New approaches of Sustainable Aviation Fuels

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Abstract. In order to reach climate neutrality, as required by the EU Green Deal, the aeronautic sector has two main targets: by 2030 the introduction of low emission aircrafts, enforcing the use of sustainable fuels and making it available for airlines by 2035; by 2050 the climate neutral aviation, with the use of sustainable aviation fuels and decarbonized alternative energy carriers.

Sustainable aviation fuel includes biofuels from biomass or waste, advanced biofuels synthesized from solid feedstock, biomass like crops, or algae; an option is power-to-liquid fuels, also known as synfuels, synthesized from H2 and CO2 taken from industrial, biomass or direct-air capture. All these biofuels are drop-in and can be handled in the same way as kerosene.

Another alternative fuel is hydrogen, which has three times higher gravimetric energy density compared to kerosene, but requires larger tanks on-board the aircraft and modified aircraft/engine designs.

In order to transform aviation and reach climate neutrality will require an integrated and synergic approach, involving technology providers and innovators, manufacturers and operators, public sector authorities and travelers.

In the present paper, the possible strategies to reduce emissions in the aviation sector by low-carbon alternative fuels, which have been considered in the framework of the Horizon 2020 project PARE – Perspectives for Aeronautical Research in Europe -, will be discussed.

1. Introduction

The European Green Deal [1] aims to drive EU toward a sustainable and fair society. The goal is to reach in 2050 no net emissions of greenhouse gases (GHG) and improve the resource usage for an efficient and competitive economic growth (Figure 1). The decarbonization of the transport sector is a fundamental part of the plan and aviation is considered as the most difficult-to-decarbonize. International Air Transport Association (IATA) aims at reducing by 50% CO_2 emissions, compared to the 2005 level.

To decarbonize, the aviation industry has to implement a combined action of new, low-carbon propulsion technologies and/or new fuels [2, 3, 4].

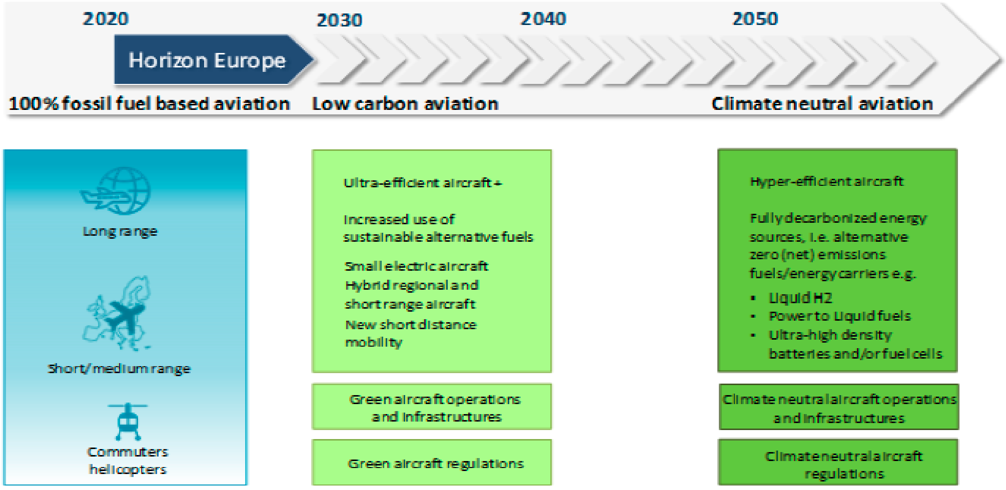

Figure 1. Possible trajectory towards climate neutral aviation [5]

New propulsion technologies include battery- and turbo-electric technologies, as well as hydrogen combustion in turbines and fuel cells that power electric motors. Batteries can be applied in combination with conventional propulsion ("turbo-electric aircraft") or hydrogen fuel cells [6, 7, 8, 9]. Since electrification is still far away for commercial aircraft, and although energy efficiency is possible, it cannot make the required impact alone. Then, the use of low-carbon alternative fuels, commonly addressed as Sustainable aviation fuels (SAF), is necessary. They have reduced particulates, nitrogen, sulfer and critical greenhouse gases.

Several kinds of **SAF** are under study:

- *biofuels* from biomass or waste (cooking oils and fats)
- *advanced biofuels* that are synthesized from e.g., solid feedstock, biomass like crops, or algae
- power-to-liquid fuels, also known as *synfuels* synthesized from hydrogen and CO2 taken from industrial, biomass or direct-air capture
- *hydrogen*.

Biofuels and **advanced 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. Biofuels are already commercially available. The fact the biofuels rely on feedstock, changes in land use, high water usage, and/or monoculture, since sometimes it is necessary the production of a single crop, means that the aviation industry will be competing with industries that need the feedstock for their other purposes.

Electrofuels use renewable energy for fuel synthesis; among them the most studied are the **Synfuels**. In this case, unlikely biofuels, electricity is used to firstly produce hydrogen and to capture carbon, that are then combined into a kerosene-like fuel. Synfuel can also be used in current aircraft engines and fuel infrastructure [10, 11, 12].

Hydrogen can be used as a fuel for aircraft when it is combusted in a H2 burning engine or reacted in a fuel cell powering electric motors. It has a gravimetric energy density three times higher than kerosene, though hydrogen requires larger volume and hence larger tanks on-board the aircraft, with the consequent need of adjusting the aircraft designs. The size and weight of H_2 tanks pose major limitations for high energy demand on long-range flights [13, 14]. Hydrogen has the advantage that can be produced directly from renewable energy and in perspective synergies with other sectors that use hydrogen can be realized. The drawback is that additional equipment and capacities to liquefy the hydrogen are needed.

The present paper is aimed at presenting the main issues relevant to the different SAF in order to provide a first glance view of the possible evolution towards the decarbonization of the aviation sector.

2. Discussion

The composition of the ***advanced biofuels*** is currently mostly paraffinic, indeed many of them are defined as Synthetic Paraffinic Kerosene (SPK) or iso-paraffins. They can be blended in variable amounts up to 50%, depending on the fuel type with conventional commercial and military jet fuel while synthetic kerosene. Other biofuels have the addition of aromatics (SKA: Synthetic Kerosene with Aromatics) and can replace fossil fuels or lower blending percentages are needed. Blending is required with SPK fuels because they lack sufficient aromatic hydrocarbons, that are present in fossil fuel. Aromatic hydrocarbons are limited in kerosene to prevent smoke formation during combustion, nevertheless a minimum aromatic content is needed because they allow elastomer swell in aircraft engines and increase fuel density.

The Commercial Aviation Alternative Fuels Initiative (CAAFI) is an organization formed by stakeholders leading the development and deployment of alternative jet fuels for commercial aviation. It reports that there are 7 major fuel routes approved by the ASTM D7566 standard and there are other 6 routes currently under approval process, furthermore other 15 are waiting to enter the qualification process [15, 16].

Feedstocks considered for the production of aviation advanced biofuels 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. The feedstocks types themselves cannot be considered sustainable: the sustainability is related to the specific production chain in which are entered, according to internationally recognized standards like RSB (www.rsb.org) or ISCC (www.iscc-system.org) and the Directive 2009/28/EC. Wastes and residues that do not require land to be produced usually have less sustainability concerns. Micro algae are also interesting, since their use does not require use of large amounts of water or dedicated fields and competitions with other intended use. Advanced biofuels can reduce lifecycle emissions by between 20% and 95% when compared with petroleum-derived jet fuels [17]. In Table 1 the approved advanced biofuels and the feedstock used are reported.

Table 1. Pathway processes approved by ASTM [18]

Pathways Processes	**Feedstock**	**Date of Approval**	**Blending ratio by Vol**
Fischer-Tropsch Synthetic Paraffinic Kerosene (**FT-SPK**)	Biomass: forestry residues, grasses, municipal solid waste	2009	50%
Hydroprocessed Esters and Fatty Acids (**HEFA-SPK**)	Oil-bearing biomass: jatropha, camelina, carinata	2011	50%
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (**SIP-HFS**)	Microbial conversion of sugars to hydrocarbon	2014	10%
FT-SPK with aromatics (**FT-SPK/A**)	Renewable biomass: municipal solid waste, agricultural wastes and forestry residues, wood and energy crops	2015	50%
Alcohol-to-Jet Synthetic Paraffinic Kerosene (**ATJ-SPK**)	Agricultural wastes products: stover, grasses, forestry slash, crop straws	2016	50%
Hydroprocessed Esters and Fatty Acids Plus (**HEFA +**)	Oil-bearing biomas: algae, jatropha, camelina, carinata	2021 (?)	50%
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)	2020	50%
Hydroprocessed Hydrocarbons (**HH-SPK**, or **HC-HEFA**)	Bio-derived hydrocarbons, directly from oils (triterpenes) produced by the Botryococcus braunii algae	2020	10%
Co-processing	Fats, oils, and, greases (FOG), from petroleum refining, biocrude	2018	5%

Electrofuels are produced by combining hydrogen with carbon extracted from CO_2 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***”). The synthesis of synfuels is achieved using 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 is an alternative fuel source for aviation in the long term in the perspective of decarbonization [19].. Some potential electrofuels potentially applicable as aviation fuels are: n-octane, methanol, methane, hydrogen and ammonia [20]. 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.

A new technology has been developed for electrofuels production in which, using a single step co-electrolysis process, it is possible to convert renewable electricity, water and CO_2 captured from ambient air and unavoidable CO_2 sources into syngas. Renewable jet fuels, are then produced through further processing and refining. The output of the full-scale plant would save an estimated 250,000 ton of CO_2 emissions annually and fuel the five most frequently serviced domestic routes with a 50% blend.

Hydrogen is an almost ideal electrofuel and has been considered a promising energy carrier for the future energy systems [21]. 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 it difficult to store. The main ways to store hydrogen effectively are compression and liquefaction, with a consumption of 15.5% of the hydrogen’s inner energy content for the compression and up to 45% for liquefaction [22]. The use of hydrogen yields efficiencies from 40% for its oxidation in a combustion engine or up to 55% in a fuel cell (“cold combustion”). A new independent study, commissioned by Clean Sky 2 and Fuel Cells & Hydrogen 2 Joint Undertakings, 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 already be used to power aircraft for short-range aircraft already by 2035.

2.1. Technical feasibility, Combustion and Chemical Characteristics

The advanced biofuels 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 ignition behavior depends on the fuel composition and structure, and advanced biofuels have shorter ignition delay compared to conventional kerosene [23, 24]. Furthermore, the pressure increase due to ignition in the combustion chamber is higher than that of conventional kerosene. Since advanced biofuels are all “drop in” fuels, they can be handled as the traditional kerosene and used in turbofan powertrain technology.

Electrofuels like methanol, methane, hydrogen and ammonia differ significantly from jet fuel regarding their combustion properties. The mass flow of fuel differs due to the specific energy, while the mass flows of air for combustion and cooling the burned hot gases are not so different than fossil kerosene, therefore a basic research on flame stabilization and emission is required in order to adapt the design of combustors to the fuels. The main drawback of electrofuels is, anyway, their low volumetric energy density, which requires larger tank systems, that has to be either under high pressure or be cooled down to liquefy the fuel. On the other hand, n-octane is nearly similar to jet fuel in terms of specific energy, energy density, autoignition temperature, lower and upper explosive limits. Other properties such as flash point, vapor pressure and boiling point could be adjusted by adding small amounts of mixable hydrocarbon-based fuels with high energy densities. The alternative electrofuels may be used in current turbine designs without major performance impacts if mixed with n-octane. The current designs are compatible with the aerothermodynamics of the hot gas path, but the increase in rotor speed changes the mechanical loads and thus requires modifications in the turbomachinery design. The electrofuels, therefore are not yet drop-in options.

Hydrogen and fuel cell technology has undergone significant development in the last decades. Hydrogen has much larger stability limits and therefore lean combustion is possible without approaching lean blow out limits, this avoids the instabilities when flame temperatures are reduced with the aim implement low NO_x emission combustion technologies.

2.2. Availability and impacts

Advanced biofuels to be sustainable, within the ICAO CORSIA scheme, the life-cycle emissions have to demonstrate a minimum GHG (Green House Gases) saving of 10% compared to fossil kerosene. The most important impact is related to the feedstocks used for the production of the biofuel. Sustainable biofuels should not be produced from biomass obtained from land converted after 2009, moreover the production of the feedstock has to be based on fallow land rotation (RED, Renewable Energy Directive). Microalgae have the advantage that yield more oil per hectare of land, produce higher-quality fuel, not require arable land or fresh water.

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. As with sustainable advanced fuels, there is a risk of some residual emissions from electrofuels. The zero carbon production depends on their potential displacement impacts, the technology used for their production and therefore on the broader decarbonisation of the economy.

Hydrogen can be produced carbon-free, moreover there are no CO_2 emissions, therefore liquid hydrogen combustion could reduce climate impact in flight by 50 to 75%, and fuel-cell propulsion by 75 to 90 %. This compares to about 30 to 60 % for synfuels. When the hydrogen production for shorter range aircraft will be scaled, as well as synfuels, there will be a great diffusion and acceptance, with a consequent large scale availability of hydrogen for medium and long range aircraft.

2.3. Economics, costs

SAFs are currently significantly more expensive than traditional jet fuel, therefore currently SAFs are not the most economic method of carbon reduction in aviation. The delivered cost of a feedstock accounts for the total costs of cultivation/plantation, harvesting and other postharvest processing, storage, and transporting to the production plant [25]. For SAF adoption to become prevalent, the costs of production must come down significantly, to below that of jet fuel plus conventional carbon offsets. The fact that SAFs are admissible under CORSIA will aid their economic viability over the coming years.

The cost implications of electrofuels will remain substantial also with the future developing of the technology, increasing plane ticket price by 60%. Direct air capture costs are falling but will remain considerable for some time. Renewable electricity costs are decreasing toward parity or below non-renewable electricity costs, nevertheless electrofuels production requires enormous quantities of electricity, as a consequence its cost will likely exceed that of untaxed kerosene. It is unlikely that, even with carbon pricing, electrofuels will reach cost parity with kerosene.

Liquid Hydrogen has the potential to completely decarbonise civil aviation. At the moment it is not considered within the industry, mainly due to the anticipated higher costs. But considering heightened environmental awareness emissions taxation scenarios, and the sheer necessity of transformation, the cost will be relatively modest for this kind of long-term solution. A growth in hydrogen demand across sectors would resolve scale effects partially decreasing the initial cost disadvantages.

As various projects scale up and economies of scale kick in, costs should naturally come down, this will be more effective for some pathways, among them Power-to-Liquid is the more promising.

2.4. Commercialization readiness, Distribution, infrastructures

According to ICAO, from 2011 up to 2019, more than 40 airlines have developed experience using SAF and 185,000 commercial flights have used blended alternative fuels. Worldwide locations offering daily flights are growing, in 2018 SAF volume was already approximately 0.01% of total fuel demand [26]. Advanced biofuels have had larger diffusion compared to other SAF, this is mainly related to the fact that the feedstocks used are easily available and there is no need to change the existing engines of the aircrafts, due to the compatibility of biofuels once blended with fossil kerosene.

Electrofuels are having an increasing diffusion. On June 2020, an industrial consortium is planning Europe's first power-to-liquid (PtL) plant that will produce hydrogen-based renewable aviation fuel in Norway. It will have a production capacity of 10 million liters per year and will be upscaled 10-fold to produce 100 million liters of renewable fuel before 2026 [27]. The certified end products can be used directly in existing infrastructures. The renewable fuel would be generated from CO_2 and water using 100% renewable electricity.

Commercialization and distribution of liquid hydrogen aviation fuels are dependent on the related technology readiness. Conventional aircraft development cycles occur about every 15-20 years until a new aircraft platform is introduced. The challenges affecting the airport refueling infrastructure and operations will require significant development and planning. Scalable refueling technology has to be studied, refueling practices have to be optimized, and airport infrastructure have to be re-configured to introduce parallel fuel systems. The most viable near-term liquid hydrogen refueling technology seems to be the liquid hydrogen refueling truck, in the longer term, liquid hydrogen hydrant pipeline systems may become a viable solution.

Conclusions

The development of sustainable aviation fuels is complex as the industry faces with the challenge of sustainability. SAFs will play a key role in dealing with this challenge, in particular Power-to-Liquid fuels, together with other technologies such as electric and hydrogen propulsion. In the near-term, advanced biofuels will be the most used being available to contribute towards sustainability targets before electric and hydrogen technologies will become mature. When hybrid-electric technologies will start to be commercialized, the engines should be designed to be compatible to more promising biofuels such as synfuels and liquid hydrogen, allowing a double environmental benefit. In the long-term, SAFs will remain the only viable solution for sustainable long-distance aircraft. In parallel, investments into electric and hydrogen-powered flight will be needed.

Considering environmental, economic, safety, ethical issues, several figures and the largest possible assembly of stakeholders should be involved in order to consider the different perspectives associated to such multi-facet and challenging r-evolution toward the aviation of the future.

Acknowledgements

The authors acknowledge the project PARE (Perspectives for Aeronautical Research in Europe) funded by European Union's Horizon 2020 research and innovation programme under grant agreement no. 769220.

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