuels, their potential to become both short- and long-term solutions towards carbon-neutral aviation, together with the challenges that oppose their future mass implementation in the industry.

2. Drop-In Alternatives

Although there is no universally agreed definition of sustainable aviation fuels (SAF), it is most commonly used to describe a wide range of drop-in kerosene alternatives that can be produced from a variety of feedstocks [25], though ICAO presents a more general definition for SAF as alternative aviation fuels (AAF) that meet defined sustainability criteria [26]. For the remainder of this paper, SAF will be associated with drop-in fuels, hence differentiating from alternative propulsion methods such as hydrogen or electric propulsion.

Research into alternatives to petroleum-based fuels can be traced back to the early beginnings of turbine engines [27]. At the time, economic and supply concerns were the main motivators, and research efforts were only significantly increased once the climate crisis began to establish itself as the current century's biggest concern. In 2008, the Sustainable Aviation Fuel User Group (SAFUG) was formed, and the first test flight using a mix of conventional fuel and biofuel was performed by Virgin Atlantic [28]. Since then, the first SAFs were approved for commercial use, and by 2019 more than a quarter of a million SAF flights had been performed by more than 45 commercial airlines [9], though current usage still only accounts for less than 0.1% of jet kerosene consumption [2].

Another issue lies with the current limitations on the mixture levels required. Studies show that SAF can decrease life cycle carbon emissions up to 80% [29], while also lowering emissions of other pollutants, such as soot [30], sulfur oxides, and ultrafine particles [31], as well as mitigating the climate impact of contrails [32]. However, blending ratios for certified pathways only allow between 5 and 50% mixing, depending on the conversion process. This is due to the use of nitrile O-rings, which require a minimum of 8% in the level of aromatic content in the fuel in order to function properly [27], a level that early pure SAF did not meet. Recent improvements, both in SAF conversion processes and new O-rings made from fluorocarbons that do not require the same aromatic content in fuel, could lead to regulation changes in the near future [33]. In December 2021, United Airlines performed a successful demonstration flight using 100% SAF in one of its engines [34].

2.1. Certification Process Overview

In order to be “drop-in ready”, SAF must meet the qualities and characteristics of conventional jet fuel (see Appendix A for a comparison with non-aviation fuel characteristics as well). The international standard most used to define the kerosene-based fuel used in commercial aviation is ASTM International's D1655, *Standard Specification for Aviation Turbine Fuels*, which sets the necessary requirements for both Jet A and Jet A-1 to meet, the first one being the fuel used in the United States (US), while the latter is predominant in the rest of the world. The main difference between these two types of fuels lies in their maximum freezing point, which is lower in Jet A-1, making it more suitable for long international flights that use polar routes, but also more expensive to produce [35]. Table A1 in Appendix A summarizes ASTM specifications for a selection of critical fuel properties.

The process for a new aviation fuel to become certified for commercial usage is a complex and rigorous one, and is defined by ASTM D4054, *Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives*, a three-phase, four-tiered testing process [36], represented in Figure 4. Once an SAF completes all the required testing procedures successfully, it is then added to ASTM D7566, *Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons*, that regulates drop-in fuel specifications, and can be used in commercial aviation up to the approved blending ratio.

The comprehensive and meticulous method set by D4054 requires different fuel volumes in each different tier, and the 3–5 year process has a cost of at least \$5 million on candidate fuel producers [37,38]. Aiming to address this issue and to promote and accelerate research, in January 2020, ASTM approved a Fast Track Annex to D4054, but new fuels approved under this process are limited to a 10% blend percentage [38].

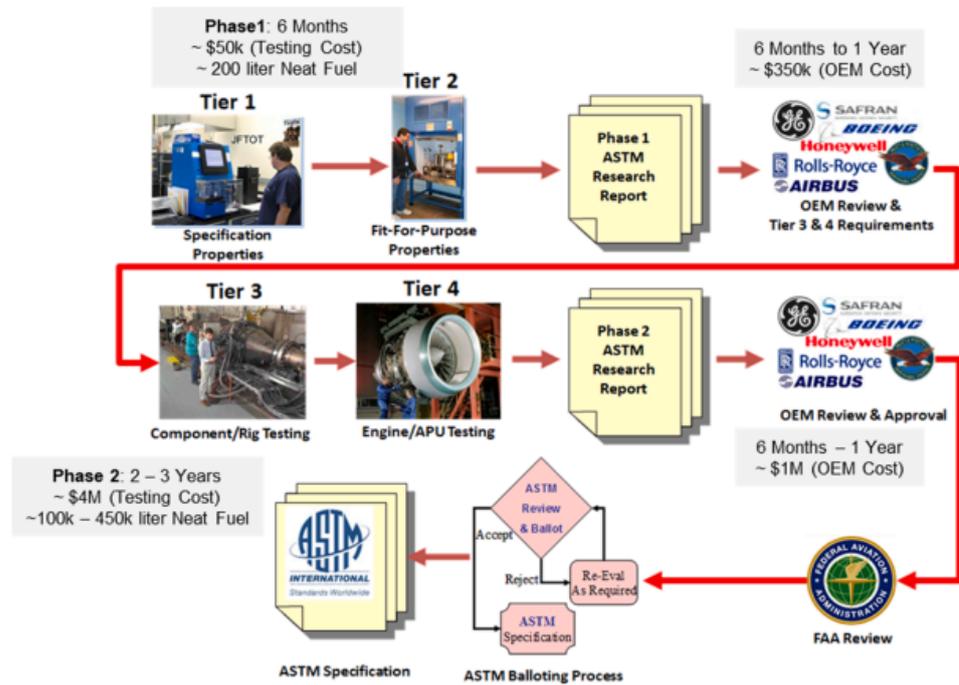


Figure 4. A nominal ASTM D4054 evaluation process with fuel and cost requirements, not including the cost of fuel production [37].

2.2. Biofuels

Biofuels are alternative fuels that can be produced from any renewable carbon-based material, or feedstock. Since plants are the most common sources for biofuel production, associated carbon life cycle emissions can be significantly reduced, as some of the CO₂ will be reabsorbed by the next generation of crops [39]. Figure 5 shows a comparison of carbon life cycle emissions between fossil-based jet fuel and bio SAF.

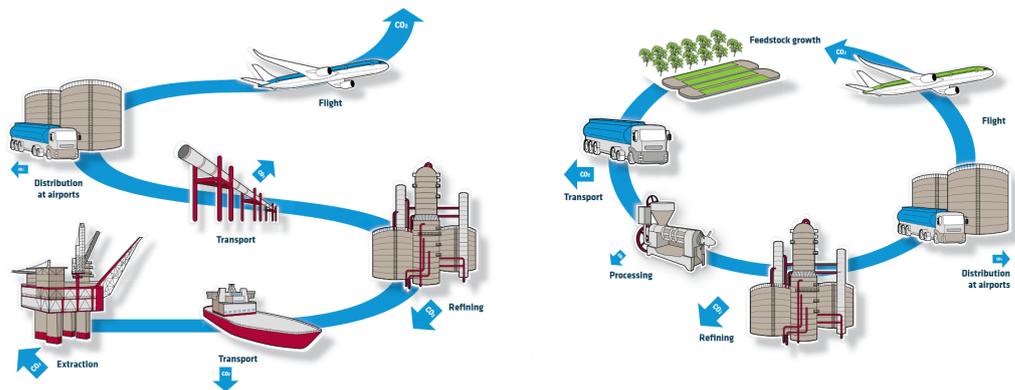


Figure 5. Carbon life cycle diagram for fossil jet fuel (left) and sustainable biofuel (right). Adapted from [40].

The production pathway of biofuels encompasses a series of steps [41]. First, the required feedstock needs to be produced and collected; then, depending on the feedstock type, there is a series of pretreatment steps until the necessary properties for the conversion process to take place are achieved. Only after the conversion process has been finalized, the fuel is ready for transportation and usage.

2.2.1. Renewable Feedstocks

It is important to notice that not all biofuels can be used in the aviation sector [40]. Biodiesel, for example, does not meet the performance requirements to enable its use in air-

craft, mainly due to lower energy density and higher freezing point than Jet-A fuel [42]. Some bioalcohols, on the other hand, have shown potential in studies conducted with internal combustion engines—an example is bioethanol, which has been used to reduce diesel emissions at both start-up and warm-up periods, and mixtures of biodiesel, conventional diesel fuel, and n-butanol have also shown significant emission reductions [43,44]. However, in order for a biofuel to be classified as an SAF, it needs to meet further emissions and sustainability criteria. That is not the case for biofuels made from first-generation feedstocks (edible crops), which is why these are not considered viable alternatives for future implementation [6,45].

SAF-suitable feedstocks can be grouped in four categories: oil, sugar, starch, and lignocellulosic feedstocks [41,46]. Each category requires different kinds of pretreatment routes, and is suitable to separate types of conversion processes. Sometimes wastes from anthropogenic activities, especially industrial by-products, can also be considered as a separate feedstock category [47].

A complete, extensive description of possible biofuel feedstocks would fall out of this paper's scope, but a selection of some of the most promising materials for SAF production is presented next.

Camelina

Biofuels from oil feedstocks used to be mostly produced from first-generation feedstocks, such as palm oil and soybean [41], but these can lead to sustainability issues, such as negative effects of food prices and changes in local environments, due to the use of pesticides and other agents [39].

Second-generation biofuels are comprised of non-food crops and other alternative raw materials that do not seek to compete with edible feedstocks for land usage, and are therefore more likely to meet the sustainability standards required. Camelina (*Camelina sativa*) falls under this category. It is a non-edible energy crop with a high lipid oil content, its main use is precisely as a feedstock for fuel production and, after the oil extraction process, leftover material can also be used as feed supplement for livestock [39].

In addition, like other plants such as *Brassica carinata* and *Thlaspi arvense* or field pennycress, Camelina can be used as a rotational cover crop [6]. Cover crops are grown in periods in which land used for cereal crops is typically left fallow. Besides potential economic benefits for farmers, cover crops can also improve soil quality in comparison with monocropping [39], as it reduces erosion and improves water infiltration and carbon sequestration [6], though the sustainability benefits of this practice are still not completely clear and need further analysis, for it can create other problems such as reducing livestock fodder [48].

Jatropha

Jatropha (*Jatropha curcas*) is another potential lipid oil source as it can yield around 2.5–3 metric tons of oil per hectare [6]. It is also poisonous both to humans and animals so, unlike Camelina, leftovers from the oil extraction cannot be reused as fodder [49].

The main pro for using this plant as fuel feedstock is its ability to be grown on degraded soils, in otherwise non-arable lands such as in arid ecosystems [39]. A use of only a small percentage of this type of soil could boost current SAF production numbers [6], without the need to compete with edible crops or being dependent on their rotation timelines [50]. However, there are long-lasting production challenges that still need to be overcome to make it a viable option. These include low seed yield (and limited biogenetic studies on technologies that could help boost breeding programs, such as cloning and gene expression), susceptibility to viral infections and pests such as insects and rodents, and high complexity and cost of efficient oil extraction methods [51].

Halophytes

Halophytes are a group of salt-tolerant grasses that can grow in areas where plant life normally could not prosper [39]. These show significant potential both as oil and

lignocellulosic feedstock. Oil yield varies with each species, with studies showing that species such as *Ricinus communis* and *Helianthus annuus* are capable of yielding very high oil content (up to 50% of total dry seed weight) [52]. Though different salinity in soil can affect crop productivity, genetic modification and synthetic biology advancements could present a solution and potentially increase future yields [53]. Etihad Airways already performed demonstration flights using fuel derived from Halophytes [41,54]. Another example of the versatility and potential of Halophyte usage is the fact that it can be used for fuel production, while simultaneously serving other objectives, such as desalinating previously fertile land [55].

Algae

“Algae fuels” are a range of fuels also known as third-generation biofuels [45,56]. These are differentiated from second-generation fuels because algae exhibit much faster growth rates and need less land surface compared with other feedstocks [57]. Microalgae can typically double their biomass within a day, with doubling times being as short as 3.5 h during exponential growth [58].

One of the main advantages of using algae is their excellent carbon absorption properties, which makes them highly suitable for carbon capture [39]. Moreover, algae can thrive on a variety of wastewaters, collecting nutrients such as nitrogen and phosphorous, thus playing also a role in treating those waters, which further enhances their environmental and economic benefits [59].

Algae can be grown on marginal lands such as desert edges, and are viewed as potentially the best choice for future production of large quantities of renewable biofuels [39].

Waste Oil

Several different sources and types of waste products can be utilized for SAF production through different conversion processes [50]. Used cooking oil, animal fats, fish oil, tall oil, and other residue lipids can account for at least 20 million tons of SAF and 20 million tons of renewable diesel, though there is still some debate about the sustainability of some of these products [6].

Agricultural and forestry residues also have ecological value as fuel feedstock. These can include leftover stems and leaves from food crops, wheat chaff and other processing residues, as well as residue branches and other material from logging [48]. Wood residues in particular present high lignocellulosic yield and low-cost potential [41]. Studies estimate that the European Union alone could provide over 150 million tons of sustainable agricultural and forestry wastes [60], and other estimates indicate that 2030 global feedstock availability could provide for around 135 million tons of SAF per year [6].

Municipal solid waste also shows great potential, due to its vast supply of about 2 billion tons produced every year on a global basis, half of it of a biogenic nature [6]. It is comprised of grass clippings, furniture, food scraps, clothes, newspapers, packages, and other examples [50]. Another great advantage of using municipal solid waste for biofuel production is that doing so prevents landfill dumping, which gradually emit CO₂, methane, and other gases into the atmosphere from anaerobic decomposition, thus enhancing emissions savings [50,61].

Waste-to-energy transition using plastic feedstocks can also become a future alternative for aviation fuel production, since studies assessing its feasibility as diesel fuel replacement show promising results in efficiency and emissions with up to 40% blending ratios [62].

2.2.2. Certified Pathways

Presently, ASTM has approved eight technology platforms, or conversion processes, for SAF production, specified in as many annexes to the already mentioned standards, mainly D7566. These are related to different feedstock types, and have specific maximum blending ratios associated.

Fischer–Tropsch Synthetic Paraffinic Kerosene (FT-SPK) and Fischer–Tropsch Containing Aromatics (FT-SKA)

The first ASTM approved process, listed as Annex A1 of D7566, was the Fischer–Tropsch process, in 2009, with a blending limit of 50%. The FT synthesis was developed by Franz Fischer and Hans Tropsch in the 1920s as a method for producing liquid hydrocarbon from coal, and is a proven and well-established pathway [28,63,64].

The process consists of a catalyzed thermochemical reaction in which a purified gas mixture of carbon monoxide (CO) and hydrogen (H₂)—known as “synthesis gas” or “syngas”—is converted into a liquid and gas combination of hydrocarbon chains of different lengths, using a reactor with cobalt or iron catalyst. A refinement stage then takes place, where the product faces hydrocracking and isomerization, before distillation occurs, with one of the final products being a synthesized paraffinic kerosene (SPK) with similar characteristics to commercial aviation fuel.

Syngas is produced through high temperature gasification (1200–1600 degrees Celsius), and it can be obtained from practically any carbon-based feedstock, ranging from fossil fuels such as coal (coal-to-liquid—CtL) or natural gas (GtL) to biomass (BtL) [63]. Sustainable feedstock options include municipal solid waste, agricultural and forestry residues, algal biomass, and woody energy crops. Additional pretreatment phases are necessary with BtL, which somewhat hinders the total reduction in life cycle carbon emissions, but FT fuels also show a decrease in NO_x emissions [25].

Another variation of the FT pathway received approval in Annex A4 of D7566, in 2015. Fischer–Tropsch synthetic paraffinic kerosene with aromatics (FT-SPK/A) uses the same FT synthesis process but also includes alkylation of light aromatics, mainly benzene, which results in that the end product hydrocarbon has an aromatic content, making it more compatible with current engines in respect to fuel leakage avoidance. Though currently this process can also only be used in blends up to 50%, it has the most potential of having that value increased in the future, with likelihood of eventually being certified for 100% conventional fuel replacement [25,36,46,65,66].

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

The HEFA process was the second ASTM approved conversion process, receiving certification in 2011 as Annex A2 to D7566, again with a 50% maximum blending ratio. Before 2011, this process was usually referred to as hydrotreated vegetable oils (HVO), but a new name was introduced to cover the whole range of possible feedstocks. Another acronym used to describe this procedure is HRJ, which stands for hydrotreated renewable jet [28,67].

HEFA transforms oil from lipids to hydrocarbons by a four-stage process. The first stage consists of the purification of the biogenic material. Then, the oil goes through a deoxygenation stage, by means of a chemical reaction using hydrogen and catalysts (hydrodeoxygenation). Other less desirable molecules are also removed in this stage. The resulting hydrocarbons are then cracked and isomerized, until chain lengths yielding the desired specifications are achieved. Finally, distillation occurs, and the final products are separated, with the jet fuel obtained being designated by HEFA-SPK. This process is also suitable for achievement of hydrotreated renewable diesel; jet fuel production requires additional cracking of the longer chain carbon molecules.

Due to lower combustion temperatures, HEFA fuels also show reduced NO_x emissions [25]. Furthermore, another advantage of this process is that it can be integrated into an oil refinery with just an additional step, which is why it is currently the most commercially viable option for SAF, having powered over 95% of all SAF flights to date [65].

The feedstock for HEFA is a triglyceride, typically a solid fat or oil, and so sustainable options are more limited than those of the FT process. This includes animal fats (tallow), used cooking oil, and other waste FOGs (fats, oils, and grease), and oil from algae or plants such as Camelina or Jatropha [36,46,65–67].

Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)

Annex A3 of D7566 [36] covers the use of SIP fuels and was approved in 2014. Prior to ASTM certification, this pathway was also referred to as DSHC (direct sugar to hydrocarbons). Contrary to FT and HEFA fuels, HFS-SIP does not produce a synthesized paraffinic kerosene, and so are required to be used in mixtures not exceeding 10% blending ratio, though test flights using 20% blends have been run successfully.

This pathway relies on a biochemical conversion, in which a biological platform (modified yeast or microbes) is used to convert sugars into hydrocarbons, specifically a C15 alkene with four double bonds called farnesene, through fermentation. Then, hydroprocessing converts it into the respective alkane, farnesane, which is afterwards distilled to obtain aviation fuel. Other products such as traces of remaining farnesene and olefins (partially hydrogenated farnesene) may also be present in the final product.

Sugar cane is currently the main feedstock used in this process, though other cellulose-based sugars can be used as alternatives to avoid food–feed–fuel conflicts. One disadvantage of this pathway is the high operational costs associated with the necessary processing steps. It is expected, though, that once the supply chain scales up these costs will be significantly reduced [25,36,46,65,67].

Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK)

The ATJ route produces SPK fuel from alcohol, and was approved in 2016 as Annex A5 of D7566 [36]. After the necessary feedstock pretreatment procedures are complete, the alcohol molecules undergo a sequence of processes, starting with dehydration (water elimination), followed by oligomerization (creation of more complex molecules) and hydrogenation (addition of hydrogen). Distillation is the final step, yielding a hydrocarbon jet fuel, among other by-products, such as diesel. The maximum blend ratio currently allowed is 50%.

At the time of approval, only isobutanol was allowed for production. This was due to lack of documentation from other subpathways to be included in the approval. In 2018, ethanol was included as an ATJ feedstock, and it is expected that in the future Annex A5 will cover all five carbon alcohols. The source for these alcohols is not specified by ASTM, so possibilities range from the typical sugar/starch options, such as sugar cane and sugar beet, to more sustainable alternatives, such as lignocellulosic biomass or wastes [36,46,65–67].

Catalytic-Hydrothermolysis-Synthesized Kerosene (CH-SK, or CHJ)

Catalytic hydrothermolysis is one of the two pathways that were most recently certified for commercial use - again, with a maximum blending ratio of 50%—in 2020 (Annex A6 of D7566 in the case of CH). Across the literature it has also been referred to as hydrothermal liquefaction, BIC (biofuels ISOCONVERSION), or HEFA-SKA.

The first step of this conversion process is a catalytic hydrothermolysis, which names the whole pathway. Here, fatty acid esters and free fatty acids are combined with preheated feed water and then passed to the CH reactor where, at high temperature and pressure conditions, the oil is converted into n-paraffins, iso-paraffins, cycloparaffins, and aromatic compounds. After a subsequent hydrotreatment to saturate residual olefins and remove residual oxygenates, the material is distilled and fractionated into the final products, which include kerosene.

The feedstocks suitable for jet fuel production through CH are similar to those of the HEFA pathway, with carinata being used during the qualification process [66–68].

Hydroprocessed Hydrocarbons, Esters, and Fatty Acids Synthetic Paraffinic Kerosene (HHC-SPK or HC-HEFA-SPK)

The final annex to D7566, namely Annex A7, was approved in May 2020 and it covers for the production and use of a type of synthesized paraffinic kerosene from hydrocarbon–hydroprocessed esters and fatty acids. This was the first pathway to receive certification through the ASTM D4054 “fast-track”, and therefore it is only allowed for use up to 10% blending ratio.

HC-HEFA works similarly to the HEFA process, starting with hydrodeoxygenation, followed by cracking and isomerization. The difference lies in that, unlike the fatty acids or fatty acid esters found in HEFA production, this addition describes the hydroprocessing of bioderived hydrocarbons obtained from oils found in a specific algae (*Botryococcus braunii*), the only feedstock source for this conversion process [36,46,65,66,69].

Figure 6 shows a timeline of approval for the mentioned pathways, and in Figure 7, the feedstock to fuel process for each ASTM D7566 certified fuel is presented.

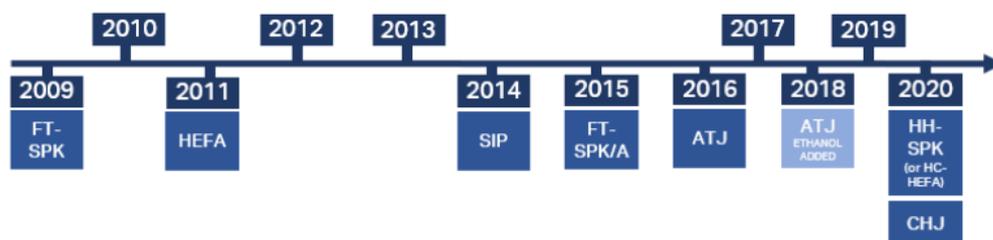


Figure 6. Timeline of D7566 approved pathways [66].

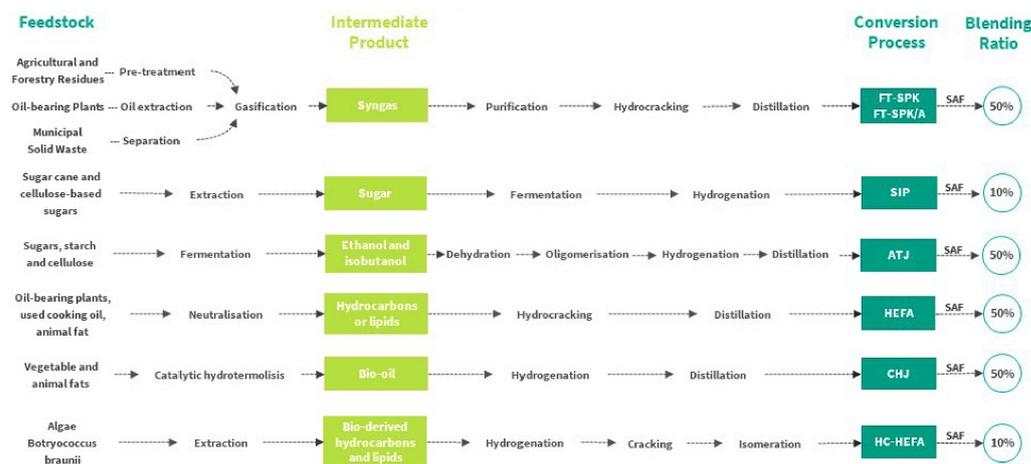


Figure 7. Feedstock to fuel process for D7566 approved pathways [46]. Source: PtX Hub (2021). All rights reserved.

Co-Processing

The seven conversion processes described earlier require the blending of two final products, SAF and conventional jet fuel, which is why those are specified through annexes of ASTM D7566. However, in 2018 co-processing of renewable content with conventional crude oil was approved and added to Annex A1 of ASTM D1655 [70].

With co-processing, biocrude is blended with crude-oil-derived middle distillates in a petroleum refinery [36]. Presently, the percentage of renewable content allowed in co-processing is only up to 5%, and when this method was first approved it could only be obtained from lipids (plant oils and animal fats), but Fischer–Tropsch-derived biocrude (unrefined hydrocarbon content coming from an FT reactor) was also allowed in 2020 [71].

One of the main advantages of producing SAF in petroleum refineries is the fact that the higher capacities of those refineries allows for higher fuel output, and offers significant cost reduction opportunities [72]. However, there is not a consensus regarding the sustainability and potential for GHG reduction in this process, with some companies arguing that fuel resultant from co-processing should be ineligible for SAF classification [73].

2.2.3. Other Pathways

In addition to the aforementioned approved pathways, other methods are currently seeking future certification in different phases of the D4054 process. Other candidate pathways are in the pre-qualification stages for ASTM approval.

The US-based company Virent is conducting research in hydrodeoxygenation synthetic kerosene (HDO-SK), currently inactive [36]) and hydrodeoxygenation synthetic aromatic kerosene (HDO-SAK) through their patented technology, known as BioForming. This process is also known as aqueous phase reforming (APR). APR is a thermochemical catalytic process used to produce alkanes and hydrogen from biomass-derived sugars. A wide range of cellulosic material (such as wood or straw) and sugars can be used as feedstocks, though much of the development so far has been on corn-based sugars. Despite being the only pathway that has passed to Phase 2 of D4054, this technology is still far from being ready for commercial scale production [67,74].

High-freeze-point hydroprocessed esters and fatty acids synthetic kerosene (HFP HEFA-SK), also known as HEFA+, and integrated hydrodryolysis and hydroconversion (IH2) are in Phase 1 OEM Review of D4054. The main difference between HEFA+ fuel and HEFA-SPK is the longer molecule chain of the former. This leads to a higher freezing point, which in turn means that less processing steps are required, giving it a production cost advantage over HEFA-SPK [74]. Boeing and Neste are leading the research efforts on this technology. The IH2 method was developed by the Gas Technologies Institute (GTI) and is now sub-licensed by Shell, and it converts lignocellulosic biomass or MSW into fuels. One advantage of this technology is that it is designed so that the hydrogen production requirements can be produced internally [74].

Finally, Swedish Biofuels and Byogy are currently developing a variation of the ATJ process that can produce jet fuel with a higher level of aromatic content (ATJ-SKA) through the addition of an aromatization step, which is currently in Phase 1 Testing of D4054 [36,67].

2.3. Synthetic Fuels

Unlike biofuels, synthetic or e-fuels do not rely on biomass to produce liquid hydrocarbons. This means that sustainability issues adjacent to large-scale production of renewable bio feedstocks, such as land usage disputes or food–feed–fuel ethical and economical problems would be significantly avoided [4], which in turn implies that, though research is not as advanced as is the case with bio SAFs, e-fuels could potentially become the best choice for short- and medium-term decarbonization efforts.

Typically, e-fuel production rests on the process of obtaining syngas through the combination of “green or e-hydrogen” with CO₂ captured from concentrated sources or directly from the air. The power-to-liquid process relies on electrolysis of water with “green electricity” for hydrogen production, and is closest to being ready for wider applications of e-fuel distribution. However, recent advancements in solar thermochemical technology led to the development of an alternative pathway—the sun-to-liquid process—but is still in early development stages.

2.3.1. Power-to-Liquids (PtL)

Production Pathways

There are two established pathways for production of PtL fuels—the Fischer–Tropsch (FT) pathway and the methanol pathway [63]. They present similarities in that both require a supply of captured CO₂ and of H₂, with the latter being obtained through electrolysis of water; from then on, though, they differ in how hydrocarbons are synthesized and upgraded into fuel. Figure 8 presents a generic scheme of the PtL production chain.

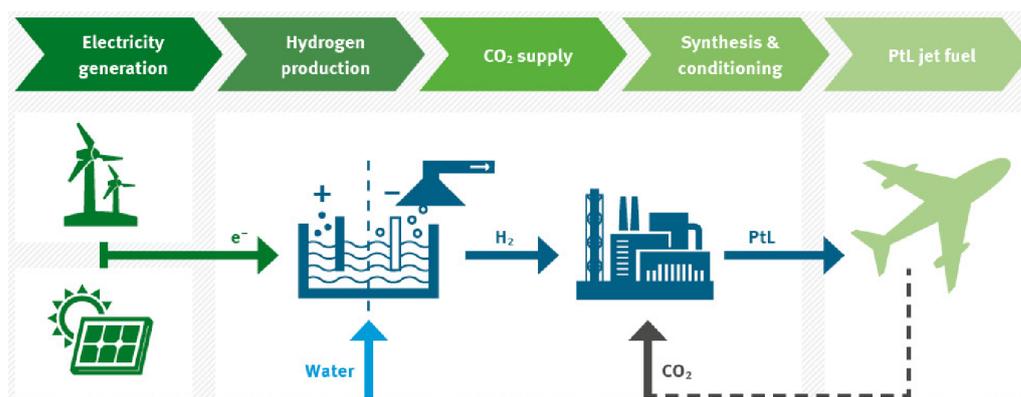


Figure 8. Generic Power-to-liquid production stages [75]. Source: LBST GmbH (2016). All rights reserved.

The Fischer–Tropsch pathway requires syngas production, which will force that, if regular electrolysis is applied to obtain H_2 , an additional step of reducing the sourced CO_2 to CO must be undertaken [76]. This can be achieved through a reverse water–gas shift (RWGS) process [77]. After syngas is produced, the following steps mirror those of biofuel production through FT synthesis. Providing that the FT process employs iron or cobalt catalysts, ASTM does not restrict the feedstock origin for drop-in FT fuels, and so this pathway can already be used in commercial aircraft up to 50% blends [63,74].

The methanol pathway is an alternative that, while currently not yet certified by ASTM for jet fuel production [63,78], could present itself as an interesting option for the aviation sector. Methanol is currently produced especially from syngas, through a sequence of exothermic reactions, and requires a stoichiometric H_2/CO ratio of 2 for maximum efficiency [79]. This process is well established and used on an industrial level. There have been, however, advancements in direct CO_2 to methanol conversion [80], which would eliminate the need for CO_2 reduction through RWGS, and thus improve cost efficiency of the whole production line. However, there are still several technical challenges that need to be addressed in the near future [63].

Methanol-to-gasoline (MtG) is a common process that is used in other sectors, also enabling other middle distillate fuels to be obtained, in this case kerosene fuel. These processes, first developed in Mobil facilities, rely on converting a mixture of methanol and dimethyl ether (DME) into light olefins with the use of shape-selective zeolite catalysts (particularly ZSM-5 zeolite catalyst), and subsequent oligomerization and hydrotreatment to obtain the final products [63]. Aromatic compounds are also generated through this process, which is of extreme interest and could contribute towards achieving higher engine compatibility specifications, and to receive certification for higher blending ratios or, potentially, total replacement of conventional kerosene [63].

Electrolysis

Hydrogen production from electrolysis of water is a fundamental step in the PtL process, common to both the FT and the methanol pathways. Although it is still far from being the most industrially used method to obtain H_2 [81], it is a growing market and the most promising process to achieve carbon-free hydrogen production [82].

Early power-to-X projects relied on alkaline electrolyzers [83], a matured technology which typically uses aqueous solutions of KOH or NaOH as the liquid electrolyte [84]. Polymer electrolyte membrane, or proton-exchange membrane electrolysis (PEMEL)—where two electrodes are pressed against a proton-conducting polymer electrolyte [84]—is also an already established process that has recently gained market share in PtL projects, since it shows advantages such as good partial load range and dynamic behavior [83].

Solid oxide electrolysis (SOEL) is a recent, less developed technology when compared with AEL and PEMEL that is just now entering the market [83,85], but it is considered a more promising long-term option for carbon-neutrality pursuit [86]. SOEL uses

oxide-ion-conducting ceramics as solid electrolyte and to separate the two electrodes [84]. One of the main advantages of this technology is the high operational temperature range (up to 1000 °C [84]); this enables that waste heat to be reused from both the exothermic FT reaction or methanol synthesis [75], which reduces the energy demand and results in significantly higher efficiencies than AEL or PEMEL [87]. Another possible feature from SOEL is the ability of co-electrolysis of CO₂ and steam to produce syngas, which would be of extreme interest since it would also eliminate the need for RWGS, but this technology is in an early development stage [63,87].

Similarly, there have also been recent breakthroughs in alternative technologies that can potentially enhance SAF performance, namely hydroxy (HHO) production with dry cell electrolyzers. Studies show that HHO has advantages over H₂ in reducing CO and CO₂, and increased efficiency and reduction in some GHG emissions have been reported with dual-fuel setups in diesel engines [88].

Resources

There are three resources that can be seen as “feedstocks” for production of PtL fuels—water, (renewable) electricity, and CO₂. Water is necessary for hydrogen production (1.3–1.4 liters of water per liter of jet fuel [75]), as well as cooling and heating purposes during other phases [76]. Though demand is substantially lower when compared with biofuel production [75,78], sustainability issues may emerge if, for example, the used water source conflicts with agricultural land requirements, and such factors need to be evaluated before any future large-scale facilities enter production.

Electricity is used throughout the whole process chain, but the highest energy demand happens during electrolysis. As previously mentioned, SOEL could help in decreasing the amount of energy necessary. Nevertheless, using renewable energy is still fundamental for PtL fuels to show significant improvements in GHG emissions [76]. Though current PtL projects address this by demonstrating a clear trend toward inclusion of renewable energy sources, there is no clear preference regarding the type of technology preferred [83].

Carbon capture can occur either from concentrated point sources, or directly from ambient air—direct air capture (DAC). Currently available sources can have fossil origin, for example industrial waste gases, or renewable origin such as gas from biomass combustion. CO₂ from fossil origin is not a sustainable long-term solution but could be of interest in the short-term to prove production of scale [89]. Waste gas from industrial processes in which decarbonization is an especially complex endeavor, such as the cement or limestone industries, could be used to create a CO₂ cascade—a process in which CO₂ from non-sustainable sources is re-utilized before being finally released into the atmosphere [76]. However, this process would still nevertheless increase CO₂ atmospheric levels, and so it is not a realistic option towards achieving future goals.

DAC requires ambient air to pass through a filter where either adsorption, absorption, or mineralization removes carbon dioxide [83]. However, at the moment this is still an underdeveloped technology, and disputes regarding its feasibility for larger scale production due to high operating costs are ongoing [90]. These higher costs are due to significantly higher energy requirements for DAC when compared with point source capture [75]. Most current projects obtain carbon dioxide from biogas or biomass plants [83].

2.3.2. Sun-to-Liquid Process

Sun-to-liquid processes differ from PtL pathways in that solar energy is directly used to synthesize liquid hydrocarbon fuels. There are, however, alternate definitions in the literature, which encompass all pathways in which sunlight is used to produce renewable fuels. This would include not only PtL fuels that use sun power for electricity production, but also biofuels from plant crops or algae, which require sunlight to grow [91]. This paper will focus on the thermochemical process to produce fuels from concentrated sunlight that is being developed by the European Union-backed consortium SUN-to-LIQUID. The process

is based on the formation of syngas from H_2O and CO_2 , with a redox reactor (Figure 9) that is powered by concentrated solar radiation flux.

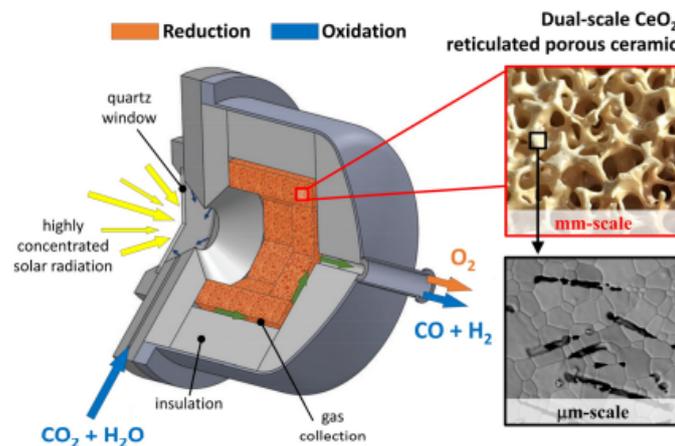


Figure 9. Sun-to-liquid solar reactor configuration using ceria reticulous porous ceramic structures [92].

Cerium oxide (ceria) is used as the redox-active material because this compound presents good properties regarding its high oxygen ion conductivity and cyclability [93]. Other materials may present superior redox performance but have not yet proven to be as stable as ceria. The first step corresponds to a high-temperature endothermic reduction, where ceria is partially reduced to a non-stoichiometric state. Then, the low-temperature exothermic oxidation reactions occur, where the reduced ceria reacts with H_2O and/or CO_2 , and H_2/CO is formed. A dual-scale reticulated porous ceramic (RPC) structure is used, so that different void sizes can maximize the efficiency of each reaction, with studies showing rates of $0.17 \text{ mL}_{\text{O}_2} \text{ min}^{-1} \text{ g}_{\text{CeO}_2}^{-1}$ and $0.60 \text{ mL}_{\text{CO}} \text{ min}^{-1} \text{ g}_{\text{CeO}_2}^{-1}$ for mean reduction and mean oxidation, respectively, for a cycle duration of 25 minutes, and solar-to-fuel energy conversion efficiency of 1.72% [94]. The two-step redox cycle guarantees that the syngas and O_2 are generated in separate steps, which avoids the formation of explosive mixtures while also removing the necessity for high-temperature gas separation [95]. After the reaction, fuel production follows the PtL pathways (the SUN-to-LIQUID project, as is illustrated in Figure 10, uses the FT process [93]). CO_2 capture can also be made from any of the aforementioned processes.

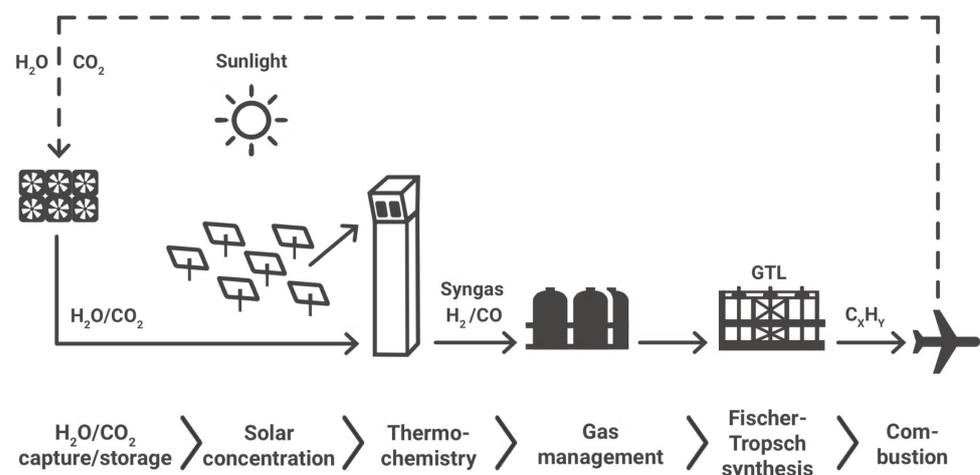


Figure 10. SUN-to-LIQUID fuel production chain [96]. Source: IEA (2018) World Energy Outlook. All rights reserved.

Despite the excitement generated by the numerous environmental advantages that this technology can potentiate [97], it will not be ready for commercialization in the foreseeable future. A predecessor project—SOLAR-JET—established proof of concept by successfully designing and operating a 4 kW solar reactor at ETH Zurich [93]. The current 4-year project focuses on establishing a 50 kW pre-commercial plant in Spain. Due to the high energy demands, facilities include a 500 m² heliostat field, capable of delivering almost 300 kW of radiative power to a 15 m solar tower [92].

3. Other Alternatives

As previously mentioned, drop-in fuels are the best short- and medium-term alternatives to address the climate issue, due to various technological and logistical factors [98]. However, this does not mean that other long-term alternatives should be dismissed. Apart from the development of advanced gas turbine combustion techniques [99,100], such is the case for hydrogen- and battery-powered aircraft. Unlike SAFs, which rely mostly on carbon offsetting to reduce life cycle emissions, the latter technologies would eliminate in-flight CO₂ emissions, and though their potential flight coverage is limited, they can still play an important role in decarbonizing aviation, which is why numerous projects involving several airlines are currently under development [101].

3.1. Hydrogen

Hydrogen consumption has been progressively increasing in recent decades, but not on a sustainable manner, being mostly produced from gasification of coal or reforming of natural gas, with associated CO₂ emissions exceeding 800 million tons per year [81]. Hydrogen production can be differentiated through a color-based international conventional [102]; for sustainability purposes, green hydrogen—produced from electrolysis of water using renewable power—is of primary interest. This has been the method used when describing other sustainable fuel pathways, i.e., e-fuels.

Liquid hydrogen has a variety of properties that make it suitable to be a replacement for conventional kerosene, namely containing 2.5 times more energy per kilogram than kerosene [103]. Hydrogen could be used to power aircraft as combustion fuel or in fuel cells. If used as a liquid fuel replacement, and though the same combustion principles as with current aircraft apply, there would have to be engine reconfigurations to due to variations in the combustion gases and properties between the kerosene and hydrogen [104]. A hydrogen fuel cell generates electricity via an electrochemical reaction between hydrogen and oxygen. Proton exchange membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) have different operating principles, but both are theoretically suitable for aviation usage. Furthermore, there are no NO_x emissions with the usage of this propulsion system [104].

Though hydrogen fuel cells are an emerging technology in other sectors such as road transportation, their potential for the aviation industry is hindered due to range limitations. H₂ fuel cell aircraft in development are only targeting short-range flights, and though hydrogen turbine aircraft are expected to be capable of flying larger distances, it is not expected that they will be able to cover long-distance flights [6]. This is mainly due to its small energy by volume number when compared with conventional kerosene, even in its liquid form [105]. This also leads to problems regarding hydrogen storage, which require critical aircraft design changes to accommodate the amount of fuel required for longer flights. Furthermore, other contingencies need to be taken into account in hydrogen storage to ensure safety requirements, due to other properties, such as wider flammability range [103]. Nevertheless, alternative solutions have been proposed and are currently being evaluated. An example is storing liquid ammonia instead, with subsequent “cracking” of the chemical to obtain hydrogen, but this would lead to other problems such as ensuring sustainable ammonia production [106].

3.2. Battery Electric

Aircraft propulsion through the use of batteries has the highest potential to reduce not only CO₂ emissions, but emissions of other GHGs, such as NO_x as well [107]. However, it is also affected by limited range barriers. Current research has been focusing on developing vertical take-off and landing (VTOL) technologies for urban mobility and other small-range applications that are scheduled to enter commercialization in upcoming years [108]. Still, even by 2050, large battery-powered aircraft are not expected to cover distances of more than approximately 500 km [107]. Despite recent breakthroughs in battery energy density [109], the inclusion of batteries as kerosene replacement adds a significant amount of weight, and, unlike kerosene that burns off, such weight remains constant throughout the entire flight, which increases energy requirements in a substantial manner [6].

Hybrid electric systems that combine electric and combustion engines can, therefore, provide a better alternative since these explore the advantages of both systems, and will also play an essential role in maturing electric aircraft technology [9]. Current development projects already plan to achieve ranges above 1000 km in the near future using small-capacity aircraft [108]. E-Fan X, an Airbus partnership with Rolls-Royce and Siemens, was developed with the goal of building a hybrid electric demonstrator that could accommodate 50–100 passengers, but was canceled in 2020 before any flights were made [110]. Different hybrid configurations are possible, but smaller combustion engines are required to counter-balance the added weight of the batteries. Another advantage of this technology is that it can potentially enable a combination of using both hybrid systems and SAFs/H₂, which could further boost environmental benefits.

4. Challenges

There are numerous barriers to the scale-up and expansion of the alternative fuels market, which can be classified in various categories—the lack of maturity of some, if not most, of the fuel pathways; unavailability of required feedstock quantities and, in the case of bio SAFs, sustainability problems associated with the increase in feedstock production; and not enough support from local governments and international organizations to accelerate and facilitate the fossil to renewable conversion. The combination of all these issues produce negative effects on the cost-effectiveness of SAFs, which, if these problems were to be left unaddressed, and the economic viability of these fuels remained questioned, could lead to a deceleration in the decarbonization efforts, thereby undoubtedly preventing the sector from achieving the set objectives for the next decades.

Biofuels are closer to wide-scale commercialization than other alternatives, but, despite increasing number of flights using SAFs, especially employing HEFA-SPK, no pathway has yet achieved the highest technological readiness level [74] (if co-processing is discarded as it has the lowest maximum blending limit permitted and there are environmental concerns regarding this method). All pathways requiring H₂ are dependent on future advancements in the production of green hydrogen that close the gap in production cost when compared with production from fossil sources. Power-to-liquid processes are also relying on new improvements in both high temperatures and co-electrolysis, and while at the moment they are nowhere near as close to compete with biofuels in terms of cost, it is expected that in the long-term this pathway becomes the most economically competitive [6].

As it has been mentioned throughout this paper, a vital aspect to biofuel production is ensuring that feedstock sustainability criteria are met. This is achieved through life cycle assessments that are made for comparison to imposed limits, and by making sure that no disputes regarding food security or land usage/conservation arise [28]. ICAO, for example, has set, through the CORSIA scheme, specific regulations for eligibility as “CORSIA eligible fuel—CEF”, that also address other aspects, such as social development and labor rights [111]. There is some skepticism regarding the capability of biogenic feedstocks to address expected future fuel demand without compromising some of these obligations [63]. When establishing economies of scale, regardless of the type of alternative fuel produced, land used for infrastructure and logistics must also face sustainability evaluations. In addi-

tion, most fuel production pathways also generate other products, and even if production is optimized to obtain jet fuel, valorization of co-products should not be neglected [83].

Policies regarding SAFs must act as catalysts that encourage companies to increasingly shift focus from fossil to renewable fuels. Naturally, financial support mechanisms are of highest importance, since it can influence a project's financial viability [112]. Examples include tax exemptions, recently approved in the United States [113], or direct funding of projects. Another way to promote SAF use is through legislation, such as the European Commission's ReFuelEU Aviation, a mandate that sets specific targets for SAF integration in EU airports, from 2% in 2025 to 63% in 2050, for biofuels, and to 0.7% for 2030, for e-fuels [114]. Regarding other technologies that are far from being technologically ready, namely hydrogen and battery-power, focus should primarily target R&D funding. Accelerating ASTM certification procedures, as well as a revision of maximum blending ratios allowed, would certainly play an important role in boosting alternative fuel market as well.

5. Conclusions

The need for sustainable aviation is undeniable as it is expected that the sector will occupy an increasingly prominent position in global transportation. As the climate crisis deepens, COVID-19 provided an unexpected "breather" in GHG emissions, but numbers will soon return to their pre-pandemic tendencies. Furthermore, so, the whole industry, despite facing an inevitable but unprecedented financial crisis, must increase efforts in accelerating the transition towards carbon neutrality.

Sustainable fuels will play an important role in this transition. Drop-in fuels have the advantage on other alternatives, not only due to being more matured technologies, but also because their compatibility with current aircraft and logistics makes it possible to address the urgency of the problem. Within this category, jet fuel from biogenic sources is currently easier and less expensive to produce in meaningful quantities, and can be achieved through several different pathways. There are, however, known obstacles to future larger scale implementations, derived from the complexities involved with feedstock growth that may compromise long-term sustainability targets. Synthetic fuels, especially from PtL methods, will likely become a protagonist in decarbonization, once current technological barriers are surpassed. Nevertheless, biofuel research and promotion should not be abandoned, as they are still crucial to prove economies of scale as well as to achieve initial significant reductions in emissions. Similarly, hydrogen- and battery-powered aircraft can contribute, in the long term, to eliminate fossil dependency. However, in the absence of revolutionary breakthroughs within this field, the scope of such alternatives will be limited mostly to short-range flights. Finally, it must be emphasized that synergistic efforts between the scientific community and political entities are essential to potentiate and accelerate future developments.

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Abbreviations

The following abbreviations are used in this manuscript:

AEL	alkaline electrolysis
APR	aqueous phase reforming
ATJ	alcohol-to-jet
CH	catalytic hydrothermolysis
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	direct air capture
EU	European Union
FT	Fischer–Tropsch
GHG	greenhouse gas
HEFA	hydroprocessed esters and fatty acids
HFS	hydroprocessed fermented sugars
ICAO	International Civil Aviation Organization
IH2	integrated hydrolysis and hydroconversion
MSW	municipal solid waste
OEM	original equipment manufacturer
PEMEL	proton exchange membrane electrolysis
PtL	power-to-liquid
RWGS	reverse water–gas shift
SAF	sustainable aviation fuel
SKA	synthetic kerosene with aromatics
SPK	synthetic paraffinic kerosene
SIP	synthetic isoparaffins
SOEL	solid oxide electrolysis
US	United States

Appendix A. Jet Fuel Overview

Appendix A.1. Comparison with Non-Aviation Fuels

Due to the different and more challenging operating conditions faced by air travel, jet fuel specifications must inherently differ from other types of fuels, such as gasoline and diesel. The main difference lies in the hydrocarbons that compose each type of fuel, most importantly the number of carbon atoms. As Figure A1 illustrates, gasoline ranges from molecules with 4–12 carbon atoms, and diesel can vary between 8 and 23 carbon atoms. Jet fuel, on the other hand, is a middle distillate of the two products—its molecules have 8–16 carbon atoms. Kerosene fuel also significantly varies from gasoline due to a lower freezing point and higher flash point, which widens its operational range. Diesel values are more approximate, making these fuels more compatible, which is why in some extreme cold environments jet fuel has been used in diesel engines.

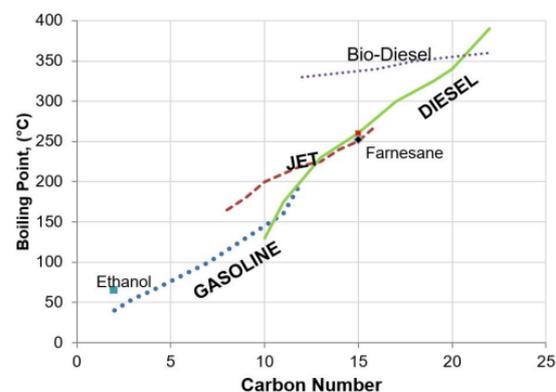


Figure A1. Carbon number comparison for gasoline, jet and diesel fuels [38].

Another crucial difference between jet fuel and non-aviation fuels lies in the additives used. Additives are present in all petroleum-derived fuels in varying degrees, but, again, due to the particularities of air travel, specification regarding approval and use of additives is more complex, with some being mandatory while others are optional. Among the additives used in jet fuel are anti-static chemicals, deicing agents, anticorrosive agents, and antibacterial agents [35,38,115]; while these focus primarily on safety, studies are being conducted on additives that enable emission reduction in GHG in various petroleum fuels [116], and future technological breakthroughs are likely to be applied to SAF as well, which could help in boosting their environmental benefits.

Appendix A.2. Jet Fuel Properties

Table A1. Selection of ASTM D1655-specified jet fuel properties [35,117].

Property	Jet A/A-1
Aromatics, % vol., Max.	25
Sulfur, mass %, Max.	0.30
Distillation, °C (°F)	
Initial Boiling Point (IBP)	-
10% recovered, Max.	205 (400)
50% recovered, Max.	Report
90% recovered, Max.	Report
End Point, Max.	300 (575)
Flash point, °C (°F), Min. (Specified by D56)	38 (100)
Density, 15°C, kg/m ³	775–840
Freezing point, °C (°F), Max.	−40 (−40) Jet A; −47 (−52.6) Jet A-1
Viscosity, −20 °C, mm ² /sec, Max.	8.0
Specific energy, MJ/kg, Min.	42.8
Smoke point, mm, Min.	18.0 Jet A; 19-0 Jet A-1
Naphthalenes, vol. %, Max.	3.0
Copper corrosion, 2 h at 100 °C, max rating	No. 1
Filter Pressure drop, mm Hg, Max.	25
Visual tube rating, Max.	<3
Anti-icing, vol. %	Agreement
Antioxidant	Permitted
Corrosion inhibitor/Lubricity agent	Agreement
Metal deactivator	Permitted
Conductivity improver	Permitted
Conductivity, pS/m (if conductivity improver is used)	50–450

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