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Review Article

Hydrogen in Aviation: A Review of Storage, Infrastructure, Propulsion and Fuel Demand

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ABSTRACT

This paper explores the potential of hydrogen as an alternative aviation fuel, focusing on its production, storage, and application in aircraft propulsion. Hydrogen offers high specific energy and zero carbon emissions, making it a strong candidate for decarbonising aviation. The paper compares production methods and evaluates storage options including liquid hydrogen, cryo-compressed hydrogen and metal hydrides. It further examines hydrogen's use in modified gas turbines and fuel cells for electric propulsion. Key industry initiatives, along with safety and environmental considerations, are discussed together with projections for future fuel demand. In the case of hydrogen, under the most optimistic scenario, demand is projected to reach 568 Mt by 2050, whereas the demand for sustainable aviation fuel is expected to reach 445 Mt by 2050. The paper concludes that hydrogen, especially in liquid form, is a viable long-term solution for medium- and long-range aviation, assuming the development of scalable production and supporting infrastructure.

KEYWORDS

Alternative fuels, Hydrogen storage, Turbine engines, Fuel cells, Fuel demand, Aviation.

INTRODUCTION

Traditional fossil aviation fuels pose a significant environmental and political burden and strongly contribute to greenhouse gas (GHG) emissions [1]. Within the European Union (EU), the aviation sector is the second-largest producer of GHG emissions after road transport, and its share of emissions is expected to grow in the future [2]. The different global and local imperatives, such as the EU's 2030 Climate and energy framework [3], the EU's 2050 Long-term strategy [4], and International Civil Aviation Organization's (ICAO) Carbon offsetting and reduction scheme for international aviation (CORSIA) [5], aimed at reducing emissions, have promoted a wave of research and development into alternative fuels that promise to revolutionise the way aircraft are powered. These imperatives strongly focus on CO_2 reduction, since lowering CO_2 emissions also leads to reductions in other climate pollutants such as methane, black carbon, sulphur dioxide, nitrogen oxides, and fine particulate matter [6]. Currently, various biofuels derived from sustainable feedstocks like waste oil, fats, green and municipal waste [7] and non-food crops like wastepaper [8] or synthetic fuels produced through innovative processes [9] are significantly researched. All these fuels have in

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common that they are hydrocarbon based. For aviation purposes, they must be manufactured and tested in accordance with the standards issued by the American society for testing and materials (ASTM) under ASTM D7566 [10]. Currently, there are eight approved pathways to produce sustainable aviation fuel (SAF) [11]. SAF should be a "drop-in fuel" that means it is ready to be mixed with fossil fuel and no requirements for changes in aircraft engine design or fuel infrastructure are needed. SAF reduces CO_2 emissions by up to 80% when carbon is captured directly from the air [12]. Currently, the most viable biofuel for aviation seems to be Hydro-processed esters and fatty acids (HEFA) as it can reduce carbon emissions without compromising performance or safety [13]. In the HEFA process, lipid feedstocks, including plant or algae oils, animal fats, and waste greases such as used cooking oils, are deoxygenated and subsequently hydro-processed to produce a pure hydrocarbon blending component for fuels [14]. Its maximum blending ratio with conventional kerosene is 50% [1]. HEFA creates over 95% of all SAF flights to date [11].

However, the adoption of aviation biofuels has some challenges. Technical problems, infrastructure limitations, and economic considerations all pose considerable barriers to overcome [15]. From an economic point of view, SAF produced entirely from renewable sources achieved the worst results compared to traditional and other alternative aviation fuels due to the significantly higher production costs [16]. Moreover, the use of the first generation of biofuels as a fuel, consisting of agriculture crops such as corn, sugarcane, sugar beets, soybean, and canola, is debatable because of negative effects on food prices and changes in local environments, due to the use of pesticides and other agents [17].

An alternative to biofuels is hydrogen, which offers the potential to be a cleaner fuel, with minimal production and consumption emissions, while improving efficiency and performance [18]. Hydrogen has the lowest global warming potential among other aviation fuels, such as kerosene, ethanol, methanol, and ammonia, as proposed in [19]. Moreover, hydrogen reduces, compared to traditional fossil fuel, acidification potential by 46% in the long-term horizon (2050) [20].

Another benefit of hydrogen could be lowering direct operating costs [21], however, this will strongly depend on supply infrastructure [22]. In [23], the price forecast of crude-oil-based Jet-A fuel, green Jet-A fuel and hydrogen is compared. It concludes that the price of hydrogen is expected to be equal with crude-oil-based Jet-A fuel in 2040. The price of green Jet-A fuel is expected to decrease throughout the monitored period, but it will still be significantly higher than the price of hydrogen and crude-oil-based Jet-A. Moreover, in [24] the authors forecast that in the short term, fossil kerosene combined with direct air capture and remote sequestration of CO_2 will be employed, as it requires no modifications to aircraft engine and infrastructure. In the medium term, renewable kerosene is expected to be implemented, requiring only modest engine adaptations. In the long term, hydrogen produced from renewable electricity is projected to be adopted, as it represents the least expensive solution for achieving carbon-free aviation.

There are also several issues which must be overcome, namely, the effectiveness of hydrogen production, its storage methods, particularly for the aviation sector [25], risk of explosion when leaked and its distribution to the end user [26]. For instance, in the EU it will be necessary to build facilities with an electrolysis capacity of 518 GW to produce domestic green hydrogen by 2050 [27]. In [28], cost optimisation of compressed hydrogen transport via trucks and pipelines is proposed for Europe under different scenarios, considering factors such as distance, hydrogen demand, pipeline diameter, and the presence of enroute compressor stations. Several extensive reviews on hydrogen-fuelled aircraft are presented in [18], [21], [29], [30], [31]; however, none of these studies provide detailed projections of future demand for potential aviation fuels. The main scope of this paper is, in addition to addressing the utilisation of hydrogen in aviation, including production, storage, airport infrastructure, and forms of hydrogen propulsion, to provide the reader with detailed and comprehensive information on aviation fuel demand up to 2050 for conventional fossil-based fuels, SAF, and particularly hydrogen.

In preparing this review, the technical aspects were derived primarily from peer-reviewed journal articles, conference proceedings indexed in Scopus or Web of Science (WoS), and technical reports, while survey-type information was additionally obtained from reputable websites. The search employed keywords such as “hydrogen in aviation,” “hydrogen in aerospace,” “hydrogen storage,” “hydrogen production,” “hydrogen infrastructure,” “fuel cells in aviation,” “hydrogen aircraft engine,” “sustainable aviation fuels,” and “hydrogen demand,” covering publications up to 2025.

HYDROGEN PRODUCTION AND STORAGE

The deployment of hydrogen powered aircraft in any form will not be feasible unless a sufficient supply of hydrogen is ensured at a level comparable to conventional Jet fuel, or if its cost remains significantly higher than that of other alternative fuels. This chapter examines both existing and emerging hydrogen production pathways, as well as the options for its storage on board aircraft. Moreover, airport hydrogen infrastructure and the economic aspects of hydrogen in aviation are here presented.

Hydrogen Production

Hydrogen is the most abundant element on the Earth’s surface which can be found, e.g. in water, fossil fuels or in biomass. It is a non-poisonous, tasteless, colourless, and odourless gas. Hydrogen is considered to be a renewable source of energy. It is not available in ready to use form in nature, however, it can be produced from primary energy sources by various methods **[32]**. These methods can be divided according to the raw materials containing hydrogen into conventional and renewable (**Figure 1**). Conventional methods utilise to process fossil fuels pyrolysis, coal gasification or hydrocarbon reforming methods (natural gas steam reforming and oil reforming). The trend is, however, to avoid fossil fuels to produce hydrogen, regardless of its efficiency and produced purity. On the other hand, renewable methods utilise for hydrogen production water splitting or biomass. Attention is currently focused on the production of hydrogen from municipal solid waste, as leaving it to decompose in landfills contributes to methane formation. Traditionally, the steam gasification method is used for this purpose **[33]**. Nowadays, also biological methods of hydrogen production from municipal solid waste are emerging and proving to be feasible **[34]**. Hydrogen can also be produced by algae or some bacteria by bio-photolysis, where the carbohydrate containing materials are converted to organic acids and then to hydrogen gas by hydrogenase enzymes.

Moreover, the conversion of liquid fuels, as methanol, ethanol and dimethyl ether, for onboard hydrogen production via cold plasma has good prospects, however, today, this method is not feasible yet **[35]**. In **[36]**, authors propose a broad review on plasma-catalytic technologies as gliding arc discharge, microwave discharge, dielectric barrier discharge, corona discharge, glow discharge and nonthermal plasma reactors. Authors conclude that plasma reformers have rapid startup and fast transient response and produce negligible soot. Moreover, plasma reformers are capable of reforming a wide range of fuels. They have compact size, and they are suitable for onboard applications.

Another promising method to produce hydrogen is electrolysis, where water (H_2O) is separated to hydrogen and oxygen molecule with aid of direct electric current. There are various ways to perform water electrolysis, i.e. alkaline water electrolysis, proton exchange membrane water electrolysis, solid oxide water electrolysis, and alkaline anion exchange membrane water electrolysis **[37]**. Main benefit of water electrolysis in ground applications, in contrast to aviation, is that the surplus renewable energy can be used. The selected properties of different hydrogen production pathways are summarised in **Table 1**. From this, it can be seen that methods used to produce hydrogen from fossil fuels are more efficient compared to those from renewable sources currently, due to their level of technological maturity. However, their

renewable potential is lower. Moreover, the carbon footprint is here expressed as the ratio of kg CO_2 emitted per kg of H_2 produced.

Hydrogen can be classified based on the level of ecological friendliness of its production into grey, blue, and green. Grey hydrogen is produced from fossil fuels, and its overall carbon footprint is equivalent to that of burning fossil fuels. Blue hydrogen is obtained from natural gas; however, the carbon produced during the conversion to hydrogen (through the process of reforming) is captured rather than released into the air. Green hydrogen is produced solely from renewable energy sources through a process called electrolysis, however, current wind, solar and water powerplants cannot supply enough energy to achieve it.

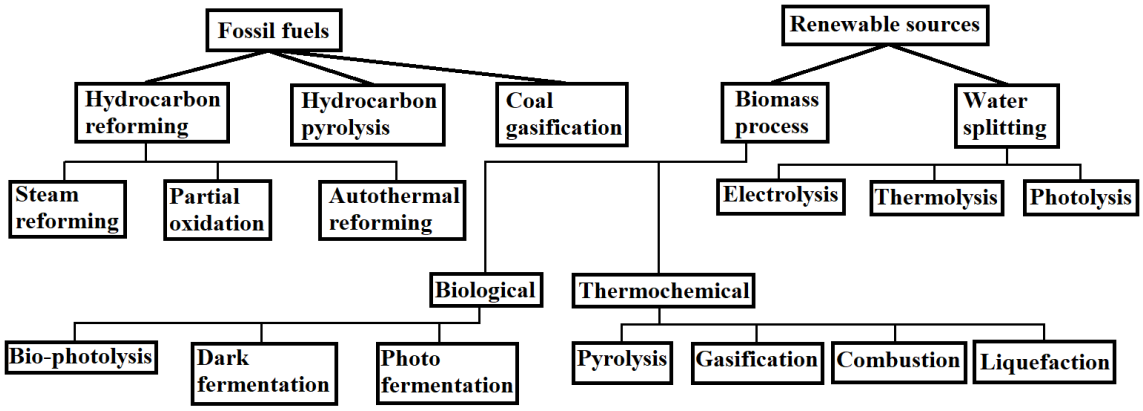

Figure 1. Pathways for hydrogen production [32]

Table 1. The selected properties of different hydrogen production pathways [32], [37], [38], [39], [40], [41], [42]

	Hydrogen production pathway	Efficiency [%]	Carbon footprint[1]	Technology maturity	Renewable potential
Methods for fossil fuels	Steam reforming	70 – 85	Medium	High	Low
	Oil reforming	65 – 75	High	High	Low
	Autothermal reforming	60 – 75	Medium to High	High	Low
	Coal gasification	45 – 55	High	Medium to High	Low
Methods for renewable sources	Biomass gasification	40 – 60	Low	Medium	Medium
	Biological fermentation	10 – 30	Low	Low	High
	Electrolysis (alkaline, PEM)	60 – 80	Low	High	High
	Steam gasification	50 – 70	Medium to High	Medium	Medium to High
	Bio-photolysis	1 – 5	Very Low	Low	Very High

[1]Carbon footprint categories: very low (0 – 3 kg CO_2 per kg H_2), low (3 – 10 kg CO_2 per kg H_2), medium (10 – 15 kg CO_2 per kg H_2) and high (>15 kg CO_2 per kg H_2).

Hydrogen Storage

It is difficult to store hydrogen in compact way at standard pressure because gaseous hydrogen has a very low density, only 0.0841 kg/m³ at International standard atmosphere conditions (15 °C and 101 kPa). For onboard application, it is necessary to compress hydrogen

to approximately 70 MPa compared to 20 MPa for ground applications [43], however, its volumetric energy density will be still approximately 6 times lower than petroleum (5.6 vs 32 MJ/l, respectively).

It is also difficult to store hydrogen in liquid form due to its very low temperature, which is −253 °C. It requires a lot of energy and time to cool hydrogen to this temperature. The energy loss during the hydrogen cooling process is estimated to be 40%, compared to just 10% for compressed hydrogen [44]. However, liquid hydrogen (LH_2) enhances its energy per unit volume relative to gaseous hydrogen approximately three times [45], which makes it viable for use in aviation. A weight penalty associated with the insulation components for storing liquid hydrogen at a low pressure and cryogenic temperature is less than the weight and volume penalty associated with storing gaseous hydrogen at a high pressure. To conclude this, the aircraft shape must be redesigned due to increased volumes or weights of hydrogen tanks, which will negatively affect the fuel consumption [25]. To minimise heat transfer, the optimal tank shape is spherical; however, this is impractical for aviation purposes, so a cylindrical design is used as an alternative. Such tanks, however, can no longer be placed within the wings. Blended wing body configuration was proposed as a solution; however, it still has some energy penalty over the kerosene fuelled aircraft. In [46], the authors claim that a hydrogen-fuelled blended wing body aircraft has an energy penalty of 3.8% compared to its kerosene counterpart, while the energy penalty for a hydrogen fuelled tube-and-wing configuration is 5.1%. In [47], the authors proposed a structural sizing methodology for a liquid hydrogen tank for a commercial aircraft, including the stiffening structure. The developed model is capable of sizing a cylindrical tank with hemispherical end caps of any dimensions or materials, located at the rear of the aircraft. For aviation purposes, the storage of neat hydrogen imposes the problems due to hydrogen embrittlement in a variety of materials including titanium and nickel-based super alloys [48], however, according to [49] aluminium and its alloys are not prone to hydrogen embrittlement.

From safety aspect, the hydrogen in a concentration of 4% to 75% forms a flammable mixture with air at a pressure of 100 kPa [50]. Its lower ignition limit increases with decreasing pressure and vice versa [51]. This fact could favourably affect the safety of the flight, in case of gradual release of hydrogen into the surrounding atmosphere from a cracked tank. The second factor increasing safety is the flight speed itself. However, during ground handling or parking of the aircraft, the release of hydrogen into the environment would create a flammable, even from a concentration of 18%, an explosive atmosphere [52]. This risk must be evaluated especially during refuelling process, thus hermetically sealed hoses and couplings are considered. A similar system was tested for LH_2-powered vehicles at Munich airport in the 2000s [53]. In [50], the authors model hydrogen diffusion in the event of a leak into the cockpit from tanks located inside the fuselage. They conclude that forced cabin ventilation is necessary; however, it will not be sufficient to ensure that the hydrogen concentration remains below its lower flammability limit.

Solid state materials, as metal hydrides (MHs) and chemical hydrides (CHs), containing hydrogen are considered in many papers, e.g. [54], [55], [56], however, for aviation purposes such a solution is currently impractical, due to its heavy weight and long recharge time. In MHs, hydrogen is stored in the metal itself, for example in lithium hydride, sodium bicarbonate, and magnesium hydride. MHs are expensive to produce but can have fast hydrogen release rates when catalyst is present [54]. MHs, in order to work efficiently, operate in a temperature range $-40\ °C < T < 85\ °C$ and pressure $1\ MPa < p < 70\ MPa$, however, these ranges can vary depending on MH type [55]. CHs include substances like ammonia borane, formic acid, and hydrazine. CHs are favourable for use in fuel cell (FC) vehicles because they can store a large volume of hydrogen in a small area, but the hydrogen release process is slow [57] and in some cases the process is irreversible [56].

Currently, to reach a short hydrogen recharge time the powerful cooling system must be applied – assuming a refuelling time equal to 10 min, the cooling capacity of the MH bed must

be about 13 kW [58]. Practical realizations show the recharging time for the BL-60 metal hydride with a hydrogen capacity of 60 – 69 normal litres is about 6 hours [59], and for the BL-740 metal hydride with a hydrogen capacity of 740 – 822 normal litres the recharge time is about 48 hours [60]. Currently, the research is focused on lowering recharge time of hydrogen to MH. As a promising method the hybrid hydrogen storage containers appears to be, in which, MH is placed into a high-pressure container filled with compressed hydrogen gas [61]. Moreover, hybrid hydrogen storage system allows for a significant increase in the volumetric hydrogen storage capacity, which prolongates the driving time of vehicles, e.g. from 1.5 hours with pressurised gaseous hydrogen to 5 hours with hybrid hydrogen storage for golf cart, and from 3 hours with pressurised gaseous hydrogen to 5 hours with hybrid hydrogen storage for marine vessel [58]. Innovative hydrogen storage solutions for aerospace based on a combination of high-pressure storage in hollow microspheres and chemical hydrogen storage are investigated in [62]. Such a system can reach hydrogen storage capacities of up to 10% of its weight at ambient pressures and temperature.

Next methods of hydrogen storage are cryo-compression, physical absorption and liquid organic hydrogen carriers. Cryo-compression combines the properties of both the compressed gaseous hydrogen and the cryogenic hydrogen. This method requires no liquefaction. The gas is compressed to 30 MPa at − 233 °C. The advantage of cryo-compressed hydrogen over liquefied one is its approximately 13% higher volumetric energy density and greatly reduced boil-off losses, however, this method is less efficient [63]. Physical absorbents of hydrogen are materials that can store hydrogen through physical adsorption, where hydrogen molecules adhere to the surface of the absorbent material without forming chemical bonds. The advantage of this method is short refuelling time due to high rates of hydrogen absorption and desorption [63]. On the other hand, this method is efficient only at cryogenic temperatures and/or higher pressures. Its volumetric energy density is only 23% of cryo-compressed hydrogen. Another drawback is desorption loses. To store hydrogen as a liquid organic hydride, the hydrogen must chemically react with hydrogen deficient organic molecules. The main advantage of this method is that existing storage and transport mean for traditional fuels can be utilised [64]. The drawback of this method is that it requires a high temperature for dehydrogenation [65]. In **Table 2**, the comparison of basic hydrogen storage methods is listed and in **Figure 2** the evolution of hydrogen storage methods in hydrides is presented.

Table 2. The comparison of basic hydrogen storage methods [63], [66], [67]

Hydrogen storage form	Compressed gas	Liquid	Solid
Volumetric energy density	Lowest	Highest	Medium [1]
Gravimetric energy density	Highest	Highest	Lowest
Safety	Lowest	Medium	Highest
Maturity level	Highest	Medium	Lowest
Time for refuelling	Lower	Lower	Higher
Infrastructure requirements	Lower	Higher	Lower

[1] Some hydrogen carriers have high volumetric energy density

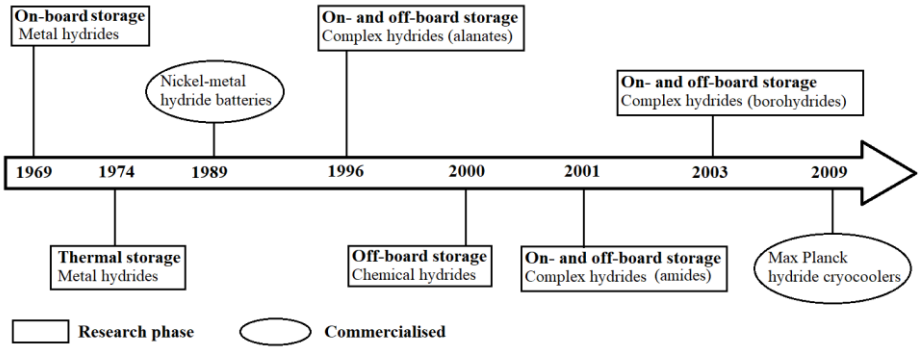

Figure 2. Evolution of hydrogen storage methods in hydrides [68]

Hydrogen Infrastructure and its Economic Implications

In addition to solving the problem of storing hydrogen onboard the aircraft, it is also necessary to adapt the entire infrastructure of the airport to hydrogen, including the connection to its central warehouses and manufactures/importers. For economic and geographical reasons, it will not be possible to produce hydrogen in every country in which the inclusion of an airport offering hydrogen is being considered, so it will be necessary to solve the issue of its transport to the given country, which will also increase its price. Since the most likely form of hydrogen onboard the aircraft is liquid, it is necessary to establish a facility for liquefaction either at the airport or in a sufficient vicinity. Since the costs of this infrastructure are high, hydrogen will only be offered at some central airports. In [69], the authors present the readiness of seven major international airports for hydrogen-powered flights and propose a timeframe for the necessary implementation depending on the expected volume of hydrogen flights. They conclude that these airport master plans show very little preparation for the adoption of hydrogen technology. The study [70] provides a detailed analysis of the supply and handling of LH_2 at Rotterdam Airport. It concludes that on-site hydrogen production and liquefaction at the airport are not cost-effective, and that importing liquefied hydrogen from the Port of Rotterdam would be more economical. The authors of [71] reached the same conclusion, noting that green hydrogen-powered flights in Europe in 2050 will be feasible, from a cost/infrastructure perspective, only for airports located within 20 km of a seaport, whereas inland airports are expected to rely primarily on SAF and electric energy. The paper [21]presents a detailed cost assessment of hydrogen infrastructure for aviation. It shows that the direct operational costs of short-range hydrogen-powered aircraft are approximately 6% higher, and those of mid-range aircraft are about 10% higher, compared to kerosene-powered aircraft; however, airport infrastructure cost was not included into this assessment. Moreover, it presents that from an infrastructure perspective, the largest share of costs is associated with production (60%) and liquefaction (31%), with the remainder accounting for transport (3%), storage (4%), and refuelling (2%). The study [72] compares the prices of liquid hydrogen, liquid methane, SAF and fossil Jet-A-1. For an aircraft with a capacity of 180 passengers, the costs are 3.08, 4.57, 5.11 and 1.15 EUR/(PAX×100 km) for liquid hydrogen, liquid methane, SAF and fossil Jet-A-1, respectively. For a regional aircraft, the corresponding costs are 4.73, 7.01, 8.14 and 1.53 EUR/(PAX×100 km). In [73], the authors present an analysis of an airline's transition from kerosene to hydrogen propulsion over the period 2030 – 2050. In the kerosene-only scenario, total direct operating costs (fuel, maintenance, crew, insurance, depreciation, and carbon taxes) over the 2030 – 2050 period are estimated at USD 69.22 billion, whereas in the mixed kerosene/hydrogen scenario, they rise to USD 102.55 billion (a 48% increase).

HYDROGEN FOR AIRCRAFT PROPULSION

Hydrogen is one of the energy carriers that can be utilised for decarbonisation purposes in aviation sector in the near future. Its noncarbon content and high energy capacity makes it

advantageous over traditional fossil fuels and biofuels. Hydrogen's energy per unit mass is 98% higher than diesel and 87% higher than natural gas [57]. Hydrogen can be utilised directly as a fuel in gas turbine engines, however, some modifications must be implemented, e.g. minor changes of inlet manifold and combustion chamber design, exchange of the kerosene nozzle to gaseous ones, fast fuel metering system for gaseous hydrogen, and new control software. Reference [57] provides a detailed review of articles focused on the use of hydrogen in aircraft turbine engines, including unmanned aerial vehicles (UAVs). Moreover, it highlights the benefits of using hydrogen fuel with water injection and the application of exhaust gas recirculation, which enhances engine performance and reduces emissions, respectively. In [74], the authors converted the auxiliary power unit (APU) GTCP 36-300 (used, for example, on the Airbus A320) into a test rig for hydrogen operation and proposed a new engine control algorithm. In [75], the authors converted a small gas turbine engine, the KHD T216, and the APU GTCP 36-300 to hydrogen operation and demonstrated their safe ignition and engine start procedures. The other way how hydrogen can be utilised in aviation is the use of FC as a source of electrical energy for electric propulsion.

History of Hydrogen in Aviation

History of hydrogen in aviation began with inflation of first hydrogen balloon in France on August 27, 1783 by J. A. C. Charles [76]. Since then, hydrogen balloons and airships have rapidly gained popularity, the most famous being the Graf Zeppelin and the Hindenburg, whose unfortunate fate contributed to a gradual cease of operation of these vessels [77]. The first hydrogen powered turbojet engine was demonstrator engine HeS-1 designed by Dr. Hans von Ohain in 1937. The engine demonstrated good performance during both acceleration and deceleration. Further details on the engine's construction and research background are provided in [78]. In 1950s, the J-65-B-3 engine was tested with both kerosene (JP-4) and gaseous hydrogen fuels, incorporating just simple combustor modifications. When operated on hydrogen, the engine exhibited superior performance, including stable combustion up to higher altitudes (65,000 vs. 89,000 feet), a 2 – 4% increase in thrust, and a 60 – 70% reduction in specific fuel consumption [79]. In 1957, Martin RB-57B Canberra was NASA's testing aircraft with liquid hydrogen powered J-65-B-3 turbojet engines [80]. Similar altitude tests were performed on J-47 and J71-A-11 engines [81]. However, many hydrogen-fuelled prototypes, such as Lockheed's CL-400 and various NASA concepts, were never realised due to the absence of liquid hydrogen infrastructure. Since then, the aerospace projects, utilised liquid hydrogen, like the US Space program and the Space shuttle program were conducted [82]. In 1988, the experimental Tupolev Tu-155 aircraft used liquid hydrogen to power one of its three engines [83], and an advanced cryogenic fuelling complex was constructed for this purpose [82]. Later, the aircraft was also tested using liquefied natural gas (LNG) as fuel. Based on the ongoing oil crisis, the German-Russian cooperation (DASA – Tupolev) was established in 1990s with the aim to modify Airbus A310 to run on liquid hydrogen. However, this project was cancelled in progress due to the fact that oil crisis was over [84].

The history of hydrogen FCs stems in the first FC, called „gas battery" which was developed by Sir William Grove in 1839; however, the first practical FC was engineered by Francis Bacon in 1950s. It was an alkaline type of fuel cell. Proton exchange membrane fuel cell (PEMFC), with power output 1 kW was first developed by General Electric in the 1960s for use by NASA on their space vehicle Gemini spacecraft [85]. In the late 1960s, International Fuel Cells developed a FC power plant for the Apollo spacecraft and in the 1970s, they developed a more powerful (up to 16 kW) alkaline FC for NASA's Space Shuttle Orbiter [86].

Hydrogen Fuel for Turbine Engines

Currently, the aircraft manufacturers are proposing various concepts of zero carbon future aircraft. For instance, Airbus has an ambition to bring to market the world's first hydrogen-powered commercial aircraft by 2035. Airbus' ZEROe concept aircraft has four

variants. The first variant is ZEROe-Turbofan aircraft for 200 passengers with range of 3700 km, where two hybrid-hydrogen turbofan engines provide thrust. The liquid hydrogen storage and distribution system is located behind the rear pressure bulkhead. The second variant is ZEROe-Turboprop aircraft for 100 passengers with range of 1850 km, where two hybrid-hydrogen turboprop engines, which drive eight-bladed propellers, provide thrust. The liquid hydrogen storage and distribution system is located like previous concept. The third variant is ZEROe-Blended-Wing Body for 200 passengers with range of 3700 km, where two hybrid-hydrogen turbofan engines provide thrust, however, the unique aircraft design enables to place liquid storage tanks underneath the wings. The last variant is ZEROe-Fully electrical concept which features a fully electrical propulsion system powered by FCs.

Since the mid-2000s', Boeing has conducted six hydrogen technology demonstrations with crewed and uncrewed aircraft using hydrogen FCs and combustion engines. Moreover, in 2021, Boeing successfully tested a cryogenic tank with capacity of 73 m^3 of liquid hydrogen, which is energy equivalent of Jet-A fuel in typical regional jet **[87]**.

In **[88]**, three aircraft concepts to illustrate the potential for zero-carbon aircraft using liquid hydrogen as a fuel are proposed by FlyZero project. As reference aircraft, FlyZero project chose ATR 72-600 with use of FCs as regional reference aircraft, Airbus A-320neo with hydrogen-powered combustion engines as narrowbody reference aircraft and Boeing 767-200ER with hydrogen-powered combustion engines as midsize reference aircraft. This study concludes that The FlyZero narrowbody reference aircraft concept uses around 4% less energy compared to the baseline aircraft for the design mission. This saving is achieved by placing the smaller diameter engines and fuel system in the aft part of the aircraft, also by using dry wings technology, which make it possible to place the flap actuators directly in the wings, also by using folding wing tips technology, and by the variable cross-sections of fuselage to encourage natural laminar flow.

As was mentioned above, hydrogen has a great potential to be used as an alternative fuel in aircraft gas turbine engines, suitable even for hypersonic operation **[89]**. In **Table 3**, the energetic and volumetric properties of hydrogen are compared with current and some alternative aviation fuels. In **Table 4**, the selected hydrogen properties, regarding its combustion, are listed and compared with aviation Jet-A1 and Avgas fuels. It should be emphasised that hydrogen has the highest gravimetric energy density of all known substances, i.e. its lower heating value (LHV) is approximately 120 kJ/g, moreover, stoichiometric fuel-air ratio of hydrogen is 1:34, whereas kerosene's is 1:15, and hydrogen has wider flammability limits. As a result of these differences the jet engine requires some modifications to burn the hydrogen. In conventional high-performance engines, the engine is cooled with air bled from the compressor. In LH_2 aircraft, hydrogen can be used through a heat exchanger to cool the engine **[90]**, thus such engines work under a slightly lower turbine temperature. In **[91]**, authors present that all main performance parameters of three-spool jet engine during take-off phase were equal for kerosene and hydrogen fuel but the inlet turbine temperature, which was in case of hydrogen fuel 60 °C lower. Similar results were obtained by **[92]**, where turbine entry temperature drop was about 37 °C in case of hydrogen fuel, which has a significantly positive effect on turbine life.

The higher water content, approximately 2.5 times, compared to kerosene in the exhaust gas of a hydrogen-powered gas turbine engine increases thermal load due to faster heat transfer **[49]**, although the total exhaust temperature can be reduced up to 40 °C. On the other hand, higher water content leads to a smaller pressure drop in the turbine, which leaves more energy to be converted into thrust **[93]**. Higher water content in hydrogen-fuelled engines causes more frequent contrails and contrail cirrus formation compared to kerosene fuelled engines **[94]**. This fact could be most evident during flights in the tropics and subtropics. Contrail cirrus represents the largest component of radiative forcing, contributing approximately 50 mW/m², compared to 35 mW/m² from CO_2 and 5 mW/m² from NO_x **[95]**. The influence of aviation fuel composition on the formation and lifetime of contrails is reviewed in **[96]**. It must be emphasised that not all contrails cause climate warming.

Table 3. The basic characteristics of selected fuels

Fuel	Energy per unit mass	Energy per unit volume	Mass per unit volume
Petroleum	1	1	1
Kerosene	0.97	1.13	1.16
JP-5	0.97	1.1	1.13
Methanol	0.44	0.51	1.16
Ethanol	0.62	0.68	1.1
Gaseous hydrogen (70 MPa)	3.08	0.16	0.05
Liquid hydrogen [1]	3.08	0.29	0.09
Hydrogen in metal hydride	0.046	0.36	7.8

[1] Valid for temperature 25 °C except for liquid hydrogen (-253 °C).

The specific energy fuel consumption of hydrogen-fuelled aircraft was according to various studies improved by approximately1% [92], 3% [91] and 4% [97]. Despite the lower aerodynamic efficiency, the hydrogen-fuelled long-range aircraft uses approximately 12% less energy per seat than its kerosene-fuelled counterpart, however mid-range and short-range hydrogen aircraft use 5% and 18% more energy per seat than kerosene-fuelled equivalents [93], which contradicts the results obtained in [88].

Lean mixture of hydrogen and air leads to a lower flame temperature, subsequently it leads to a reduced production of NO_x, however, the major task is to thoroughly mix hydrogen and air, preventing thus hot spots formation which leads to increased NO_x formation. Lean direct injection and micro-mix combustion are two main methods to prevent the formation of hot spots during hydrogen combustion. Based on [30], it was achieved NO_x reduction by a factor of four with the utilisation of micro-mix burners on Airbus A-320 APU, whereas the combustion was stable with no flashbacks. The risk of flashback in turbojet engines is evident especially during engine starting due to the presence of ambient air in the ducting, which in turn leads to higher NO_x emission [98], so it will be necessary to modify these engines with combustors containing heat exchangers [18]. Inert gases such as nitrogen can be used to purge fuel lines during engine start-up to eliminate hydrogen flashback [75]. However, this procedure cannot be applied during normal engine operation, when the fuel lines contain a hydrogen–air mixture. To prevent flashback during engine operation, several methods can be employed, such as the use of flame arrestors [99], metallic mixing ducts [100], or premixed swirl burners designed for hydrogen mixtures with other components, e.g., methane or air [101]. However, these methods have been researched primarily for stationary gas turbines. LH_2 fuel must be preheated before reaching the combustion chamber to ensure that it is fully vapourised at its maximum flow rate from the cryogenic storage tank. Moreover, controlling the flow of gaseous hydrogen is considerably simpler than that of LH_2 [102].

To heat the hydrogen the heat exchangers are used instead of placing fuel lines in hot sections of the engine which would lead to its ignition in case of hydrogen leakage. Heat exchangers take heat from the hot section of the engine which leads to reduction of the amount of energy required for combustion. However, during engine starting, the electric heaters will be required to heat the hydrogen. To utilise the cryogenic temperature of hydrogen for reducing specific fuel consumption, the authors in [103] proposed two solutions: precooling the air at the inlet, and cooling bleed air around the combustor and mixing it before the turbine, thus enabling increases to the turbine inlet temperature. They assume the reduction of fuel consumption of 5.7% and 2.1%, respectively. In [104], the authors highlight the advantage of preheating hydrogen using an intercooler and recuperator, which resulted in a fuel consumption reduction of approximately 4.8%. To supply LH_2 to the engine, positive

displacement pumps must be replaced with centrifugal high-pressure pumps, as the latter offer superior performance with cryogenic hydrogen [105]. In [106], various thermodynamic and energy performance models were proposed for LH_2-fuelled ultrahigh bypass ratio geared turbofan engine. The authors concluded that optimised LH_2 engines have an 11% smaller diameter, a 5.5–7.5% shorter length, a 6 – 14% lower turbine entry temperature, and a 7 – 17% lower weight compared to Jet-A and non-optimised LH_2 engines.

The authors in [107] found that operating the engine using only hydrogen may significantly shorten its service life when run at high rpm. and elevated temperatures, due to accelerated material consumption. Mixing jet fuel and hydrogen led to an increase in temperature during the combustion process, almost 180 °C at 50,000 rpm., however, consumption of jet fuel was reduced. In [108], authors tested hydrogen (25%) / biogas (75%) mixture in a small turbojet engine. Such a mixture improved engine performance, increased thrust by 4.2% at high speeds and reduced fuel consumption by 2.2%. For industrial applications, diffusion flame combustion, wherein water is injected into the combustor are investigated. This method enables to mix hydrogen and natural gas in any ratio [109]. Another method is the mixed-fuel dry low emission technology, which enables to mix up to 30% hydrogen with natural gas [110].

Table 4. The selected properties of hydrogen and Jet-A1 fuel

Fuel properties	Hydrogen	Jet-A1	Avgas
Aromatics content [Vol. %]	negligible	< 25	< 16
Sulphur content [Wt. %]	negligible	< 0.3	< 0.05
Octane number	> 130[1]	15	> 100[2]
Auto ignition temperature [°C]	585	210	250
Boiling point [°C]	– 252.7	159.4	170
Stoichiometric fuel-air ratio	1:34	1:15	1:14.8
Lower heating value [MJ/kg] (at 25 °C and 1 atm)	119.93	43.15	44.3
Flash point [°C]	– 253	38	– 40
Density [kg/m^3] (at 20 °C and 1 atm)	0.083	802.8	721.1

[1] RON – Research octane number

[2] MON – Motor octane number

To conclude this section, it should be noted that hydrogen was also successfully tested in a non-aviation heavy-duty gas turbine [111], small gas turbine [112] and microturbines [113], originally operating with natural gas. Moreover, hydrogen was tested with good results for use in internal combustion engines [114], [115].

Hydrogen Fuel cell as a Source for Electric Propulsion

Between 1998 and 2006, Glen Research Center conducted development of regenerative FCs under the projects such as the Environmental research aircraft and sensor technology project, and the Low emissions alternative power. These projects explored regenerative FCs for unmanned electric aircraft and dirigibles. The project's output was 5 kW regenerative fuel cell with overall efficiency of 50.4% [116]. Currently, the Glenn Research Center aims to achieve a 55% round-trip efficiency with its new regenerative FC for lunar surface applications [117]. The European Space Agency is currently developing regenerative FCs with promising performance targets. These systems are expected to achieve an energy density greater than 400 Wh/kg with an efficiency above 50% or even surpass 600 Wh/kg with efficiencies over 70% if

waste heat is effectively recycled. The theoretical upper limit of regenerative FC energy density is estimated at 1000 Wh/kg [118]. Such values are significantly higher than the current state-of-the-art lithium-based batteries, which typically achieve only 200–250 Wh/kg. However, the regenerative FCs under development for space applications are designed primarily for relatively low power outputs, on the order of 1 kW.

In 2005, AeroVironment successfully completed the flight tests of a scaled prototype of the Global Observer which featured distributed electrical architecture in which liquid hydrogen FCs provided electricity to electric motors driving eight propellers [119]. However, for efficiency reasons, the propulsion system was redesigned as a hybrid configuration, in which an LH_2 combustion engine drives a generator that power the electric motors [120]. In 2008, Boeing successfully tested the first manned airplane (modified motor glider) with PEMFC as a primary source of energy with power output of 20 kW and lithium-ion batteries for assistance and back-up purposes [121]. However, no official statements have been released, except PEMFCs are considered a viable technology for powering small manned and unmanned aerial vehicles. In 2008, Airbus together with German Aerospace Center (DLR) carried out the flight tests of an A-320 with a Michelin's 20 kW PEMFC powering the aircraft's electrically driven hydraulic pump of a blue hydraulic line. This power system successfully moved the aircraft's ailerons and rudder [119]. In 2012, Airbus, in collaboration with the DLR, presented a new multifunctional FC system with a power output of 100 kW, intended to replace the traditional kerosene-powered APU [122].

Hydrogen FCs are considered as an alternative source of energy onboard the aircraft. There are several types of hydrogen FCs differing in electrolyte composition – PEMFC, solid oxide (SOFC), alkaline fuel, molten carbonate and phosphoric acid, however, only PEMFC and SOFC are considered for aviation purposes [123]. The main features of PEMFC and SOFC are listed in **Table 5**. The common feature of all forementioned FCs is that there are separate reactions at the anode and the cathode, and positive charge carrier move through the electrolyte, while electrons move through the external circuit. Moreover, in all these FCs the electrodes must be porous to secure the contact of gases with electrode and electrolyte at the same time.

Table 5. The main features of selected fuel cells

Feature	Types of fuel cells	
Name	PEMFC	SOFC
Electrolyte	Ion exchange membrane	Yttria-stabilized zirconia
Operating temperature [°C]	70 – 90	800 – 1000
Charge carrier	H^+	O^{2-}
Catalyst, anode	Platinum (Pt)	Nickel (Ni)
Cell material	Carbon- or metal-based	Ceramic
Fuels for cell	H_2	Reformate or CO/H_2 or CH_4
Reforming	External or direct	External, internal or direct
Feed for fuel processor	MeOH, natural gas, LPG, gasoline, diesel, jet fuel	Gas from coal or biomass, natural gas, gasoline, diesel, jet fuel
Oxidant for cell	O_2/air	O_2/air
Cell efficiency [1]	40 – 50%	50 – 60%

[1] Lower heating value electrical efficiency.

The basic operation of SOFC (**Figure 3a**) is that the oxygen is reduced into oxygen ions at the cathode, consequently, these ions can diffuse through the solid oxide electrolyte to the anode where they can electrochemically oxidise the fuel. The FC's products are electricity, heat, air depleted of oxygen and water. The basic operational principle of PEMFC (**Figure 3b**) is that the catalyst at the anode separates hydrogen molecule into electron and proton. Oxygen is fed to the cathode. Separated electrons then flow through the external circuit to the cathode and protons flow through the internal circuit. The FC's products are electricity, heat, air depleted of oxygen and water.

PEMFC is type of low temperature FC, whereas SOFC are type of high temperature FC **[124]**. Low temperature FCs must be operated with hydrogen with a very high purity of more than 99.9%, whereas high temperature FCs can be operated also with reformate gas with hydrogen concentration of about 50 to 75%. If PEMFCs are to be operated with reformed hydrocarbon fuels, the traces of CO generated during reforming must be converted into CO_2 before the fuel gas enters the cell, as the anode is highly sensitive to the presence of CO. CO must be reduced to <10 ppm **[125]**. Fuel processing methods of gaseous, liquid and solid fuel for both, low and high temperature FCs are depicted in **Figure 4**.

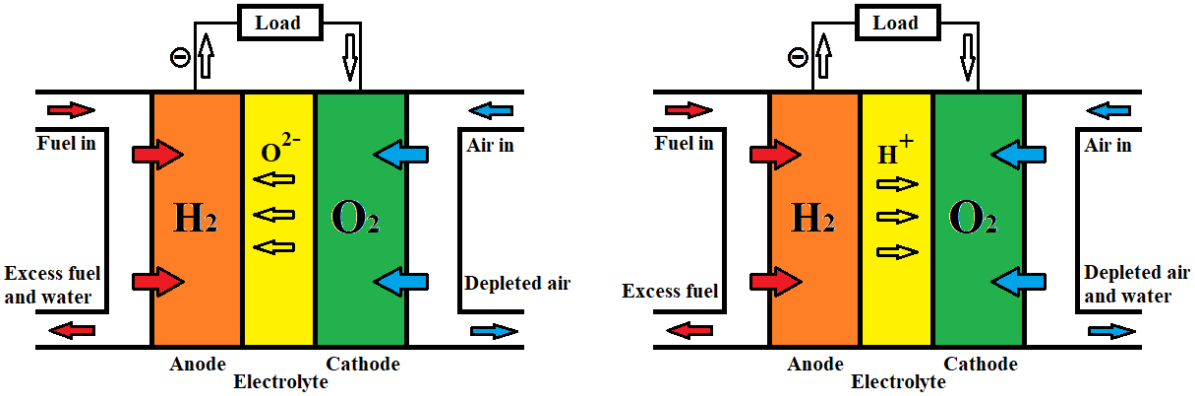

Figure 3. Operational principle of: a) SOFC, b) PEMFC

As can be seen in **Figure 4**, for both liquid fuel and natural gas, the process of desulphurisation must be incorporated as the organic sulphur compounds pose a major problem for catalysts in the FC and also for the catalysts used for reforming **[126]**. Most manufacturers of FCs recommend that the total sulphur concentration must be below 1 ppmw (parts per million by weight) in the feed fuel. This requires sulphur concentrations in the hydrocarbon feed to the reformer to be in the range of 1 – 10 ppmw **[127]**. Such a concentration must be guaranteed during the whole flight which makes it very challenging.

PEMFC contains solid polymer electrolyte and SOFC uses a ceramic solid-phase electrolyte which both eliminate the corrosion and safety risks associated with liquid electrolyte FCs. Solid electrolytes offer flexibility in the design of FCs, allowing for various shapes and configurations to suit different applications. PEMFC's low operating temperature provides instant start-up and requires no thermal shielding. On the other hand, SOFC's high operating temperature causes thermal stressing on the materials including the sealants and the longer start-up time **[128]**.

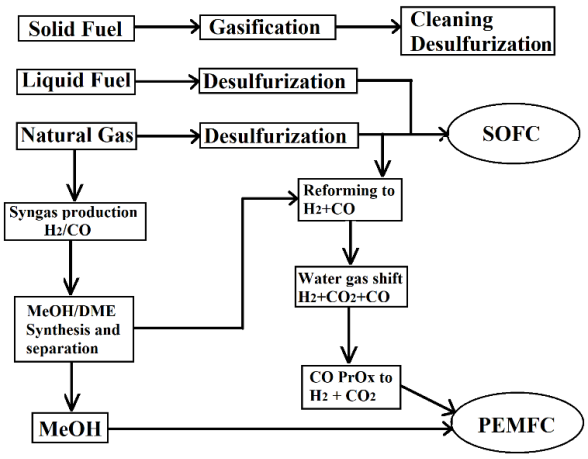

Figure 4. Fuel processing methods of various fuels for SOFC and PEMFC [125], [129]

Aircraft manufacturers Airbus and Boeing are currently investigating the use of FCs as a replacement for traditional kerosene-fuelled APUs. The motivation stems from the high noise levels associated with conventional APUs, which represent a concern for approximately 40% of global airports, as well as their significant contribution to overall on-ground aircraft emissions [130]. According to [131], based on emission measurements conducted at 325 airports in the USA, APUs contribute approximately 10 – 15% of total aircraft CO emissions and 15 – 30% of NO_x and SO_x emissions. Furthermore, the Cryoplane project estimates that the adoption of SOFC APUs could reduce ground-based aircraft NO_x emissions by up to 80% [132]. If external ground power (excluding diesel generators) is used while the aircraft is on the ground, total emissions can be reduced by as much as 47.6% [133].

According to [134], SOFCs are considered more suitable for powering the APUs of large aircraft in the near future, as they can operate on hydrogen generated through kerosene reforming. Consequently, their fuel processors do not require additional reactors for CO reduction and removal. This approach also eliminates the need to carry hydrogen onboard the aircraft. In [135], the authors conclude that the flight range of a Boeing 737 MAX, which is normally 6,382 km under the given conditions, would be reduced to 3,082 km if an ammonia-fuelled SOFC were employed.

The main disadvantage of SOFC over PEMFC for aircraft application is the higher weight of SOFC components – a reformer, compressor, pumps, heat exchangers and others. It must be emphasised that if an SOFC is not fuelled with clean hydrogen or carbon-neutral fuels, it will also produce CO_2, albeit at a lower level compared to conventional jet fuel.

Fuel cell APU, besides of electricity production, can be used to supply clean water to aircraft's water system [136], heat for wing anti-icing [137] and oxygen depleted air (ODA) to be used in tank inverting [138]. It is necessary to reduce water content in ODA to a specific humidity not above 2 g/kg ^{1} before it gets to the fuel tanks, in order to prevents water condensation and its subsequent freezing in low temperature environment. Depending on the condensation temperature, a PEMFC delivers about 0.5 litters of water per kWh of generated electrical power [138]. Such amount of water production is sufficient for aircraft to fill its water tank during the flight, which will significantly reduce aircraft's take-off weight.

PEMFC requires cathode humidifier because performance of the cell declines with the decreasing humidity due to the higher ohmic resistance of the cell. If cathode is too dry or too wet, the limiting overall current density for H_2/air operation is approximately 1 A/cm^2 and in case of moderate relative humidity, the overall limiting current density can be 1.7 A/cm^2 [139]. In case of H_2/oxygen operation, the overall limiting current density is up to 2.1 and 2.4 A/cm^2 for wet and dry cathode respectively [139]. However, the typical working current density is 0.5

A/cm^2 and 1.5 A/cm^2 for H_2/air and H_2/oxygen operation, respectively. In the case of SOFC, the overall limiting current density is up to 2.5 A/cm^2 [140] and typical working current densities are in the range 0.5-1.5 A/cm^2 [141]. At higher current densities, the operating temperature of the FC increases significantly [142].

In [143], a Monte Carlo-based sensitivity analysis of the performance parameters of FCs and batteries, namely the specific FC power and the specific battery energy, were performed. As a source for Monte Carlo analysis flights from Airbus A-320 and Boeing B-777 were analysed. Authors conclude that for long flights (the upper time range of operation for the A-320 and B-777 aircraft), the use of FCs is suitable, unlike batteries, which represent during the cruise "dead weight". Conversely, for short flights (the lower time range of operation for the A-320 and B-777 aircraft), exclusive use of batteries appears more appropriate, assuming they achieve the parameters estimated in research. For medium-length flights, the most suitable alternative is the use of a combination of FCs and batteries.

To conclude this section, in [127], [144] authors summarise different APUs based on FC technology for aviation and non-aviation sector. Moreover, they present state of the art of the reforming systems utilised by APUs. It was found that replacing traditional APUs with FCs will be feasible by 2024 only for small aircraft, as the FC-APU has twice the weight due to the additional LH_2 tank. The advantage will lie in higher system efficiency, lower maintenance requirements, and reduced noise and emissions.

Hybrid Aircraft

This section complements the aircraft concepts mentioned above. In the case of hybrid drives, there is a combination of two different types of energy: chemical (such as hydrocarbon-based fuel or hydrogen) and electric, specifically for airplanes. Hybrid drive architectures can be implemented in parallel, series, or combined forms, depending on the type of energy that is responsible for the propulsion (**Figure 5**).

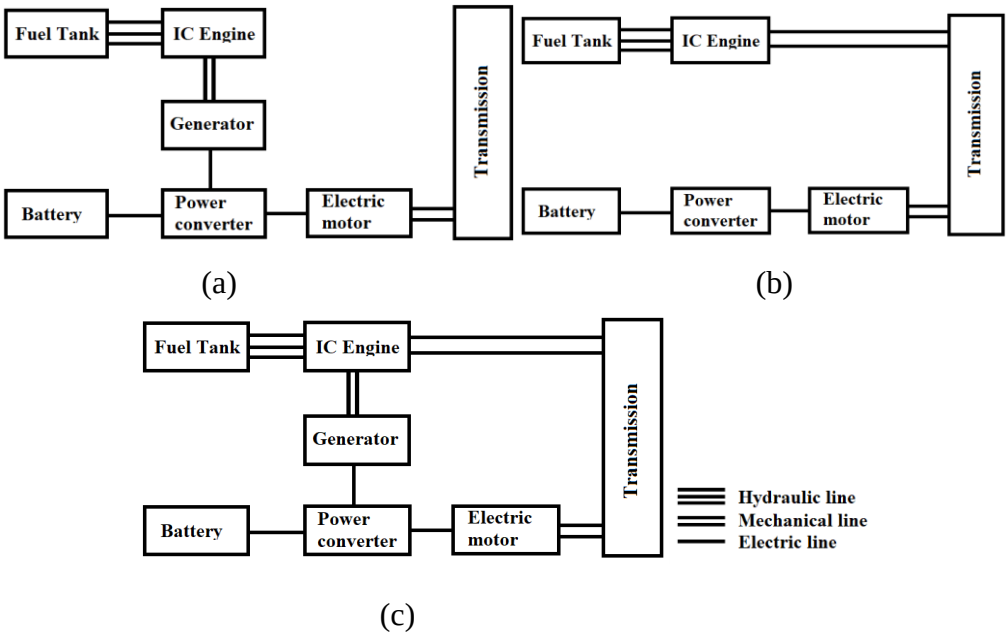

Figure 5. Architectures for aircraft hybrid propulsion a) Series hybrid, b) parallel hybrid, c) combined (series-parallel) hybrid [145]

The series hybrid architecture is characterized by the fact that the driven element, such as an aircraft propeller, is powered by only one type of energy – an electric motor. This motor is supplied by a power converter, which is fed from an electrochemical source (battery, FC) and

from a generator driven by an internal combustion engine. The first aircraft to use serial hybrid propulsion was the small aircraft Diamond DA36 E-Star, in 2011. In 2016, the HYPSTAIR consortium unveiled the prototype of the world's most powerful (200 kW) hybrid electric powertrain for general aviation [146]. Currently, these powertrains are being tested under the Series hybrid electric propulsion aircraft demonstration (SHEPARD) program [147]. The advantage of this solution is the possibility to design the combustion engine for a narrow range of speeds, thereby achieving higher efficiency. The disadvantage is that the fuel energy must be converted twice. Another drawback is that the traction motor must be dimensioned for full load. Turboelectric propulsion, where no traction batteries are used, is a variant of this method.

In parallel hybrid propulsion systems, the key component is the mechanical torque or speed coupling, which integrates the electric motor and the internal combustion engine. A parallel hybrid configuration employing a SOFC in combination with a gas turbine is currently under development for the Boeing SUGAR Volt concept aircraft [148]. The selection of SOFC technology is motivated by its high-temperature operation, which enables the preheating of air supplied to the combustor. A parallel hybrid configuration was also implemented in the H3PS (High Power High Scalability Aircraft Hybrid Powertrain) concept, developed by Rolls-Royce, BRP-Rotax, and Tecnam. This project represents the first general aviation aircraft equipped with such a propulsion system that has successfully demonstrated flight capability [149]. Although the H3PS concept does not employ fuel cells as an energy source, it has proven the feasibility of hybrid propulsion for small aircraft. Several studies have modelled the application of parallel hybrid propulsion. For example, [150] simulate such a concept for an aircraft with parameters based on the Airbus A320neo. In [151], a similar configuration is analysed for a 50-passenger aircraft, considering various operational modes such as peak power shaving, climb power boosting, electric propelled taxi, and in-flight battery recharging. The study [152] concluded that parallel hybrid propulsion for general aviation aircraft offer benefits over conventional aircraft even with today's technological standards.

The advantage of this solution compared to series propulsion is that the generator does not need to be used, the traction motor can be smaller, and there is no double energy conversion with the associated losses, thus this method is more efficient especially during steady cruise. The drawback of this method is that the transmission must be adjusted for two independent input powers, thus sophisticated power distribution method must be implemented. Another disadvantage of this method, particularly critical in aviation, is its higher weight.

To conclude this section, in [153] authors reviewed the current research state of the design and energy supervisory for hybrid electric propulsion systems. In [154], authors carried out a comparison between parallel and series hybrid propulsion systems using heterogeneous and homogeneous distributed propulsion architectures for UAVs. The study found that series hybrid propulsion systems are 20 – 40% heavier than conventional powertrains while achieving a 13 – 24% reduction in fuel consumption, whereas parallel hybrid propulsion results in an increase of approximately 8% in weight but offers a 30 – 50% reduction in fuel consumption compared to conventional configurations.

DEMAND FOR AVIATION FUELS IN 2050

This chapter outlines the projected demand for different types of aviation fuels (conventional Jet fuel, sustainable fuels, and hydrogen) over the period from 2010 to 2050, with a particular focus on the EU, the USA, and the global market.

Demand for Jet fuel

The impact of aviation on the environment is significant. A complex set of processes that lead to a net surface warming is described in [155]. CO_2 is one of the main elements that has a significant impact on atmospheric warming. In 2016, ICAO's CORSIA became the first mandatory global regulation aimed at reducing CO_2 levels in transportation. Global aviation

produced 920 Mt of CO_2 (corresponding to 292 Mt of jet fuel) in 2019, representing approximately 2.5% of all human-induced CO_2 emissions and 12% of emissions from transportation [156]. Emissions from the US, EU and China aviation sector in 2019 were 222 Mt [157], 147 Mt [158] and 95 Mt [159] of CO_2, respectively. UN-ICAO reported that global jet fuel consumption was 213 Mt (corresponding to 671 Mt of CO_2) in 2010, with the potential to reach 860 Mt (corresponding to 2700 Mt of CO_2) by 2050 if no restrictions are implemented and 570 Mt (1795 Mt of CO_2) if technological advances are implemented [160]. According to International Air Transport Association's (IATA) "Fly net zero by 2050" [161], CO_2 emissions in the aviation sector are estimated to reach 1,800 Mt (corresponding to 571 Mt of jet fuel) by 2050 if there is no fuel conversion. However, by 2050, IATA aims to reduce net aviation CO_2 emissions by 50%, compared to 2005 levels, which was then 650 Mt of CO_2 (corresponding to 208 Mt of jet fuel). Flightpath 2050 [162] projects that CO_2 emissions could be reduced by 2050 even more, by 75%, relative to 2005 levels, reaching 163 Mt of CO_2 (corresponding to 52 Mt of jet fuel). According to the Climate Neutral Group in its Climate neutral standard 2020 [163], there should be no rise in CO_2 emissions in the aviation sector after 2020, when emissions stood at 838 Mt of CO_2 (corresponding to 266 Mt of jet fuel). However, this study suggests that without the adoption of alternative fuel, CO_2 emissions are expected to rise to 1,713 Mt (544 Mt of jet fuel) by 2040 and 2,450 Mt (778 Mt of jet fuel) by 2050. In [164], authors predict that the global aviation emission CO_2 will be, according to different scenarios, 450 Mt (biofuels + CO_2 capture and storage), 1800 Mt (use of biofuel), 2000 Mt (no conversion on alternative fuels and reduced demand for fuel) and 2250 Mt (no conversion on alternative fuel) in 2050. According to ICAO's MAX scenario, it is possible to replace conventional jet fuel by SAF, but 170 new biorefineries would need to be built per year between 2020 and 2050. Demand for jet fuel in EU was 38 Mt in 2010 [159] and 40.4 Mt in 2016 [165] and is prognosed to be 52.9 Mt in 2030, with 5.4 – 9.5 Mt of SAF [166]. According to [167], the estimated demand for jet fuel in EU will be 46 Mt, 46 Mt, and 45 Mt, in 2030, 2040, and 2050, respectively. The authors of [168] project that jet fuel demand in the EU will reach 55.5 Mt in 2025, 62.8 Mt in 2030 (of which 3.4 Mt will be SAF), and 71.1 Mt in 2035, which is far more than the estimation in [167]. Demand for jet fuel in US was 45 Mt in 2010 [169] and is estimated at 90 Mt in 2030 (from which 9 Mt would be SAF) and 120 Mt in 2050 (from which 105 would be SAF) [170], however, there is, according to this study, considerable uncertainty in projected future production and use of SAF. Information on aviation fuel demand and fuel price trends is provided in [171], where the authors estimate that after 2030 the price of LH_2 will fall below that of Jet-A fuel. An extensive study on achieving net-zero aviation emissions by 2050 is presented in [172], outlining the projected fuel demand for LH_2 and SAF, as well as the technological innovations and airport infrastructure required to achieve this target. Based on the above references, **Figure 6** summarises the jet fuel demand in aviation up until 2050.

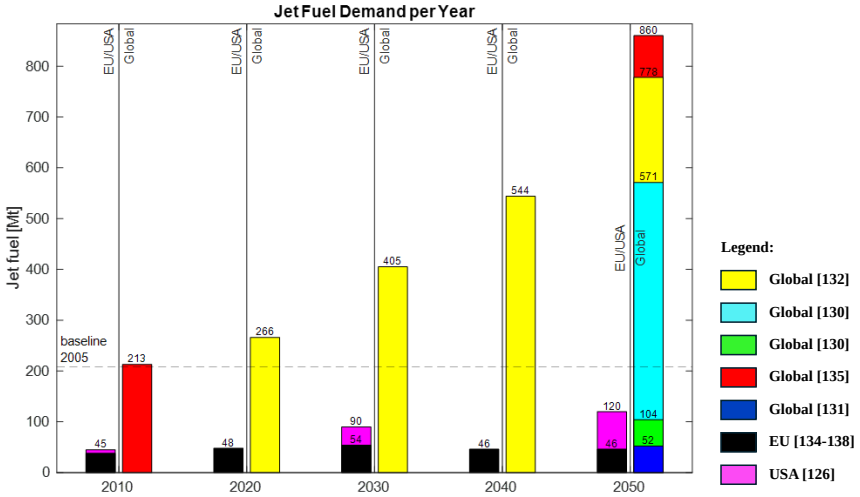

Figure 6. Demand for Jet fuel in 2010 – 2050

Demand for Sustainable Aviation fuel

According to ASTM D7566, there are eight production pathways certified to produce SAF nowadays. In 2021, the European Commission (EC) has introduced, as part of the 'Fit for 55' package, a SAF blending mandate for fuels provided to EU airports, which will see minimum SAF shares rise from 2% in 2025 to 5% in 2030 and finally to 63% in 2050. To meet this mandate, it is estimated that in EU around 2.3 Mt of SAF will be needed by 2030, 14.8 Mt by 2040, and 28.6 Mt by 2050 [173]. However, according to [174], to fulfil this mandate, it will be necessary 3 Mt of SAF by 2030 and 47 Mt of SAF by 2050. Only in Germany, it will be necessary 0.6 Mt of SAF in 2030 and 9.5 Mt of SAF in 2050 [175]. It must be emphasised, that in 2023, the EC has introduced updated version of the blending mandate, in which, minimum SAF shares rise from 2% in 2025 to 6% in 2030 and finally to 70% in 2050 [176]. This update is not often considered even in some research articles from 2024. As mentioned above, in the USA, the SAF Grand Challenge projects a demand of 9 Mt of SAF by 2030 and 105 Mt by 2050 [171]. According to [177], global demand for SAF in 2030 is expected to range from 3 Mt (if no policy support for SAF is implemented) to 17 Mt (with policy emphasis on SAF). In [178], the authors estimated that global production of aviation biofuels in 2030 will consist of 7.47 Mt of HEFA, 0.99 Mt of ATJ (Alcohol-to-jet), and 0.45 Mt of FT (Fischer-Tropsch). According to a survey of many studies, global SAF demand in 2050 will range from 245 Mt to 370 Mt [179]. However, according to the Air Transport Action Group (ATAG) [180], aviation will need between 330 – 445 Mt of SAF in 2050. The authors of [181] suggest that as demand for SAF continues to grow into 2050, biomass and its derivatives may only be able to meet approximately 50% of the total global demand. Based on the values presented in [163] and [178], it can be concluded that global aviation biofuel demand will account for only 2.2% (8.91 Mt) of total aviation fuel in 2030. According to [182], biofuels will make up 4% (pessimistic scenario) to 10% (optimistic scenario) of total jet fuel by 2030, and 10% (pessimistic scenario) to 50% (optimistic scenario) by 2050. In [167] and [168], authors estimate that the resource potential is sufficient to theoretically produced 12.2 – 14.44 Mt of SAF in EU when current technology is considered. More on SAF production, impact on environment and infrastructure challenges can be found in ICAO's Sustainable aviation fuels guide [183]. Based on the above references,

Figure 7 summarises the SAF fuel demand in aviation up until 2050.

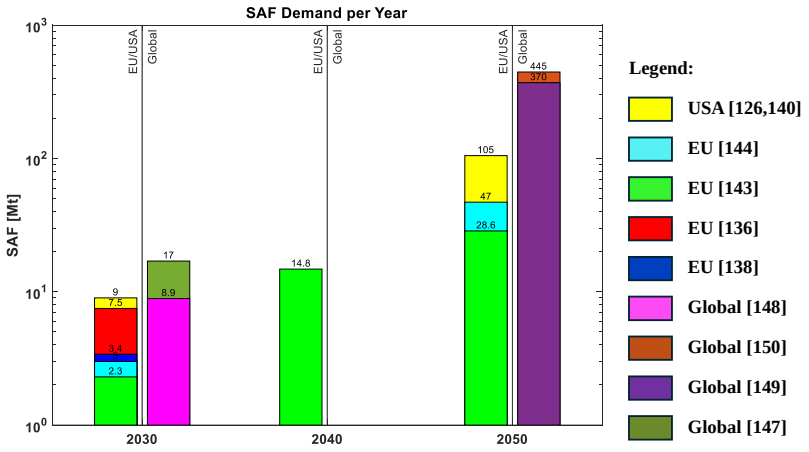

Figure 7. Demand for SAF fuel in 2030 – 2050

Demand for Hydrogen

In [184], the authors present the potential global demand for hydrogen across four different scenarios. They estimate it at 73 Mt (if current hydrogen production persists), 130 Mt (considering the current trend of increase), 162 Mt, and 568 Mt (if hydrogen becomes the main

fuel in transportation) by 2050. According to ATAG, global hydrogen demand is expected to reach between 280 Mt and 528 Mt by 2050, depending on the scenario [172], from which the aviation sector will require globally up to 43 Mt. According to trade body IATA, the global aviation industry is set to require 120 Mt of clean hydrogen per year in 2050, with 100 Mt to produce SAF and 20 Mt for H_2-powered aircraft [185]. In EU, hydrogen demand is estimated at 2.8 Mt in 2050 [172]. According to the International Energy Agency, overall hydrogen demand is estimated at 530 Mt by 2050, and in the aviation sector, for a net-zero CO_2 emissions scenario, global hydrogen demand will be 22 Mt in 2040 and 52 Mt in 2050 [186]. In [187], the authors state that overall hydrogen production will be 450 Mt per year in 2050. According to [188], global hydrogen demand in aviation is projected to be 10 Mt in 2040 and 40 Mt (130 Mt in a maximum decarbonisation scenario) in 2050. In [189], the authors estimate that global hydrogen demand for commercial aircraft on routes less than 1,500 nautical miles will be 2 Mt in 2040, 11.2 Mt in 2045, and 19.2 Mt in 2050, of which 3.3 Mt will be in Europe. They also estimate that hydrogen's share in aviation by 2050 will be only 14%, as long-haul aircraft will still use jet fuel. A similar estimation is proposed in [190], where the analysis indicates that global hydrogen demand in aviation could reach 17 Mt by 2050, leading to a 9% reduction in CO_2 emissions from global aviation. Furthermore, the authors estimate that the total market share of hydrogen-powered aircraft in the model is projected to be only 27% by 2050. According to [191], the authors assume that hydrogen demand in Germany alone will be between 16.27 Mt and 20.12 Mt by 2050, which is far more than expected in [172] and [189]. In US, hydrogen is not expected to have a significant contribution by 2050, with only 1.9% of energy share for international aviation [157]. In terms of sources, hydrogen will be produced from the following raw materials/methods in this order: water electrolysis, oil, biomass, coal, and natural gas, with natural gas accounting for nearly two-thirds of these sources [187]. This conclusion contradicts the findings in [192], where green hydrogen was expected to be the dominant source in 2050. According to [192], approximately 140 – 280 Mt of hydrogen will consist of low-carbon hydrogen, and 420 – 560 Mt will be green hydrogen by 2050. Based on the above references, **Figure 8** summarises the hydrogen demand in aviation up until 2050.

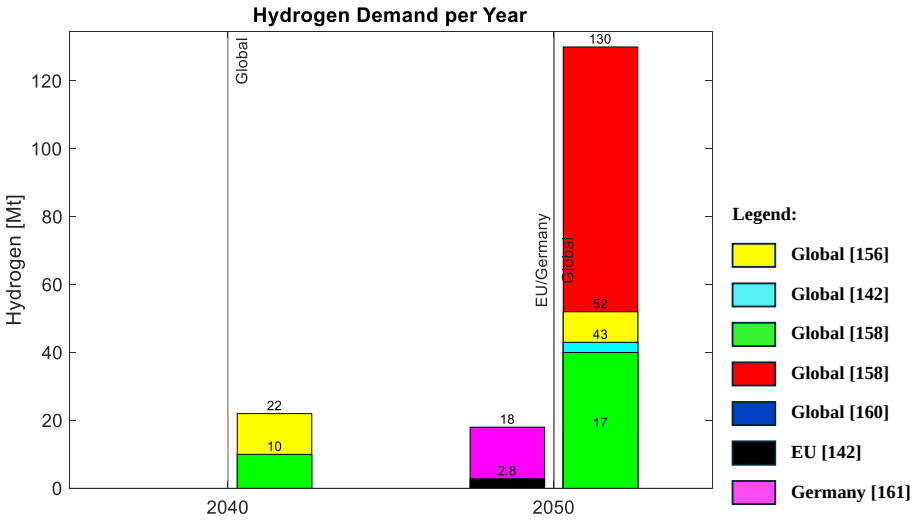

Figure 8. Demand for SAF fuel in 2030 – 2050

CONCLUSION

Sustainable aviation fuels, together with hydrogen, are considered the main candidates that could replace conventional fossil fuels by 2035, particularly in small aircraft. To achieve environmental goals, the implementation of hydrogen in aviation will only make sense if the production of green hydrogen is ensured in sufficient quantities, including the green hydrogen infrastructure.

The principal unresolved issue concerning the use of hydrogen onboard aircraft remains its storage form. The most viable option appears to be LH_2, due to its high energy density and refuelling times comparable to Jet-A fuel. Furthermore, the relatively advanced technological maturity of LH_2 storage and handling enables its accelerated implementation. However, widespread adoption will be constrained by limited supply chains and insufficient infrastructure, meaning that not all airports will be able to offer hydrogen at competitive prices. Airports located in proximity to major seaports are likely to be the most suitable candidates for early adoption. The storage form of hydrogen will also have a significant impact on overall aircraft design. Hydrogen-fuelled blended wing body concepts promise improved fuel efficiency compared to the conventional tube-and-wing configuration; however, they still possess a 3.8% fuel penalty compared to their kerosene-fuelled counterparts. Nevertheless, the most straightforward and rapidly deployable solution may be a fuselage extension designed to accommodate larger hydrogen tanks. Hydrogen is expected to be employed as a fuel for gas turbine engines, potentially enabling smaller and lighter engines, or in hybrid propulsion systems as the energy source for fuel cells, initially serving as a replacement for conventional APUs.

Hydrogen-fuelled long-range aircraft are expected to achieve approximately 12% lower energy consumption per seat compared to their kerosene-fuelled counterparts, owing to the higher specific energy of hydrogen, even when accounting for increased aerodynamic drag. For mid-range and short-range categories, however, the results are less consistent. Depending on the study, hydrogen-fuelled aircraft may demonstrate a 4% reduction in energy consumption per seat, or conversely, an increase of 5 – 18% compared to kerosene-powered alternatives.

As illustrated in **Figure 6**, global demand for aviation fuel is projected to grow approximately linearly, reaching an estimated 571–860 Mt by 2050. The share of fossil fuels is expected to decrease to a maximum of 52–104 Mt by 2050. Estimates for SAF demand in 2050 vary across studies, ranging from 245 Mt to 445 Mt globally. Regionally, the most optimistic forecasts predict SAF demand of 47 Mt in Europe and 105 Mt in the USA (**Figure 7**). Hydrogen demand is anticipated to remain limited until approximately 2050, at which point a substantial increase is expected. The most optimistic projections estimate global hydrogen demand at 568 Mt, although other studies suggest a lower demand, ranging from 17 Mt to 130 Mt (**Figure 8**).

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