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A review of hydrogen aircraft propulsion systems: recent advances and environmental perspectives

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ABSTRACT

The present work performs a review for using hydrogen in aircraft propulsion systems analyzing challenges and opportunities with the two main driveline architectures: direct combustion of hydrogen and fuel cells. First, the capability of hydrogen aircraft to become more energy efficient than conventional aircraft are discussed on system level, by extending previous review work. Then, challenges for hydrogen combustion and ways to limit emissions by lean direct injection and micromix combustion are discussed. Polymer electrolyte membrane (PEM) and solid oxide fuel cells are reviewed and the outlook for high temperature PEM fuel cells and challenges with per- and polyfluoroalkyl substances (PFAS) emissions are discussed. Dual fuel aircraft and flexible combustion are discussed as ways to provide a transition to a hydrogen economy. Additionally, hybrid configurations and new cycles that simplify hydrogen integration are reviewed. Finally, recent promising results on water emissions and contrail formation for hydrogen combusting aircraft are discussed.

1. Introduction

The aviation sector has experienced significant growth, contributing around 2–3 % of global CO_2 emissions [1,2]. In response, international goals like the European Flightpath 2050 and the Paris Agreement call for decarbonization by 2050 [3–5]. Hydrogen and possibly also ammonia [6] are the only viable zero-carbon aviation fuels that can directly replace fossil derived aviation fuels without emitting CO_2 at the point of use [7,8]. Hydrogen offers a very high specific energy, about three times that of kerosene per unit weight, making it an attractive fuel for aviation applications to achieve carbon neutrality [9–11].

Several countries have developed national hydrogen strategies, with aviation identified as a key application [12,13]. However, aircraft integration challenges remain, including storage, propulsion system architecture, and system-environment interactions [14–16]. As hydrogen technologies near commercialization, the two main propulsion paths, combustion in gas turbines and fuel cells, are being widely evaluated [17,18]. In this context, this review contributes to the state of the art by exploring recent advances in hydrogen-based propulsion, classifying the associated technologies into two main categories: combustion systems and fuel cell-based systems. Special attention is also given to hybrid-electric propulsion systems that integrate fuel cells and batteries.

Due to the high flame temperature of hydrogen, there is an immediate risk of high NO_x emissions. To mitigate this risk, micromix combustion shows great promise for reducing NO_x emissions while improving flame stability. It uses multiple small jets to create uniform micro flames, enhancing mixing and reducing hot spots [19–21]. On the other hand, Proton Exchange Membrane Fuel Cells (PEMFC) are compact and efficient for short-range aircraft, while Solid Oxide Fuel Cells (SOFC) offer higher efficiencies for longer missions despite thermal limitations [9,14]. Fuel cells are also suited for Auxiliary Power Units (APUs), reducing ground-level emissions [8]. One aim of this review is to provide an updated overview of these emerging hydrogen propulsion

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technologies. In addition, several hydrogen propulsion challenges and opportunities not covered, or only partially covered, by previous reviews are addressed.

A critical component of a fuel cell is the membrane that acts as the proton carrier. For PEM fuel cells, the current dominant membrane material type is Perfluorosulfonic Acid (PFSA)-based. The use of PEM fuel cells has been reviewed for use in aircraft applications in the past. Adler and Martins [9] discussed challenges with the PEM fuel cell operation, the role of the electrolyte, and its humidification need. Soleymani et al. [22] and Tiwari et al. [20] also covered some of the aspects of fuel cell degradation. Although Tiwari et al. [20] discusses high temperature PEMs to some degree, we extend their discussion, including a wider aspect of mechanisms for high-temperature degradation, conductivity at high temperature, and impact of pressurization, as well as survey material alternatives for reaching higher operating temperatures. High temperature fuel cells are key to increasing power density of drivelines critical for aircraft applications. Although PFSA-based proton carrier membranes have been reviewed from several aspects in the past, their toxicity, and in particular risk for carcinogenic polyfluoroalkyl substances have not. Legislation is being discussed both in the United States of America and in the European Union, including a complete ban, which may delay the introduction of fuel cells for aviation. We therefore review these aspects, including potential replacements to PFSA based materials.

To make hydrogen a competitive alternative, it is important that the energy efficiency of the aircraft becomes as competitive as possible, preferably more energy efficient than for carbon-based alternatives. The fact that hydrogen carries a much higher heat content than competing fuels may enable this, but its low volumetric efficiency threatens to inhibit this completely. The work by Adler and Martins [9] showed that gravimetric efficiency of the tank system has a very strong impact on energy efficiency. In this work, we discuss Adler's preliminary analysis further, to also include additional drag, and fuselage weight. We then go on to exemplify how this manifests in a number of existing studies on aircraft performance, in particular the recent work by Stettler et al. [23]. Understanding the limits and the potential for achieving high-efficiency hydrogen aircraft is important, not the least for the success of hydrogen aircraft compared to the power-to-liquid alternative [24–26].

For hydrogen, as with any other paradigm-changing fuel, you face the chicken-and-egg problem. A hydrogen infrastructure, may for instance, exist, but no suitable vehicles. The opposite may also be true, that is, that the vehicles are already available, but the hydrogen fuel infrastructure is not sufficiently developed [27]. Both scenarios may stop the possibility of a future hydrogen economy completely. Considering the challenges involved in replacing existing aircraft and the massive investment needed for the infrastructure update, we therefore review innovations that can enable gradual transition to establish a paced growth of both the aircraft fleet and its infrastructure [28]. In particular, dual-fuel aircraft enabling multiple fuels to be used for the same aircraft, and even during the same flight [29,30]. In parallel, advances for flexible combustion systems that can operate on a range of fuel blends. To further explore the opportunities that hydrogen offers as a fuel, we also see a need to review work on two new revolutionary propulsion architectures for which hydrogen makes their realization easier, the WET cycle [31] and the HySIITE concept engine [32]. In both instances, the large production of water for a given heat release simplifies the realization of how the propulsion system is intended to work.

Finally, we also give an update on recent advances in contrails research. Although this has been the topic of previous work [9], herein we place the focus on how the absence of organo-sulfides and soot promises to push hydrogen emissions down to the limit of background aerosols [33,34], potentially influenced by oil condensate [35]. In contrast, these very low ice crystal formation levels may not materialize for sustainable aviation fuels since they offer additional ice crystal formation mechanisms. This is a recent understanding from contrail research that may give hydrogen an advantage despite its larger water emissions per unit heat release.

2. The driveline architectures and composition of review

The two main propulsion technologies, the direct combustion of hydrogen in gas turbines and the use of fuel cells, are contrasted against each other in Table 1. They constitute the backbone for this review, around which the rest of the material is developed. The review commences by listing first achievements in hydrogen aviation and important flight test demonstrations. We then go on to discuss the energy efficiency of hydrogen aircraft to give a background for understanding how aircraft design aspects influence range, and indirectly, also choice of drive line architecture. This is followed by reviewing progress for direct combustion gas turbine architectures and then fuel cell solutions covered in two separate sections. As a means for enabling the introduction of hydrogen propulsion systems, we then also include a section on hybrid propulsion architectures. We then end the review by addressing a key climate concern for hydrogen, namely contrails formation and a section discussing possible technological pathways for the introduction of hydrogen aviation.

3. Hydrogen-powered aircraft achievements

Table 2 summarizes the first in the history of hydrogen use for the aviation industry.

The first advanced development activities for hydrogen-propelled jet aircraft were launched in the 1950s. The United States of America government studied hydrogen as a fuel for Mach 2.5+ reconnaissance aircraft, funding the Lockheed CL-400 Suntan project [117]. This project and others simultaneously included modeling and experimental studies investigating hydrogen propulsion, fuel systems, storage, and safety. In the 1970s, the oil crisis renewed interest in hydrogen, leading NASA to support studies into commercial hydrogen aircraft. However, these projects were not continued with the end of the oil crisis [117–119].

NASA performed a series of scramjet propulsion validations on the X-43 aircraft. The aircraft used compressed hydrogen as fuel and broke a number of speed records for air-breathing propulsion aircraft, achieving close to Mach 10 flight speeds, where it was being propelled by the Pegasus rocket to reach speed [120]. Between 2012 and 2014, Boeing performed a number of test flights with their unmanned aerial vehicle Phantom Eye, progressively achieving longer duration flights and higher operational altitudes (2010–2014) [64,121]. The propulsion system was based on two modified 2.3-liter Ford internal combustion engines running on liquid hydrogen. AeroVironment developed a similar internal combustion-based unmanned concept for long-range, long endurance missions [122].

Around 2010, fuel cell electric propulsion gained momentum, initially represented by smaller demonstrator aircraft. Boeing developed a test aircraft from a modified Dimona motor-glider [123], using PEM and Li-ion batteries. The aircraft achieved 20-min cruise operation solely powered by batteries. DLR developed two test aircraft: the single-seater Antares DLR-H2 [116] and later the twin-fuselage four-seater H2FLY HY4 [69,124]. The Antares DLR-H2 was the first manned aircraft that demonstrated takeoff, cruising, and landing solely on fuel cell power, whereas the H2FLY HY4 demonstrated the first piloted flight powered purely by liquid hydrogen.

In the last decade, larger commercially oriented fuel cell aircraft are being conceived and demonstrated. In 2020, ZeroAvia used a converted Piper Malibu aircraft to demonstrate the use of a PEM fuel cell stack and a lithium-ion battery pack [125,126]. This effort represented the first conversion of an aircraft used for commercial operation to demonstrate a partial hydrogen propulsion system. In 2023, Universal Hydrogen demonstrated a megawatt-class fuel cell system for a 40-passenger airliner [51]. The flight demonstration used a modified Dash 8–300 aircraft providing the main portion of the cruise thrust from the fuel cell system and running a conventional jet engine throttled back for safety

Table 1
Advantages and disadvantages of the main hydrogen propulsion technologies.

Technology	Advantages	Disadvantages
Hydrogen Combustion in Gas Turbines	(1) Uses technology that already exists in commercial aircraft [36–40]. (2) Better use of existing design tools and technologies [23,36, 41–43]. (3) High specific power potential [9,36,44–47]. (4) Traditional engine manufacturers already have plans to develop and test hydrogen engines [9, 32,37,48–50].	(1) Requires the design of new engines optimized specifically for hydrogen due to the different combustion properties compared to kerosene [19,38,51,52], as well as new delivery and conditioning systems (pre-heating for cryogenic liquid hydrogen) [53]. (2) It presents challenges in operation, requiring the development of combustion technologies [38,54–56]. (3) Risk of combustion instability due to the higher burning speed of hydrogen [18,19,57,58]. (4) Can produce nitrogen oxides (NO_x) [19,40,52, 54,58–60]. (5) Hydrogen has less energy per volume relative to Jet-A, requiring high-pressure and/or cryogenic tanks [9,17,44,46, 47,54,61–64].
Fuel Cells	(1) Zero carbon and NO_x emissions during operation, producing only water vapor [65–69]. (2) Potential for greater reliability due to fewer moving parts and higher efficiency [17,20,67,70, 71]. (3) They can eliminate the need for the auxiliary power unit (APU) and ram air turbine (RAT) [67, 72–75]. (4) High cell efficiency, up to 60 % for SOFC [17], and direct conversion of hydrogen into electricity [17,71,76,77].	(1) Difficult to size for high-power applications due to specific power and thermal limitations [11, 20,78–83]. (2) Complex thermal management, especially for PEMFCs due to the relatively low temperature operation requirements [71,79, 82–85]. (3) Hydrogen purity requirements and water purity control for PEMFCs [17,70,85–87]. (4) SOFCs have longer start-ups and shut-down times [77,78,88–92] not compatible with aircraft transients. (5) Low power-to-weight ratio [20,65,77,79,81,88, 89,93–95].
Hybrid propulsion (with Hydrogen)	(1) Potential for reducing fuel consumption [77,90, 95–99]. (2) Allows gas turbines to operate at optimal loads, generating electricity for the propulsion units [98, 100]. (3) Requires lower specific battery energy compared to all-electric aircraft for long flights [98,100–102]. (4) SOFC-GT systems can use waste heat to preheat the air in the combustion, increasing efficiency [77, 88,89,99,103]. (5) Hybridization through air treatment (Hy2PASS) can significantly reduce energy consumption and eliminate direct emissions [104].	(1) The additional weight of the electrical components requires high power density [105–107]. (2) The conversion of mechanical energy to electrical energy or the conversion of electrical energy to mechanical energy introduces losses into the system [66,105]. (3) The safety of the fuel (hydrogen) and the reliability of SOFC hybrid systems in the aerospace sector still present challenges [73,77,88, 89]. (4) Combining more than one radical technology will increase the risks [9].

Table 2
Chronological history of hydrogen in aviation.

Vehicle	Year	Remarks
Air balloon	1783	First lighter-than-air hydrogen craft [108]
Zeppelin, LZ1	1900	First rigid hydrogen airship [109]
Heinkel HeS 1	1937	First hydrogen turbojet engine [110]
Saturn SA-5	1964	First successful rocket using liquid hydrogen [111]
Tu-155	1988	First manned liquid hydrogen powered and combustion-based aircraft [112]
Hornet	2003	First fuel cell propelled drone [113,114]
Boeing fuel cell demonstrator aircraft	2008	First manned aircraft using fuel cell and lithium battery hybrid propulsion system [115]
Antares DLR-H2	2009	First manned aircraft solely propelled by fuel cell [116]

reasons. ZeroAvia is now demonstrating an advanced fuel cell driveline using a modified Dornier 228 [127], initially aiming for a range of over 450 km for 2025, followed by a 40–80 seat regional aircraft with a range of over 900 km in 2027.

Hydrogen aircraft are gaining prominence in various government and industry projects. Embraer is planning regional hydrogen turboprops for 2035–2040 [128]. In 2022, the FlyZero project [129] generated more than 100 reports on zero-emission aviation. Airbus now focuses its efforts on developing a hydrogen fuel cell aircraft [130], hence not prioritizing work on combustion and their previous ZEROe configurations: the turbofan, the turboprop, and the blended wing body aircraft. The fuel cell aircraft will have four 2-MW electric motors and will run on liquid hydrogen. These decisions reflect the technological and infrastructural challenges in developing hydrogen-powered commercial aircraft ecosystems.

Although hydrogen-powered aircraft generate significant interest and high expectations, only a few successful flights have taken place. None have been used regularly by commercial operators or governments. Table 3 lists key hydrogen-powered aircraft flight demonstrators, hence complementing the historical first achievements already presented in Table 2. Although the frequency of hydrogen demonstrator aircraft activities has increased in recent decades, it should be stated that most of them are still represented by smaller technology demonstrators.

Rather than expanding further on historical hydrogen-powered aircraft achievements, we refer to previous review work. Yusaf et al. [8] give a clear picture from a project output perspective, whereas Tiwari et al. [20] give a clear technology development perspective. Soleymani et al. [22] provide a fuller focus on the historical progression of fuel cells including SOFC. Adler and Martins [9] illustrate how early initiatives feed into more recent hydrogen aircraft demonstrations, making clear how propulsion choices evolved with technology readiness [9]. Although somewhat dated, the classical text by Brewer [131] gives a very good review of technological advancements and history, including the provision of numerical examples to support the discussion.

4. Propulsion and energy need

Several options for implementing hydrogen in aviation exist. A key technological option concerns the type of propulsion system. Two main options are being considered: hydrogen fuel cell architectures, where hydrogen is converted into electricity and subsequently drives propellers via electric motors; or the direct combustion of hydrogen in gas turbines powering turboprop or turbofan propulsion systems. Hydrogen

Table 3
Flight tested hydrogen powered aircraft (Extended from Ref. [9]).

Aircraft	First flight	Storage	Propulsion	Notes	Source
NACA-modified B-57	1957	LH_2	Turbojet	One hydrogen-powered engine	Sloop [117]
X-43 aircraft	2001	GH_2	Scramjet	Airbreathing propelled speed records. B–52B launched	McClinton [120]
Boeing Fuel Cell Demonstrator Airplane	2008	GH_2	PEMFC + Li ion battery	Fuel cells provided all power in cruise	Boeing [115]
Antares DLR-H2	2009	GH_2, 350 bar	33 kW PEMFC	Only fuel cells	German Aerospace Center [116]
AeroVironment Global Observer	2011	LH_2	ICE	Unmanned	AeroVironment [122]
Boeing Phantom Eye	2012	LH_2	Modified Ford 2.3L ICE	Unmanned	Boeing [132]
H2FLY HY4	2016	GH_2	45 kW PEMFC	Cryogenic hydrogen	German Aerospace Center [69]
ZeroAvia Piper Malibu demonstrator	2020	GH_2, 350 bar	PEMFC	Joint battery and fuel cell propulsion	Harris [125], Warwick [126]
ZeroAvia Dornier 228 demonstrator	2023	GH_2	Fuel cell	Joint battery, fuel cell propulsion and turboprop engine	Crownhart [127]
Universal Hydrogen Dash-8 demonstrator	2023	GH_2	Megawatt-class PEMFC	Fuel cell and turboprop engine	Norris [133]

combustion in gas turbines relies on technologies already in use in conventional commercial aircraft. However, it requires modifications in the fuel storage and delivery systems as well as in the combustion unit. Fuel cells produce electricity from hydrogen with an efficiency of up to 60 %, with PEMFC designs typically operating in the range 40–50 % [17]. Sizing a fuel cell stack for transport applications always involves a trade-off between efficiency and power density [17]. When a great degree of compactness is expected, as for the aviation case, their efficiencies are lower, perhaps reaching 45 % efficiency [134,135]. While combustion in gas turbines achieves similar efficiencies at much higher power densities, it generates NO_x and water vapor, impacting the environment [9,51].

The conversion of energy into propulsive power involves steps affected by the efficiencies of the system's components. When comparing systems, it is important to consider the onboard conversion chain. Fig. 1 shows four typical conversion chains: a conventional turboprop; a conventional turbofan; a battery-powered; and a fuel cell-powered system. Batteries are energy efficient, but their weight and volume present structural and integration challenges that will negatively impact aerodynamic and aircraft performance.

An interesting observation supported by Fig. 1 is that although fuel cells do not necessarily have an efficiency advantage compared to larger propulsion systems, they outperform smaller turboprops. This is primarily due to component size limitations constraining pressure ratios of combustion-based systems to be modest. The pressure ratio for the turboprop powering the ATR 42 is stated to be around 16. In contrast, the pressure ratio for one of the most modern and largest turbofans, which will power the Boeing 777-9, is quoted to be 60. Since the thermal efficiency of the Brayton cycle is directly related to the pressure ratio, even the theoretical efficiency of this type of cycle would be relatively low. In addition, smaller-size turbomachinery leads to lower efficiencies driven both by tip gaps and Reynolds number effects.

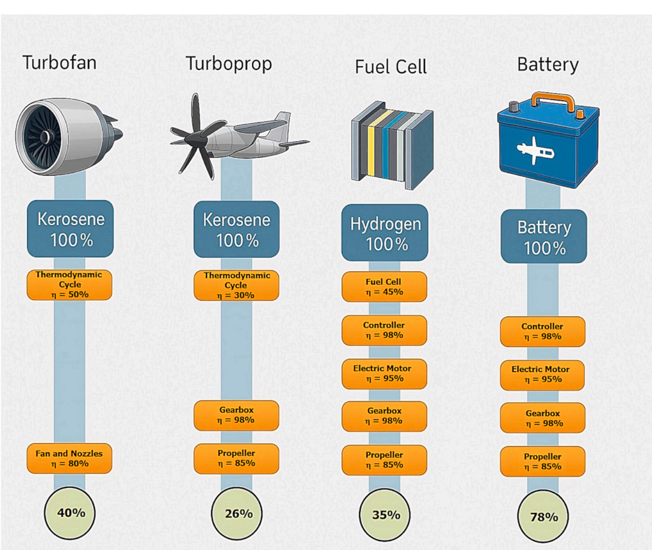

Fig. 1. Onboard conversion chains with typical component efficiencies and total efficiencies [11,17,39,41,134,136–138].

To get the full picture of the challenges that the introduction of hydrogen for aviation is facing, one must take one step beyond simply studying the propulsion system. This is due to both the exceptional gravimetric efficiency of hydrogen and its volumetric inefficiency [139]. The volumetric inefficiency poses challenges for airframe integration which are only fully understood if one addresses the aircraft and the engine together. An intuitive presentation on gravimetric challenges has been published by Adler and Martins [9]. They analyzed the Breguet range with the 777-200 ER and the GE90 engine and compared the energy use with a corresponding hydrogen aircraft, assuming the same energy efficiency but with a range of assumptions on tank gravimetric efficiency. The gravimetric efficiency is defined as below, relating the tank weight W_{tank} to the weight of the hydrogen W_{H_2} according to Eq. (1).

$$\eta_{tank} = \frac{W_{H_2}}{W_{H_2} + W_{tank}} \quad (1)$$

Their calculations have been repeated herein and are plotted in Fig. 2a. As pointed out by Adler and Martins [9], it is observed that around 55 % gravimetric efficiency all hydrogen ranges (500 NM, 2000 NM, and 5000 NM) become better, and this effect is more pronounced for longer ranges. This emphasizes the importance of a well-designed fuel system [44], and it illustrates that for lower gravimetric efficiencies, lower than 30 %, the energy need quickly becomes unacceptable as ranges increase. Note that the weight of the aircraft fuel system will be lower at the start of the Breguet range evaluation already at around 35 % gravimetric efficiency. This is due to the fuel heating value of hydrogen being almost triple that of Jet-A. However, since the hydrogen aircraft does not lose mass as quickly as the Jet-A aircraft, the tipping point, that is, when the hydrogen aircraft becomes more energy efficient, is reached for a higher value of gravimetric efficiency than 35 %. The hydrogen aircraft must simply be lighter for a larger portion of the mission for the Breguet range to become better overall. This tipping point then only reached around 55 % gravimetric efficiency and is

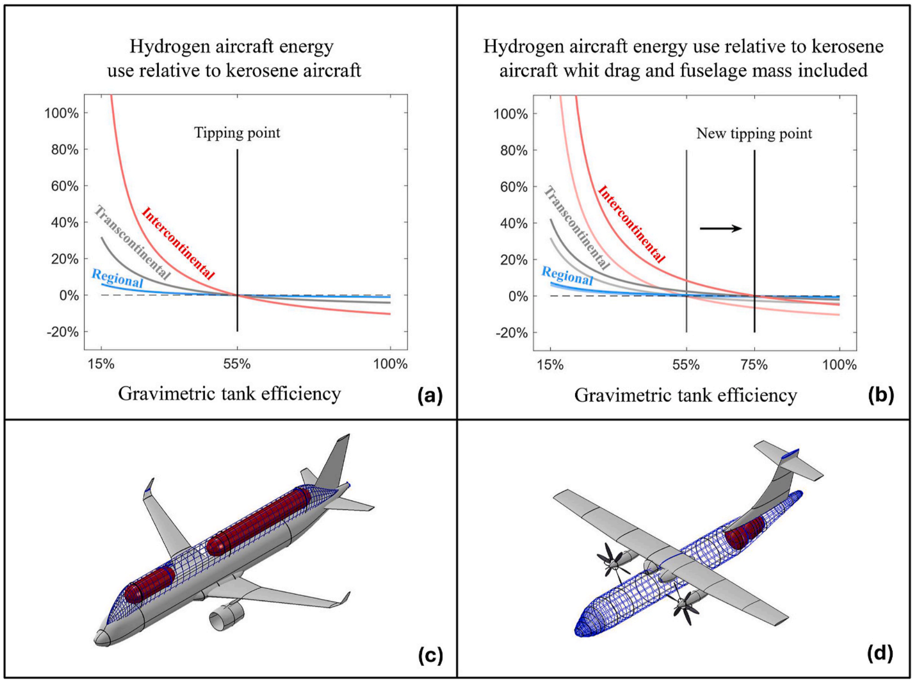

Fig. 2. (a) Effect of tank weight on energy need for hydrogen aircraft in relation to conventional Jet-A (dashed reference line). The three ranges, defined as in Ref. [9], are Intercontinental (5000 nmi), Transcontinental (2000 nmi) and Regional (500 nmi). **(b)** Effect of tank weight, increase wetted area and fuselage mass on energy need in relation to conventional Jet-A. **(c)** Long range hydrogen aircraft modeled after optimal configuration [140]. **(d)** Fuel cell hydrogen aircraft for designed for the Nordic market [135].

notably independent of the range [9]; see again Fig. 2a.

However, to get a fuller picture, the low volumetric efficiency of hydrogen should also be included to understand the limitations of hydrogen use. This becomes obvious when reviewing Fig. 2c, which is an accurate geometric representation of the long-range mission optimization study published by Xisto and Lundbladh [140]. This concept was designed for a 7500 NM mission having a gravimetric efficiency of 69 %, and the full mission computations indicated a 12 % penalty for energy efficiency. The fairing and structural integration of the tank required an increase in aircraft mass in addition to the tank weight. If an effective gravimetric efficiency was computed, that is including also the structural additions to hold the tank and the mass of the fairing, the tank gravimetric efficiency of 49 % was noted. The mission studies in Xisto and Lundbladh [140] also included the added effect of additional wetted surface needed by the fairing a fact that further increases the inefficiency of the hydrogen aircraft.

Inspired by Adler and Martins [9], we therefore extend their simplified analysis to also include the effect of volumetric efficiency on the Breguet range analysis. This is done by including two additional effects. First, the added volume required rendered an increased fuselage volume that was added to the calibrated Boeing 777-ER model presented by Adler and Martins [9]. The increased drag was calculated using the methods described in Raymer [141], estimating the same fuselage diameter as for the Boeing 777-ER model but increasing fuselage length. Added drag arising from the tank was estimated to vary from increasing total drag by 23 % at 15 % gravimetric density down to 2.5 % at 100 % gravimetric density. For the reference aircraft, approximately 11 % of the total drag originates from friction of the fuselage. In addition, the added volume for the aircraft requires added mass due to the increased fuselage length. Here, Raymer's approximate estimate of an additional 24 kg/m^2 of added fuselage was used [141]. With this extended model, estimating the impact of also the low volumetric efficiency, we derive Fig. 2b.

The break-even with respect to energy needs increases from around 55 %, when considering only the tank weight, to about 75 % when both added mass and added fuselage drag are included in the estimate. It is quite clear that long-range operation with hydrogen aircraft and combustion is feasible [44,45,140,142], but that it likely would incur an increase in energy need. Notice that the discussion above is carried out by comparing an existing aircraft with aircraft making similar assumptions about technology levels. A recent insight, which seems to have been neglected in early work [45], is the fact that a hydrogen aircraft will land heavier than its Jet-A counterpart simply because less mass is consumed during flight. This is, in turn, due to the higher gravimetric density of hydrogen. For this reason, the wing loading, normally set by the landing condition, is limited by the heavy landing, increasing wing size and cruise drag [140].

A future successful integration of hydrogen into jet engine-propelled aircraft will likely involve exploring synergies between the fuselage and the cryogenic fuel [142]. This means deviating from the ubiquitous tube-and-wing shape and moving toward, for instance, a blended wing body. Such novel shapes may allow using larger-diameter tanks that have inherently lower heat transfer per unit volume of fuel. It is clear that if future technology advances are combined with new radical airframes, substantial improvements can be reached [23], and potentially even improvements in energy use may be obtained [23], albeit with a very high gravimetric tank efficiency of 78 %.

Finally, it is highlighted that for hydrogen combustion aircraft, notable improvements in fuel efficiency can be achieved by preheating the cryogenic fuel using heat from the jet engine. Patrao et al. showed that this could be used to further improve mission fuel burn by 4 % using an intercooler as a heat source, and 7.7 % for an intercooled recuperated concept [53,107]. The effect is related to the extremely high specific heat of hydrogen, allowing it to approximately increase its heat value by 10 % from a tank temperature of 24 K to a combustor inlet of 800 K [53].

4.1. Green hydrogen and energy security

Energy security is a central concern in the development of a green hydrogen economy, which may serve as a motivator to develop the hydrogen aviation sector. Europe's hydrogen demand is expected to surpass domestic production capacity, leading to import dependency that could exceed 50 % by 2035, raising concerns about supply vulnerabilities similar to those seen in the natural gas sector [143]. Investment in electrolysis and underground hydrogen storage (UHS) can mitigate these risks and be a hedge against import disruptions through the generation of hydrogen locally from renewable electricity [143]. At the same time, it also introduces new geopolitical, market, and trade challenges — including competition for resources, high production costs, and the need for international cooperation on trade routes and infrastructure [144]. For hydrogen aviation, these considerations are critical, as the sector will rely on secure and affordable green hydrogen supplies to enable long-haul, zero-emission flights.

5. Hydrogen combustion gas turbines

Operating gas turbines with hydrogen presents challenges. Although the turbine, compressor, and other components work relatively similarly to traditional models, the combustor needs significant changes due to the different combustion characteristics of hydrogen. On the other hand, hydrogen allows for leaner combustion due to its wider flammability limits, opening for lower flame temperatures and reduced NO_x emissions [9,54].

Although the focus of this paper is hydrogen aircraft propulsion, we choose to review technology for low-NO_x combustion, not only for aero engines but also for stationary gas turbines. Stringent NO_x emission regulations in combination with the need to combust hydrogen and natural gas in a range of mixtures, has advanced stationary gas turbine low NO_x emission hydrogen combustor technology far beyond that of its aero engine counterparts. For instance, General Electric Companies (GE) recently reported on a direct lean injection combustor that allows burning up to 100 % hydrogen in a range of hydrogen-natural gas mixtures [49]. For the ultra-lean micromix combustion concept, the lead of stationary combustors over aero engine combustors is even greater. Singh et al. [56] recently argued that although aero engine combustor design is closely related to stationary gas turbine activities, stationary gas turbine micromix combustors are approaching TRL 9, whereas for aero engine applications the technology has only reached TRL 4. Another reason for reviewing stationary gas turbines is, of course, that knowledge developed in the stationary field can, to a large degree, be transferred to aircraft engine applications.

5.1. Hydrogen combustion basics

Hydrogen tends to flashback and produce high-temperature flames, which could potentially lead to higher NO_x emissions. Fig. 3 compares the flame stability limits of hydrogen and kerosene. Although hydrogen has a much higher temperature at its stoichiometric ratio, it is much easier to establish a stable flame. Lower equivalence ratios in hydrogen combustors generate low-temperature flames, requiring more intense mixing to avoid hot and cold spots to ensure effective combustion and a balanced flame profile. Operating with a lean mixture in internal combustion engines can reduce emissions and increase thermal efficiency. Excess oxygen favors the oxidation of pollutants and reduces combustion temperatures, minimizing NO_x formation and dissociation losses. Hydrogen improves combustion, and provides fuel savings, but its burning rate, up to 10 times higher than gasoline, requires control. Therefore, the addition of hydrogen must be optimized to avoid performance losses [145,146]. To maximize the advantages of hydrogen under lean conditions, it is necessary to adjust the combustor design to reduce NO_x formation, which depends on temperature and residence time. Although hydrogen's flame temperature is higher than that of kerosene, its wide flammability range allows it to operate with leaner mixtures, helping to control the flame temperature [20,21,59].

The higher flame speed and reactivity of hydrogen allow for a shorter combustor design with a shorter residence time. Gaseous fuel injection facilitates mixing with air, resulting in a more uniform temperature distribution than that of liquid fuels such as kerosene. Two hydrogen combustor concepts, the LDI (lean direct injection) investigated by NASA [57] and the micromix concepts investigated by Dahl and Suttrop [19,58], have shown good performance in real combustion tests. Both concepts indicate that the main challenge is to avoid backfiring or flashback, and that by increasing the intensity of the mixing, NO_x emissions can be significantly reduced. Additionally, high reactivity leads to flame anchoring in the proximity of the injection walls, requiring carefully designed injector cooling systems.

Micromix combustion is an innovative dry, low-NO_x technology for hydrogen-rich fuels. Its central principle is the jet-in-crossflow mixing of multiple miniaturized fuel jets with combustion air. This miniaturization results in low NO_x emissions due to the short residence time in small flames and offers inherent safety against flashback. Initially investigated with pure hydrogen, micromix has been optimized for annular combustors to operate flexibly with hydrogen-methane mixtures and

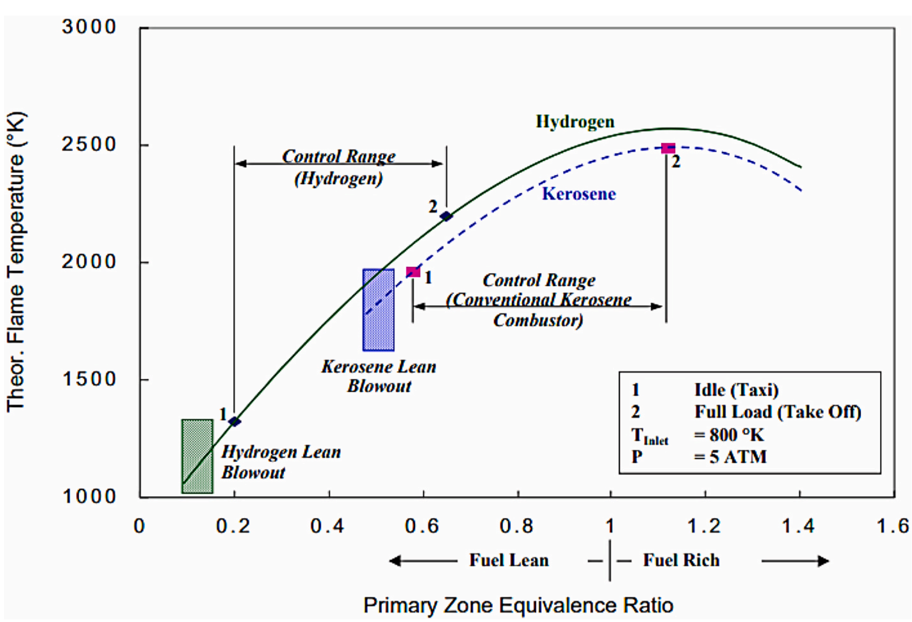

Fig. 3. Temperature characteristics of combustor primary zone (Reproduced from Ref. [21]).

hydrogen-rich syngas. In this way, tests on real gas turbines have confirmed the technology's low-NO_x characteristics [52].

5.2. Advances in hydrogen combustion

Lean direct injection (LDI) combustors have been investigated to reduce the risk of flame flashback in hydrogen combustion systems. According to Marek et al. [7], hydrogen LDI combustors perform better than advanced Jet-A LDI combustors. Studies indicate that using non-premixed fuel flow is preferable to avoid confined flame contours and minimize the risk of flashback. The design of the injectors includes a small premixing channel after injection, which is fundamental due to the reactivity of hydrogen, which is seven times that of Jet-A under stoichiometric conditions.

In addition, high temperatures on the face of the injector before the complete mixing of hydrogen and air can induce thermal stress and structural failure. To overcome these challenges, Dahl and Suttrop [19] developed a micromixing combustor without premixing, reducing the scale of the combustion zone by homogeneously distributing thousands of diffuser flames. This concept increases turbulent mixing and reduces local residence time, resulting in an approximately 80 % reduction in NO_x emissions compared to kerosene combustors.

Mitsubishi Heavy Industries [18] has developed three combustor types for gas turbines capable of operating in hydrogen co-firing with natural gas and in hydrogen combustion alone. These include the Dry Low NO_x (DLN) multi-nozzle combustors, a technology based on traditional DLN concepts but adjusted to reduce the risk of flashback. The design of this combustor promotes rapid mixing by directing the combustion air through a device that generates a rotating flow. At the same time, hydrogen is injected through small holes in the surface of the rotating fins.

Tests were conducted using a mixture containing 30 % by volume of hydrogen and natural gas [18]. As illustrated in Fig. 4, the modified DLN multi-nozzle combustors allow hydrogen to be burned safely together with natural gas without significantly increasing the risk of flashback due to their optimized design.

Mitsubishi has extensive experience in developing traditional diffusion burners, where the fuel is injected directly into the primary airflow of the combustor. Compared to premixed combustion, this process generates a high-temperature flame zone, which increases NO_x formation. To mitigate this effect, a diluent such as steam, water, or nitrogen, must be injected to lower the flame temperature and the associated NO_x emissions. Based on these developments by Mitsubishi Heavy Industries, Nose et al. [18] detailed in their studies the development of large-scale gas turbines designed to operate with a mixture of natural gas and hydrogen or with hydrogen alone, successfully achieving combustion tests with 30 % hydrogen by volume.

Kawasaki Heavy Industries has developed the micromix combustor as a solution to overcome the limitations of conventional technologies, such as wet diffusion, DLE with risk of flashback, and enabling dry combustion with low-NO_x for fuels with a high hydrogen content, including 100 % H_2. This micromix combustor technology is based on miniaturized non-premixed flames, which makes it inherently safe against flashback and enables low-NO_x dry combustion. Design improvements, such as reducing the diameter of the injection holes and adding a supplementary burner system, have been implemented to optimize NO_x reduction and operational flexibility. Demonstration tests on a real M1A-17 gas turbine validated stable operation and NO_x emissions consistently below 32 ppm or 15 % O_2, for mixtures of 50–100 vol% H_2 over the entire load range [147]. Fig. 5 shows a model of the DLE combustor equipped with a supplemental burner system.

Kawasaki Heavy Industries (KHI) began developing micromix (MMX) combustor technology for hydrogen gas turbines in 2010, announcing its CO_2 emission-free hydrogen supply chain concept. From 2014 to 2022, KHI carried out extensive research and development and improved prototypes of the MMX combustor in national programs. In 2020, micromix combustion technology was demonstrated at a cogeneration plant in Kobe using pure hydrogen. Intensive field demonstrations were conducted from December 2022 to March 2023, accumulating operating hours and validating performance. Finally, in 2023, Kawasaki commercially launched the M1A-17MMX gas turbine package, making it the first gas turbine capable of operating on 100 % pure hydrogen [147–149].

The state of the art for aerospace applications with respect to aero

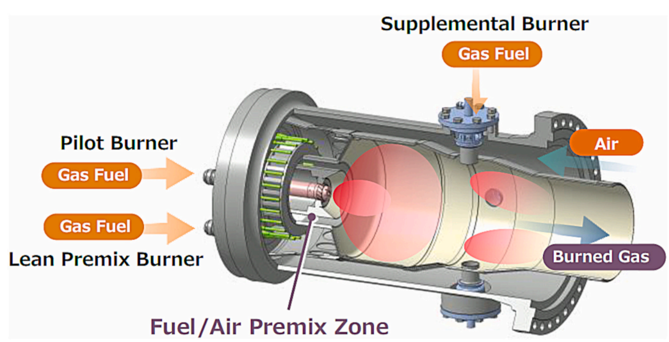

Fig. 5. DLE combustor with supplemental burner system (Reproduced from Ref. [147]).

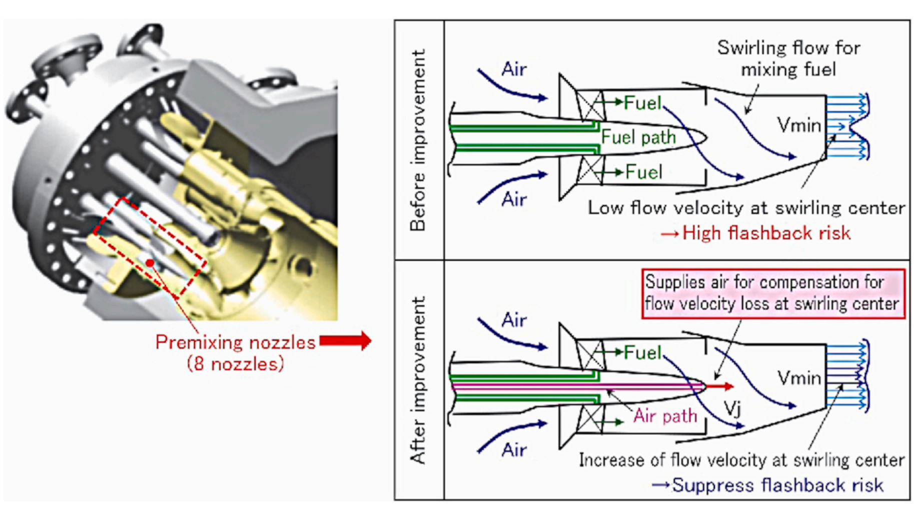

Fig. 4. Outline of the new combustor for hydrogen co-firing (Reproduced from Ref. [18]).

engines is summarized in Table 4.

To mature aero engine micromix combustion technology, there is a need for full annular rig experiments; maturing fuel staging strategies; evaluating and confirming altitude relight capabilities; assessing take-off and landing cycle and mission level results; demonstrate a full system prototype; study the upstream and downstream component integration; scale up manufacturing capabilities; and work with aviation authorities to certify safe H_2-fueled aircraft operation [56].

The four largest commercial aero engine manufacturers (GE Aerospace, Rolls-Royce, Pratt & Whitney, and Safran) have published plans to build and test hydrogen combustion aircraft engines in the coming years [150,151]. GE Aerospace and Safran are modifying a GE Passport turbofan to run on hydrogen. Pratt & Whitney announced the HySIITE (Hydrogen Steam-Injected, Intercooled Turbine Engine) project, a liquid hydrogen combustion engine with steam injection to reduce NO_x emissions [32,37]. For its part, Rolls-Royce has carried out ground tests of an AE 2100 engine adapted for hydrogen combustion and plans to carry out the same test with a Pearl 15 engine [48]. They target achieving greater thermal efficiency than fuel cells and, at the same time, a lower operating costs than expected for using Sustainable Aviation Fuel (SAF) [37,48]. A key focus for future research at Rolls-Royce is to develop a combustor with dual-fuel capability to manage the operation of 100 % hydrogen and 100 % SAF [151].

In summary, a lot of progress is reported on variable hydrogen content in fuels and the development of combustors for such gas turbines. This flexibility is key to making hydrogen economies successful by allowing operators to optimize their fuel mix depending on local availability at airports. In turn, this will support an increasing availability of hydrogen in society, which will help create the infrastructure needed for future hydrogen aviation. In addition, knowledge from work on stationary gas turbines may be adapted for use in aircraft designs, supporting the development of technology that can curb NO_x emissions in future hydrogen aviation power plants.

5.3. Steam injection cycles for aero engines

Since hydrogen combustion generates about 2.6 times more water for the same amount of heat released compared to Jet-A [152,153], water recovery is simplified substantially in WET cycles, thus potentially resulting in lower heat exchanger mass, pressure losses, and an improved fuel burn. Moreover, hydrogen enables these advanced cycles by increasing the amount of water available in the exhaust and significantly simplifying the condensation process.

Pratt & Whitney has developed the HySIITE (Hydrogen Steam-Injected, Intercooled Turbine Engine) engine concept, a project funded by the US Department of Energy that seeks a solution for zero-carbon air propulsion by exploiting the properties of hydrogen. The project promises a significant advance in the development of more efficient and sustainable propulsion systems for aviation, with reductions in energy consumption and pollutant emissions. The project's innovation centers on the injection of steam into the engine cycle, taking advantage of hydrogen's cryogenic properties and waste heat to generate steam, resulting in significant reductions in energy consumption (up to 35 %) and NO_x emissions (more than 99 %), favoring the development of commercial turbofan engines with zero carbon emissions. Pratt & Whitney's HySIITE concept features an innovative engine design with air and steam flow [32,37]. Fig. 6 shows the hybrid engine concept HySIITE.

Table 4
State of the art for micromix combustor technology.

Institution	Test Conditions	Outcome
Cranfield University	Injector pressures up to 10 bar for fuel air ratios in the range 0.25–0.5. T_3 = 600 K	Range of momentum flux ratios studied [42].
NASA Glenn	Injector pressures up to 7 bar for fuel air ratios in the range 0.1–0.48. T_3 = 700 K	Demonstrated flash-back free operation with NO_x below 10 ppm [38].

According to Refs. [32,37], air enters the engine at the rear in a small reverse-flow core. As it flows through the compressor, the air mixes with vapor injected between the compression stages before entering the combustion chamber. In the combustion chamber, hydrogen gas is ignited with compressed air, and the combustion products pass through a power turbine, which is connected by a shaft to the gear-driven fan. Instead of exiting the engine through a conventional exhaust nozzle, the exhaust gases pass through an evaporator, a heat exchanger. These exhaust gases are then directed to a series of condensers integrated into the bypass duct to take advantage of the large surface area of the engine structure. The condensers are cooled with bypass air fed by the fan. This cooling causes the exhaust gas to condense and turn into water. The water is then centrifuged onto the walls of an air-water separator. The dry air is ejected into the mixed exhaust stream at the rear of the nacelle, while the water is fed back into the evaporator, where it is converted back into steam. Although still in the study and development phase, HySIITE is claimed to have the potential to revolutionize aeronautical propulsion, contributing to cleaner and more efficient flights. Pratt & Whitney's approach with this technology could, therefore, be key to achieving the aviation sector's decarbonization goals.

MTU Aero Engines is developing the SAF and hydrogen-compatible Water-Enhanced Turbofan "WET Engine", stating a 2030+ entry into service. The cycle has potential to simultaneously reduce CO_2 emissions, NO_x emissions and contrails. In particular, contrails seem to be possible to drastically reduce; more than 90 % reduction is stated in Ref. [31]. Similar to HySIITE, the cycle works by using water injected as superheated steam into the combustor. The steam is generated by a vaporizer located in the engine exhaust, and the water is generated by condensing it from the engine exhaust.

6. Fuel cells

Due to the long-standing trend of continuously pushing electrification toward higher energy densities, the application area for fuel cells has gradually moved to higher power density installations. This has happened as cheaper battery solutions have increased their range of applicability. However, in the areas of shipping and particularly aviation, energy need are so large that battery solutions seem infeasible even in the long term [100,102], at least if shorter, smaller aircraft and hybrid solutions are excluded. According to O'Hayre et al. [17] and Martin [11], fuel cells dominate research activities for short-range aircraft because their efficiency is relatively good even for smaller size propulsion.

Hydrogen fuel cells generate electricity using hydrogen and oxygen as inputs and are suggested for small aircraft, such as regional airliners with propellers. These propulsion systems are often combined with batteries to meet high power demands and respond to rapid changes in

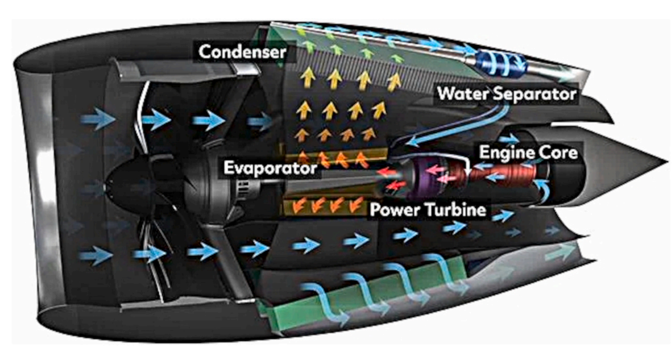

Fig. 6. The hybrid engine concept HySIITE (Hydrogen Steam-Injected, Intercooled Turbine Engine) (Reproduced from Refs. [32,37]).

acceleration. Using fuel cells reduces costs and maintenance compared to conventional jet engines. Tiwari et al. [20] point out that the quest for zero carbon in aviation has driven the development of these technologies for short and regional missions. Fuel cell propulsion systems require new electrical architecture, with power management and distribution (PMAD) providing greater reliability and efficiency due to fewer moving parts and scalability with independent energy storage. Fig. 7 shows a complete fuel cell system comprising the fuel cell stack and the balance of plant (BOP). The BOP is made up of the following elements: a gas management system (GMS), which includes the fuel and cooling system with heat exchangers and a compressor to avoid a decrease in performance at altitude; a water management system (WMS) to balance the production and removal of water inside the cells; a power conditioning system (PCS); and a thermal management system (TMS) to maintain the correct operating temperature and also to increase the efficiency of the system.

The most common fuel cells currently being researched for aircraft are the Proton Exchange Membrane Fuel Cell (PEMFC) and the Solid Oxide Fuel Cell (SOFC). Both consume hydrogen at the anode and oxygen at the cathode. The oxygen is usually extracted from the ambient air, while the hydrogen electrons flow through the circuit, generating electricity. In the PEMFC, hydrogen ions flow through the electrolyte to the cathode, forming water vapor, while in the SOFC, oxygen ions form at the cathode and flow back to the anode to generate water. Unlike conventional heat engines, fuel cells use an electrochemical reaction to convert chemical energy into electricity, offering greater efficiency at the cell level and, unlike batteries, energy is limited only by the amount of fuel. To obtain a suitable operating voltage, several cells can be connected in series, and the maximum current depends on the cross-sectional area of each cell [17,72].

A fuel cell system for aircraft power generation, including all the balance of plant subsystems, may achieve an electrical efficiency of 50 %, representing a more efficient alternative to conventional power systems. These fuel cell systems can replace units such as the auxiliary power unit (APU) and ram air turbine (RAT) to fulfill various functions, including power supply, emission-free operation on the ground, electric engine start, electrical environmental control system (EECS), portable water generation, surface heating, and cockpit humidification. Thermal management is challenging, especially for PEMFC cells, due to their low-temperature limits. Cooling approaches include coolant, phase change, and air cooling, and the best solution is to add cooling channels to the bipolar plates which, although they increase the weight and volume of the stack, allow for a more optimized design with highly conductive materials [67,71,83,84]. If PEM fuel cells are designed to replace the main power plant, a more lightweight fuel cell design may be preferred, requiring trading efficiency for weight, reaching an efficiency in the range 40–50 % [17]. This trade-off for compactness motivates the 45 % efficiency chosen in Fig. 1.

The specific power of fuel cells can be improved by increasing the operating pressure, with the compressors powered by the electricity generated by the cell itself. Schröder et al. [76] designed a fuel cell capable of supplying more than 300 kW of auxiliary power to a commercial aircraft, demonstrating that pressures between 1.5 and 2.0 bar absolute achieve optimum system efficiency. Pressurization is crucial for increasing the specific power of aircraft at higher altitudes, where the pressure is lower. Fuel cells convert chemical energy from hydrogen or other fuels into electrical energy cleanly and efficiently, functioning like batteries without the need for recharging.

Normally, PEM fuel cells use pure H_2 as fuel. H_2 is oxidized at the anode, producing positively charged H^+ ions and electrons. The positively charged ions pass through the electrolyte from the anode to the cathode. The electrons migrate out of the electrolyte through a wire connecting the anode to the cathode, producing an electric current. At the cathode, the H^+ ions recombine with electrons and react with oxygen, producing H_2O [78,79]. The half-reactions are shown below according to Eqs. (2) and (3):

At the anode, the oxidation half-reaction occurs: $H_2 \rightarrow 2H^+ + 2e^-$ (2)

At the cathode, the reduction half-reaction occurs: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ (3)

PEM fuel cells are divided into LT-PEMFCs (low temperature) and HT-PEMFCs (high temperature). Herein, we define LT-PEMFCs as those operating below 100 °C, acknowledging that no universally accepted definition exists. LT-PEMFCs offer fast start-up times and good dynamic response but require complex water and thermal management systems, which increase weight and drag. With high technology readiness levels (TRL), these cells are widely used in aircraft demonstrators, supported by partnerships between Airbus, GKN Aerospace, Elring Klinger, and Intelligent Energy [106]. There is potential to reduce cost and start-up time by up to 40 min compared to current cells. HyPoint, acquired by ZeroAvia, has demonstrated that improving the balance of plant (BOP) mass fraction from 75 % to 40 % in HT-PEMFC systems is possible. The development of HT-PEMFC cells is regarded as the next breakthrough in

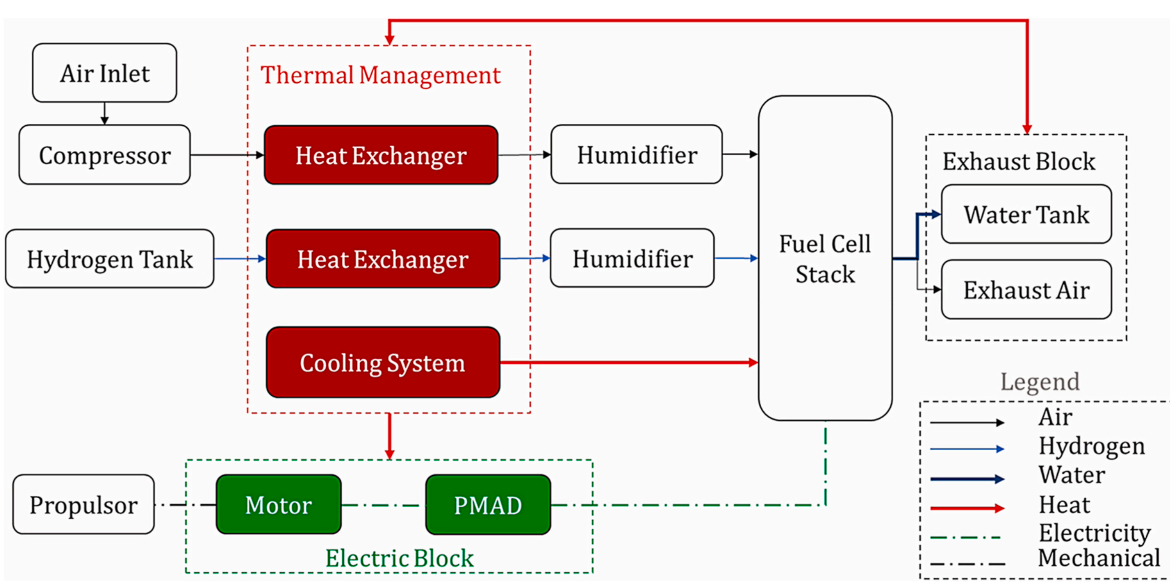

Fig. 7. Fuel cell system architecture (Reproduced from Ref. [20]).

the aviation sector [79,85].

Solid oxide fuel cells (SOFCs) operate at high temperatures (600–1000 °C), which enhances their efficiency but requires a start-up and shutdown time ranging from 10 min to 1 h, as described by Dicks and Rand [78]. Operating under these conditions eliminates the need for catalysts and allows the use of materials that do not require humidification. Although SOFCs do not have the same power density as PEMFCs, they offer advantages through their waste heat, which can be utilized in regenerative systems such as gas turbines. This waste heat is also exploited in SOFC-GT hybrid systems, where it preheats the air for the combustor. Additionally, high-temperature operation removes the need for humidity control and simplifies thermal management, resulting in a more efficient system [77,88,89].

High operating temperatures present challenges for SOFCs, including long startup times and limited shutdown cycles over their service life. These factors can cause material and mechanical issues, such as thermal expansion compatibility and sealing requirements [9,17]. Conversely, if residual heat is used to preheat air in a hybrid system with a gas turbine, SOFC-GT configurations become more advantageous, as demonstrated by numerous hybrid architectures in current research. PEMFCs are generally preferred for aircraft propulsion due to their high specific power and rapid startup capability, necessary to respond to quick acceleration changes and deliver high thrust over short durations. However, a battery is often included to serve as a buffer and to allow for greater transient peak power output [68,77,154].

6.1. Recent developments in aircraft fuel cells

Major hydrogen aviation projects reveal a convergence trend toward electric propulsion with fuel cells, which has been identified as a promising solution for decarbonizing air mobility [81,93]. When comparing PEMFC and SOFC fuel cells in hybrid propulsion systems, Guo et al. [94] show that the development of aircraft using PEMFC faces some limitations due to requirements for fuel purity, operational temperature control, management of water purity in the process, and challenges related to hydrogen storage and transportation.

Palladino et al. [95] pointed out that PEMFC fuel cells, due to the low temperatures at which they operate, require thermal management systems with large sinks for waste heat. However, increasing the operating temperature can reduce the size of the cooling system but may cause issues such as accelerated degradation and longer start-up times. In contrast, solid oxide fuel cells (SOFCs) are a viable alternative for electricity generation in the air transport sector. They offer high efficiency in converting fuel into electricity and compatibility with gas turbines due to their high operating temperatures. Integrating SOFC with a gas turbine (SOFC-GT) results in a more efficient hybrid system without energy storage capacity, whose autonomy depends on fuel characteristics. Therefore, the ability to operate at high temperatures also allows the use of various fuels, broadening the applications of this hybrid system [83,90,99,155].

Solid oxide fuel cells (SOFCs) have been investigated as an efficient and sustainable alternative for power generation, with potential applications in Auxiliary Power Units (APUs). Studies indicate that SOFC-GT hybrid systems achieve high efficiency, such as the models developed by Siemens-Westinghouse (220 kW, 53 %) and Mitsubishi Heavy Industries (250 kW, 55 %) [156]. Ji et al. [92] analyzed a hybrid propulsion system combining SOFCs, batteries, and jet engines to optimize fuel consumption and reduce emissions. The study showed that batteries supply power during take-off, while in cruise, the engines are powered by SOFCs, whose power density is close to that of jet engines at high altitudes. The system's mass distribution is approximately 15 % for SOFCs, 12 % for engines, 8 % for batteries, and 56 % for fuel. The integration of these systems shows promises of extending range and reducing emissions, especially in high-altitude, long-duration unmanned aircraft.

S. Ma et al. [157] designed a solid oxide fuel cell system using ethanol for Auxiliary Power Units (APUs), achieving an electrical efficiency of 44.4 % during the startup phase and 55.4 % during steady operation. Additionally, given the high operating temperature of around 800 °C, SOFCs can be integrated with gas turbines to recover heat from the high-temperature exhaust, aiming to achieve higher efficiency.

Guo et al. [158] proposed the integration of a turbofan engine, a solid oxide fuel cell, and an Al–H_2O reactor in unmanned aerial vehicles (UAVs), where the reactor supplies hydrogen to meet the energy demand, resulting in a reduction of more than 10 % in fuel consumption compared to conventional turbofan engines. Bakalis and Stamatis [103], meanwhile, analyzed the optimization of compressors and turbines in SOFC-GT hybrid systems, carrying out a parametric study to maximize system efficiency under different operating conditions. The results indicated efficiency gains, especially under partial load, greater energy generation, and reduced greenhouse gas emissions. These studies reinforce the potential of hybrid configurations to improve performance and sustainability in aviation.

In 2004 and 2009, NASA completed a series of zero-emission aircraft studies, showing that fuel cell propulsion was not initially viable for medium- and short-range regional aircraft, as the fuel cell system's specific power was approximately 0.3 kW/kg [68,74]. Following the significant improvement in the fuel cell's specific power, several small fuel cell aircraft demonstrators have been flown to demonstrate the technology, as already outlined in the Hydrogen-powered aircraft achievements section.

Airbus plans to carry out a flight demonstration of a megawatt-class fuel cell propulsion system on its A380MSN1 test aircraft by 2035. If successful, this system would power a concept aircraft with 100 passengers (PAX) and 1000 nautical miles (NM) specifications [159]. The FlyZero concept uses a system of six propellers, fuel cell stacks, and balance of plant (BOP) on the underside of the aircraft fuselage. It concluded that with 3 kW/kg LT/HT-PEMFC, a 75-passenger, 800 NM regional aircraft is viable by 2035 with a 2.21 % increase in energy consumption and a 26 % increase in take-off weight compared to a conventional Jet-A powered aircraft [129]. Embraer is also proposing fuel cell aircraft concepts for the year 2035, more specifically the E19H2FC, E30H2FC, and E50H2FC models with a range of up to 600 NM in a 19-, 30-, and 50-PAX variants [128].

During the Airbus Summit 2025, a new concept for a hydrogen aircraft powered by four 2-MW all-electric propulsion engines was presented. Each engine is driven by a fuel cell system supplied by two liquid hydrogen (LH_2) tanks. To address the challenges of handling and storing LH_2 in flight, Airbus partnered with Air Liquide Advanced Technologies to develop the Liquid Hydrogen BreadBoard (LH2BB). This development is part of Airbus's ZEROe concept hydrogen aircraft featuring four all-electric propulsion engines powered by fuel cells [160].

6.2. High temperature PEM fuel cells

Although PEM fuel cells exhibit a superior performance with respect to variable power output and load following capability, in relation to SOFC, cooling becomes difficult on hot days due to its relatively modest operating temperature and consequent small temperature difference for driving the heat rejection. As an example, a state-of-the-art PEM fuel cell may operate around or slightly above 80 °C [135], whereas hot day take-off temperatures for aircraft [161] may go as high as 40 °C. This only gives a driving temperature for heat rejection of 80 °C–40 °C = 40 °C. Clearly, raising the operating temperature to 120 °C would represent a revolution since the driving temperature for cooling would double (now 120 °C–40 °C = 80 °C) and hence the radiator system mass could approximately be halved. It is therefore no surprise that the research activities to increase the exhaust temperature are being very actively pursued.

Underlying the anticipated advances is the success development of new materials, which is essential to increase the exhaust temperature of the PEM fuel cells. The traditional means has been based on fluorinated polymer chains like Nafion [86], more broadly referred to as Perfluorosulfonic Acid (PFSA) polymers [86]. Several alternatives to Nafion exist, but we will use Nafion as a basis for our discussion due to its commercial success.

Nafion-based PEMs may start to undergo degradation through unzipping mechanisms present already at 90 °C [87]. The unzipping means that the backbone chain or the side chain of the polymer breaks down either from an ion attack or thermally, occurring in particular at weak end groups [87]. Although the degradation mechanisms are active already at 90 °C, it seems that careful humidity management could keep the Nafion stable above 100 °C, assuming that the system is pressurized to achieve a higher boiling temperature for water. As a matter of fact, studies have shown that Nafion may retain conductivity up to 150 °C if 100 % humidity is maintained [162], although prolonged exposure to temperatures above 130 °C is likely not practically feasible. The amount of water that is needed to achieve 100 % humidity increases rapidly with temperature, making it increasingly difficult to maintain operation, and it also becomes very energy intensive. Furthermore, chemical unzipping and membrane swelling become progressively more severe for increased temperatures. For aviation applications, the increased pressure will increase the fuel cell stack weight through increased compression need and by maintaining a pressurized enclosure for the fuel cell, offsetting some or all of the benefit of reduced radiator weight.

Currently, increased fuel cell operating temperatures are addressed both by trying to mitigate the side effects that the high operating temperature introduces by chemically changing the proton conducting mechanism of the membrane. Mitigating high temperature effects includes using inorganics hygroscopic fillers to improve water retention at high temperatures in order to avoid dehydration [163]. Mitigation also addresses ways to manage membrane swelling [163] and the use of phosphoric acid to enable proton conductivity without using water as the proton carrier [164]. Direct chemical modification of the membrane may be achieved through sulfonated carbon nanotubes [165,166] to create additional proton pathways. The use of covalent organic frameworks is another approach to achieving proton conduction [167], avoiding the use of Nafion completely [168].

An alternative at much elevated temperatures, up to 200 °C, is to use phosphoric acid-doped polybenzimidazole (PBI) membranes [82] as well as other non-flourinated membranes [169]. Here, phosphoric acid provides the mechanism for ionic transport. However, these membranes are at a lower technology readiness level and are challenged by humidity causing phosphoric acid washout leading to loss of conductivity [169,170]. The PBI membranes also only reach good conductivity above some 120–130 °C, creating additional complexity, not the least for vehicles like aircraft. In the longer term they promise to enable compact heat rejection systems and increased system specific power output to 2 kW/kg, potentially as early as 2030 [82].

6.3. *Per- and polyfluoroalkyl (PFAS) and fuel cells*

Although Nafion, here representing the Perfluorosulfonic Acid (PFSA) class of polymers, is technically a Per- and Polyfluoroalkyl (PFAS) substance, Nafion is health-wise a relatively benign compound. This is due to its low solubility in water and its chemical inertness. This inertness reduces the risk of chemical degradation and the formation of smaller PFAS molecules of higher toxicity. PFAS substances are known to be both very persistent and bio-accumulative and are linked to serious health risks, including liver toxicity, immune suppression, endocrine disruption, and certain cancers. Although one may initially view Nafion as a relatively harmless substance, it is quite worrisome that the previously mentioned unzipping mechanism that may occur at loss of absorbed water and at higher temperatures [171]. This chemical degradation process would be expected to happen at a higher rate as operating temperatures are increased, if not mitigated. Another risk for emitting potentially larger quantities of PFAS is during thermal decomposition, which, for obvious reasons is much higher than operating temperatures for fuel cells but may occur during incineration of fuel cell rest products [172].

In the European Union, the REACH PFAS initiative includes polymers of low degradability. Nafion is not explicitly exempt and is unlikely to be made such an exempt due to its degradation pathways. Similarly, in the United States, the Environmental Protection Agency (EPA) is working on PFAS hazard. In the light of current trends and alternatives, it is likely that Nafion, as well as other PFSA substances, will at least be strictly regulated and that in the future it will be needed to take responsibility for the entire production and usage chain to make its use permissible. This will increase fuel cell cost and make their introduction more complicated. PFSA substances may also be taxed extensively or even completely banned for use in fuel cells, making the development of alternatives a prioritized research area.

7. Hybrid propulsion systems

In the last decade, research into hybrid-electric platforms has expanded primarily due to their promised advantages, resulting from a more synergistic integration with the airframe and associated increase in propulsive efficiency, leading to reduced fuel consumption and a decrease in associated emissions [96]. On the other hand, the authors [97,105,173] show that electric propulsion technologies present particular challenges, such as energy storage capacity, which results in batteries and capacitors with relatively low energy density compared to traditional liquid fuels.

According to Bradley [75], the American Institute of Aeronautics and Astronautics (AIAA) established a reference document called “Guidelines for Analysis of Hybrid Electric Aircraft System Studies,” which includes various components of the powertrain architecture. These guidelines were applied after NASA and its industrial partners had described six different electric propulsion architectures for electrified aircraft concepts, including an all-electric system configuration, three hybrid electric system configurations, and two turboelectric system configurations, as shown in Fig. 8.

The electrification of commercial aircraft can significantly reduce emissions and improve performance. All-electric aircraft systems use batteries as the sole source of propulsion. On the other hand, hybrid-electric systems use gas turbine engines for propulsion and to charge the batteries, which also provide energy for propulsion during flight. In a parallel hybrid system, the battery and gas turbine engines are mounted on a shaft and can provide propulsion independently or together. In the series hybrid system, electric motors are connected to the fans, and the gas turbine drives an electric generator that powers the motors and/or charges the batteries. The partial series/parallel hybrid configuration combines fans driven by a gas turbine and electric motors powered by batteries or generators. Turboelectric systems do not use batteries for propulsion but rely on gas turbines to drive electric generators, which power inverters and individual direct current (DC) motors to drive distributed fans. The partially turboelectric system uses electric propulsion to provide part of the power, while the fully turboelectric system relies exclusively on gas turbines to generate electricity and drive the fans [174].

Hydrogen propulsion enables the concept of hybridization, with hybrid aircraft powered by batteries and fuel cells, providing more integrated architectures. Hybrid aircraft are promising due to their low fuel consumption, with gas turbines operating optimally to generate electricity for the propulsion engines. The energy density of the batteries still needs to be increased for long-duration flights, but hybrid systems require less specific battery power than all-electric aircraft. In this way, combining hybrid propulsion with fuel cells is a viable alternative for meeting emission and fuel consumption standards [98].

Hoenicke et al. [101] describe how combining a fuel cell with a battery improves the aircraft’s efficiency. The fuel cell provides energy during low-energy demand phases, such as cruising. During phases requiring high power, the battery takes over to power the aircraft’s

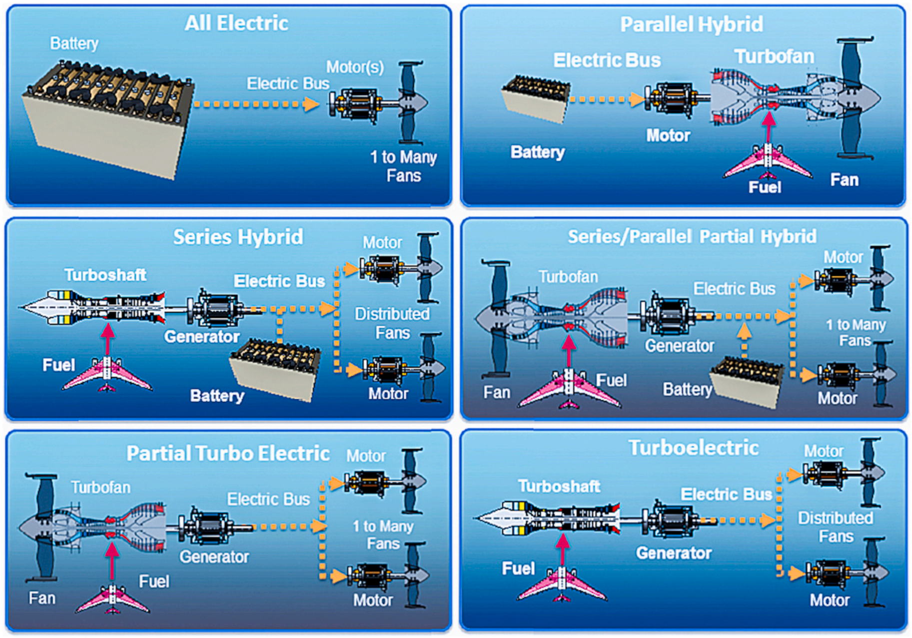

Fig. 8. NASA's representative powertrain architectures for electric aircraft (Adapted from Ref. [75]).

propulsion system; therefore, the hybrid system offers higher efficiency. Ji et al. [175] describe the great potential of fuel cells in aviation, as high-temperature solid oxide fuel cells (SOFCs), when integrated with gas turbines, achieve a thermal efficiency of approximately 52.8 %. Sharaf and Orhan [70] show that fuel cells, especially PEMFC and SOFC, offer nearly zero emissions when using hydrogen as an alternative fuel, demonstrating efficient performance with the potential to reach up to 70 % without compromising the propulsion system.

Seyam et al. [176] analyzed a hybrid propulsion system for aircraft, integrating a commercial turbofan based on the Rolls-Royce Trent 1000 with a solid oxide fuel cell (SOFC). Using energy and exergy methods, they thermodynamically evaluated the system's performance and explored alternative fuels such as hydrogen, methane, methanol, ethanol, and dimethyl ether. The results indicated that a mixture of 75 % methanol and 25 % hydrogen showed the highest thermal efficiency (48.1 %) and exergetic efficiency (54.4 %). In comparison, the combination of 60 % ethanol and 40 % hydrogen reduced carbon emissions by 73 %, with efficiencies of 46 % and 56 %, respectively. They also showed that adding hydrogen improved flame stability and reduced ignition delay. The SOFC system included steam reforming and the water-gas shift (WGS) reaction, which were modeled in Aspen Plus software and validated through error analysis. The research highlights that combining turbofans, SOFCs, and alternative fuels is a promising approach to increasing efficiency and reducing carbon emissions in aviation.

Seyam et al. [177] analyzed two hybrid propulsion and power generation systems for aircraft, combining three-axis turbofans with solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC). The energy and exergetic evaluation during cruise flight revealed that the SOFC-GT hybrid system achieved a thermal efficiency of 52.8 % and an exergetic efficiency of 66.2 %. In comparison, the MCFC-GT achieved 71 % and 87.6 %, respectively. In addition, using a mixture of 75 % methane and 25 % hydrogen significantly reduced carbon emissions. Ji et al. [91] investigated the performance of a hybrid jet engine equipped with a SOFC in different operating modes, adjusting the fuel and airflow for thrust variations between 50 % and 100 %. The comparative analysis identified the most efficient and safest mode for part-load operation.

Kierbel et al. [178] present the HYLENA project (Hydrogen Electrical Engine Novel Architecture), funded by the European Climate, Infrastructure and Environment Executive Agency (CINEA). This project aims to develop an electric propulsion system for aircraft utilizing an innovative combination of solid oxide fuel cells (SOFCs), a gas turbine (GT), and an electric motor, which can be illustrated in Fig. 9. The objective is to significantly enhance efficiency and reduce emissions by leveraging the integration of these components to optimize the Brayton cycle. There are other projects with a similar goal [179].

The project seeks to develop and demonstrate the feasibility of an advanced propulsion system for short- and medium-range aircraft, combining an electric motor and an SOFC-GT configuration powered by liquid hydrogen (LH_2). The proposed study aims to advance the concept from a low Technology Readiness Level (TRL) to TRL 3 by mid-2027. This disruptive propulsion system is designed to assess and validate the feasibility of a 'revolutionary' engine concept, integrating SOFC-GT technology to harness both the thermal energy generated by the fuel cells and their electrical output. The project combines high-temperature SOFCs with gas turbines and electric motors, providing a more efficient and sustainable solution for the future of aviation, because it differs from conventional systems that utilize low-temperature fuel cells, such as the Proton Exchange Membrane (PEM) type, or traditional gas turbines [180].

The Hydrogen Hybrid Power for Aviation Sustainable Systems (Hy2PASS) project is a NASA initiative to develop more efficient and sustainable aircraft propulsion systems. The project combines hydrogen

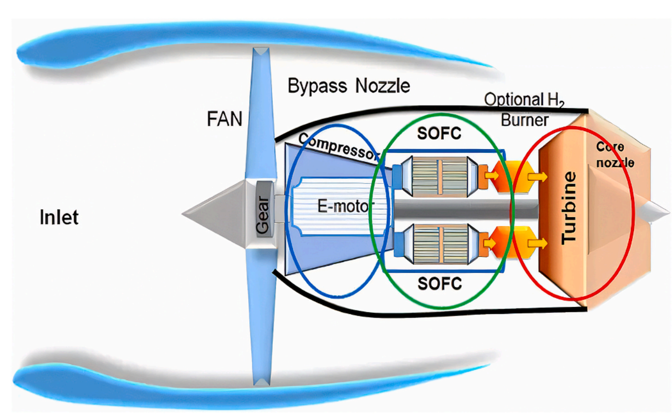

Fig. 9. HYLENA concept engine (Reproduced from Ref. [178]).

fuel cells and gas turbines, and proposes hybridization through air treatment instead of combining electrical or mechanical energy in conventional ways, i.e., combining mechanical energy between a fuel cell-driven engine coupled to the turbine shaft. This proposed architecture, as shown in Fig. 10, uses the fuel cell to power an electric compressor that supplies oxygen to the fuel cell (cathode) and the gas turbine burner, eliminating the need for compressor stages in the heat engine and allowing the compressor to operate independently of the turbine phases. This feature allows the compressor to operate at variable overall pressure rates. This hybridization architecture, which mechanically decouples the compressor from the turbine in a fuel cell/gas turbine system, aims to reduce energy consumption and eliminate direct emissions significantly [104].

Many studies demonstrate the feasibility of using hybrid configurations with solid oxide fuel cells. However, several challenges must be overcome, such as fuel safety when using hydrogen and the aerospace sector's reliability of SOFC hybrid systems. On the other hand, although this technology may present some significant disadvantages, with advances in scientific research, it can become an essential aircraft solution [73].

To summarize the achievements of hybrid propulsion research, we include Table 5 below, focusing on the area of activity as well as the main reductions of energy use and CO_2 emissions.

Table 5
Overview of output from research on hybrid propulsion.

Authors	Topic	Outcome
Sharaf and Orhan [70]	PEMFC & SOFC fuel cells	Up to 70 % efficiency with H_2, nearly zero CO_2 emissions.
Fernandes et al. [73]	SOFC-APU hybrids	Show significant efficiency potential and emission reductions (no quantified values).
Ji et al. [98, 175]	Battery/fuel cell/jet engine and SOFC-based hybrids	Improve efficiency (up to ≈ 52.8 %) and reduce fuel use.
Hoenicke et al. [101]	Fuel cell + battery hybrids	Gain efficiency from optimized load-sharing (emissions not quantified).
NASA [104]	Fuel cell combined GT output to shaft	Reduces energy consumption via a decoupled compressor–turbine design, with significant emission reductions.
Seyam et al. [176,177]	SOFC/MCFC-turbofan hybrids	achieve 48–71 % thermal efficiency, 66–87 % exergetic efficiency, and up to 73 % CO_2 reduction (ethanol/H_2 mix).
Kierbel et al. [178]	SOFC + GT + electric motor, LH_2	Targets substantial efficiency and emission reductions.

8. Multifuels

The gradual transition to sustainable aviation fuels, combining hydrogen and Sustainable Aviation Fuel (SAF), is widely recognized as a promising strategy for decarbonizing the aviation sector by 2050 [3, 181]. The European Union has adopted progressive targets for incorporating SAF into aviation fuel: 2 % in 2025, 6 % in 2030, 20 % in 2035, and 70 % in 2050. In addition, there are specific targets for synthetic fuels (produced from hydrogen), such as 1.2 % in 2030 and 5 % in 2035 [182]. Together with the development of dual fuel combustors, multi-fuel aircraft provide a path towards transitioning to sustainable energy sources. The argument is again that such aircraft may provide flexibility to operate between different geographic regions for which the availability of hydrogen and sustainable aviation fuel varies. In addition, some considerations can be made to optimize a new aircraft structure to be better adapted to hydrogen, allowing the tank placement and sizing to be adapted to the characteristics of hydrogen fuel versus sustainable aviation fuel [29].

In recent years, interest has grown in flexible jet fuel operations using multifuel concepts, such as kerosene/SAF and H_2. This trend is notable in literature, with many studies exploring this theme [55,60,183,184]. Some criteria are essential for selecting aviation fuel, such as specific and volumetric energy density, cost of the energy source, availability of the energy source, infrastructure, and sustainability, among others [63].

Energy density is an important criterion in aviation due to the need to reduce weight and volume. Fuels such as Jet-A and synthetic kerosene have good energy and volumetric densities and are suitable for the sector, although biokerosenes face cost and availability limitations. On the other hand, liquid hydrogen has a high specific energy density but low volumetric density, requiring larger tanks, although it weighs less than kerosene for the same energy supplied [29,30]. Additionally, using LH_2 in aviation has other challenges, such as safety, logistics, and infrastructure [62].

The European project HOPE (Hydrogen Optimized multi-fuel Propulsion system for clean and silEnt aircraft) aims to develop an integrated aeronautical propulsion system that combines two ultra-high bypass ratio (UHBR) turbofan engines capable of operating on multiple fuels, including kerosene, sustainable aviation fuels (SAF), and

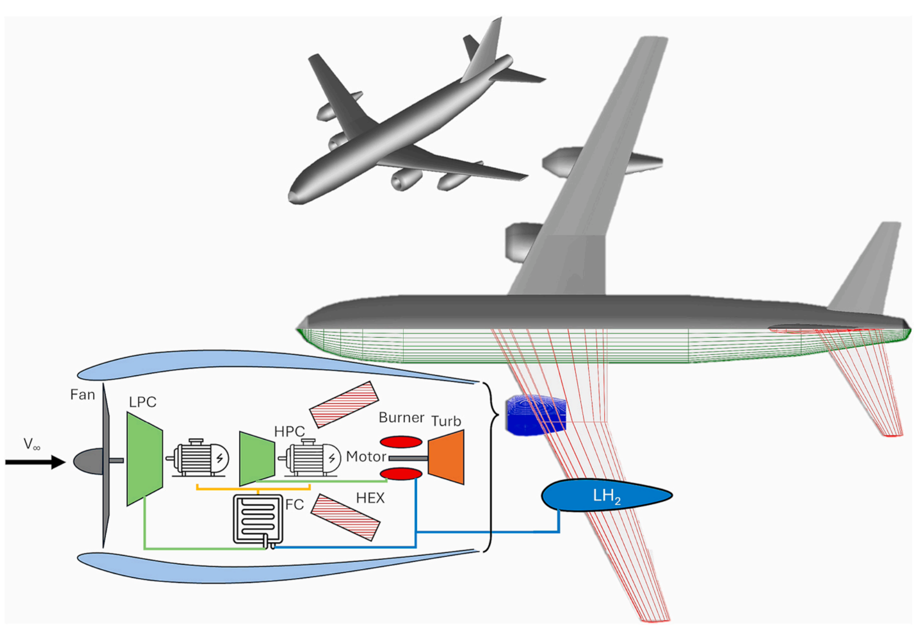

Fig. 10. The approach Hydrogen Hybrid Power for Aviation Sustainable Systems (Hy2PASS) (Reproduced from Ref. [104]).

hydrogen; a fuel cell-based auxiliary power and propulsion unit (FC-APPU), and a rear boundary layer ingestion (BLI) thruster in a tube-and-wing aircraft configuration [185,186]. Among its main objectives are a 50 % reduction in NO_x and CO emissions, an 80 % reduction in soot, and a 20 % reduction in perceived noise during the take-off and landing phases compared to 2020 technologies, such as the A320neo. It also aims to facilitate the energy transition in aviation by evaluating and exploring various sustainable propulsion technologies at different maturity levels. Alexandrou and Khatiwada [187] carried out a case study in France to illustrate strategies for decarbonizing the aviation sector. They focused on analyzing hydrogen supply chains. They also pointed out that implementing supply systems for liquid hydrogen and SAF requires significant investments in airport infrastructure.

Palanti et al. [43] performed Computational Fluid Dynamics (CFD) simulations to examine three kerosene injection strategies in a kerosene/hydrogen multi-fuel atmospheric burner, aiming to support the transition to hydrogen in aviation. The results indicate that backplane injection (INJ-1) leads to high NO_x emissions due to poor mixing and hot spots. In contrast, the mixing tube configuration (INJ-2) was not considered viable under current operating conditions. The INJ-3 configuration, with on-shaft injection, showed better mixing and lower NO_x emissions. Thus, it was concluded that INJ-3 is the most promising concept for reducing pollution, but flashback resistance and mechanical feasibility require further experimental validation.

The energy transition in aviation, using combinations of sustainable fuels with the direct replacement of fossil fuels in existing aircraft, drop-in fuels, and hydrogen through fuel cells or direct combustion, represents a strategy to decarbonize the aviation sector by 2050. The multi-fuel approach allows for a gradual transition of the technologies and infrastructures involved, facilitating the integration of new energy solutions [46,188,189].

9. Non-CO_2 emissions

From a climate perspective, the three most important emission species for Jet-A combustion-based commercial aircraft are CO_2, NO_x, and water. For the year 2018, Lee et al. [2] estimate that the corresponding effective radiative forcing from CO_2 is 34 %, from NO_x it is 17.3 % whereas for contrails and cirrus it is as much as 56.9 %. Considering that emissions of water increase by 2.6 times for the same amount of heat release [152,153] as for Jet-A, the risk of increased climate warming from hydrogen combustion aircraft seems imminent, despite the fact that no in-flight CO_2 emissions occur. However, as will be explained in this section, a number of physical phenomena combine to produce the opposite effect. Thus, a substantial decrease in effective radiative forcing should be expected for hydrogen combustion-based aviation even if only the water emission and its cloud formation are considered. It should be stressed that, when comparing hydrogen aircraft concepts with other alternative fuels, the entire chain from well to wake should be considered [190]. Herein, we focus primarily on the abatement of emissions related to the propulsion system and simply acknowledge that the full picture of the environmental impact of hydrogen aviation is substantially more complex.

The fundamental understanding of the concept of contrails formation was provided by Schmidt and Appleman [191,192]. Their work establishes a mixing line that predicts successive mixing and thus drying and cooling as the jet engine exhaust gases mix with the surrounding atmosphere. By comparing this mixing line with the local saturation conditions above ice and water, a condition for contrails formation can be established. In Fig. 11 below, the basic process is depicted. The analysis uses a simple estimate for the cruise performance of the PW1100G engine as an input [193].

The basic argument in play for Fig. 11 is that the exhaust from a turbofan is very hot and very humid. Due to the high temperature, there is initially no risk of condensation, freezing, and contrails formation. However, as the exhaust air is diluted by mixing with the ambient air,

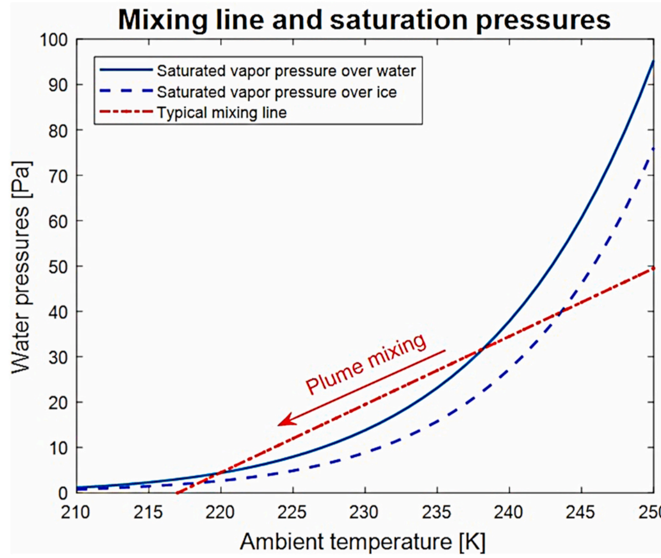

Fig. 11. Simple mixing case for PW1100G engine exhaust at 35,000 ft altitude and M = 0.78. The ambient humidity is 0 % and ISA atmosphere is assumed [193].

the plume gets colder and drier. Schmidt and Appleman [191,192] showed that the rate at which the air gets drier in relation to the ambient conditions can be quantified by a simple linear curve as indicated in Fig. 11. If the mixing passes the saturated humidity line, water forms by condensation and ice crystals then start to freeze out. If the ambient air is humid enough, the line will not continue and pass through the saturation over the ice line. Then, the contrails are persistent. In Fig. 11, we assumed 0 % ambient humidity which then would lead to the vaporization of the linear contrails and thus non-persistent contrails.

It is well known that linear contrails can spread from their initial linear shape into cirrus clouds [194]. Furthermore, the warming from the cirrus clouds may be approximately an order of magnitude higher than for the linearly shaped cloud [195]. Fortunately, several positive aspects of contrails formation in association with hydrogen combustion seem to be present. Firstly, hydrogen is a clean fuel, allowing the formation of combustion soot particles to be eliminated. Soot particles provide a key mechanism for contrails formation in the combustion of conventional fuels [33,196]. The key mechanisms are represented in Fig. 12 [33]. The absence of soot particles reduces the expected numbers of ice-particles substantially. Likewise, the absence of sulfur/organic species inhibits the formation of large numbers of particles formed by competing mechanisms occurring substantially below the threshold temperature for contrails conditions (blue line). The remaining mechanism by which contrails are then expected to form for hydrogen combustion propulsion is then limited to formation through background aerosols [34] and through lubricant oil droplets that act as condensation nuclei [35]. The paper states that in the range of 2–12 mg of oil emissions could be expected per kg of jet fuel. Thus, there has only been a modest commercial need to reduce oil loss further, and it would be likely that this emission could be reduced substantially if it is proven that a major part of the contrails arises from its emissions. If oil related contrails formation nuclei can be removed or reduced to low numbers, an 80–90 % reduction in contrails ice particles could be possible [34], indicating a substantial advantage over sustainable aviation fuel combustion, making a strong case for the development of future hydrogen aircraft.

Due to the inherently higher flame temperature that occurs from hydrogen combustion as compared to Jet-A, the introduction of hydrogen combustion should increase the NO_x emissions substantially. However, we have already discussed several lean burn technologies which are particularly suitable for hydrogen combustion and promise to

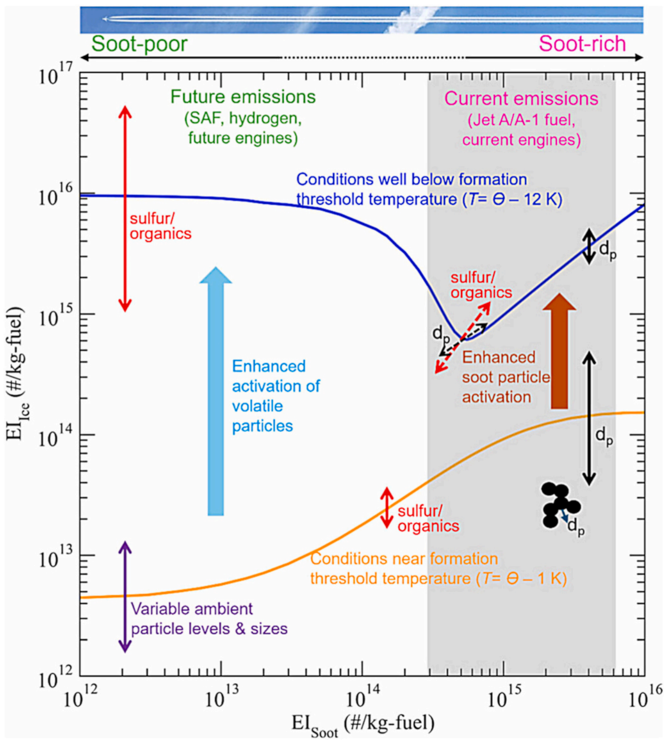

Fig. 12. Emission index of ice (EI_{ICE}) and its dependence on atmospheric temperature, number of particles, size, and contrails formation mechanisms (Reproduced from Ref. [33]).

reduce NO_x. Historically, the jet engine industry has also been hugely successful in developing new combustion technology that has allowed them to keep NO_x emissions down [40].

Fuel cells and contrails are relatively uncharted territory. Although [80,197] argue that the use of fuel cells will likely increase contrails emissions due to colder exhaust temperatures and larger water emissions than those for combustion engines, a number of factors contributing to inhibiting contrails can be observed. Firstly, fuel cells are in the foreseeable future expected to be used primarily for turboprops that fly at considerably lower altitudes and hence higher ambient temperatures. Also, the emissions of oil should be down to virtually no emissions, leaving only ambient aerosols as the option for nucleation sites. This should further reduce the contrails problem arising from using fuel cells.

Hydrogen is a relatively potent greenhouse gas with an estimated GWP100 of 11.6 ± 2.8 [198]. Hence, for hydrogen aviation to become successful, it is very important to minimize the leakage of hydrogen from its production, transportation, and use [199]. The amount of leakage from hydrogen use is estimated to be in the range from 1 % up to 10 %, but we view the higher end of this range as unlikely considering the increased costs associated with such a hydrogen loss [200]. Anyhow, the future leakage rates of a future hydrogen economy are quite uncertain, and they contribute to increasing the risk of committing resources to hydrogen projects.

10. Technology pathways and the introduction of hydrogen aviation

As already argued, hydrogen-powered aircraft have generated significant interest over the years and promise to remove in-flight CO_2 emissions. Still, only a few successful flights have taken place, and hydrogen aircraft are still to be used regularly by commercial operators. The lack of commercial experience with hydrogen aviation makes it very difficult to predict the future of hydrogen aviation with any certainty. Still, it is possible to outline some pathways for its introduction, and in a wider discussion, it can serve to highlight both the limitations and opportunities that critical technology may bring to hydrogen aviation.

The emergence of hydrogen-powered aviation is dependent on the broader progress of the global energy transition. In this context, the availability of low-cost green hydrogen is a fundamental prerequisite. In 2022, global hydrogen demand was 95 million tons, but only 1 million ton originated from low-emission hydrogen [27]. Although electrolyzer manufacturing capacity could reach 155 GW/year in 2030, only 8 % had started in 2022. At the end of 2023, the global installed capacity of electrolyzer-based hydrogen production was 1.4 GW [201]. In light of this relatively slow introduction of green hydrogen, the Airbus reprioritization of their original ZEROe efforts, focusing on fuel cell driveline configurations [130], reflects a slowing down from previous predictions. Another argument that hydrogen will first be introduced at the lower power end spectrum, apart from the limited availability of green hydrogen, is that shorter-range aircraft are generally propelled by lower in efficiency turboprops with efficiencies in the order of 30 % or lower [136–138]. As indicated in Fig. 1 fuel cell aircraft then have a clear advantage in total efficiency.

Another option for hydrogen use is to employ it as a component for producing e-fuels [202], avoiding major investment in airport infrastructure as well as the design and production of new aircraft. Future fuel selling price for electro jet fuel and electrolysis-based liquid hydrogen are very uncertain, often, estimates vary by a factor of 3 from lower to higher-end price estimates [203] with e-fuels usually indicated as higher cost than cryogenic hydrogen, but with a large uncertainty driven, among other things by future electricity price [203] and the cost for emitting CO_2 [204].

Assuming abundant hydrogen availability, and purely looking at the limitations of technology, multiple aircraft architectures and driveline configurations may emerge, each adapted for its individual range requirement. Fig. 13 illustrates a scenario for the introduction of hydrogen aircraft, taking a conservative perspective on range [135]. The lowest range segment using hydrogen aircraft would be operated using fuel cell aircraft [80,125,126], indicating a maximum range somewhat short of 2000 km. An example of a conceptual design for such an aircraft has been illustrated in Fig. 2d [135]. Development of high-temperature fuel cells could enable heavier, longer-range fuel cell aircraft. Although quite feasible, no hybrid propulsion system is anticipated in the scenario represented by Fig. 13. Combustion-based hydrogen is indicated in the range of 2000–4000 km, although substantially longer ranges can be achieved if tank gravimetric efficiency becomes high enough, indicating a feasible range of close to 14,000 km [14,23]. Stettler et al. [23] exploit the synergy between a blended wing body fuselage and the integration of a low surface-to-volume tank, making the studied aircraft even more efficient.

Prerequisites for the shorter-range fuel cell aircraft to emerge include

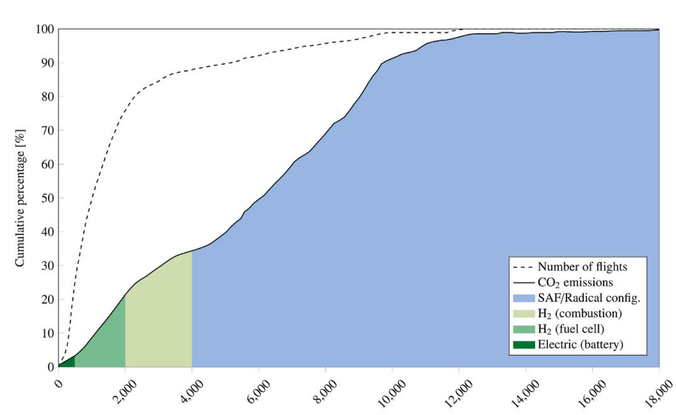

Fig. 13. Potential division of range between hydrogen aircraft types (Reproduced from Ref. [135]).

the development of materials and procedures that avoid the emissions of PFAS into nature. For the longer-range hydrogen combustion alternative, a low total global warming emission will be expected. The potential advantage of hydrogen against sustainable aviation fuels, as discussed herein, may serve as an enabler for future hydrogen propulsion. For hydrogen-based aviation use to develop at all, the demonstration of a complete design with a very low level of hydrogen leakage needs to be demonstrated.

11. Conclusions

The present work aimed to conduct a literature review on hydrogen use for sustainable aviation and aircraft propulsion systems.

The two main hydrogen propulsion technologies being researched for aviation today are direct combustion in gas turbines and hydrogen fuel cells to generate electricity and drive electric motors. Hydrogen combustion in gas turbines takes advantage of existing infrastructure and knowledge in aeronautical propulsion. It mainly requires some modifications to the fuel delivery and conditioning system, as well as a new combustor to deal with the different combustion characteristics of hydrogen, such as its higher flame speed and tendency to flashback. This requires the development of technologies such as LDI and micro-mix to reduce NO_x emissions.

On the other hand, for the 1–3 MW power class, fuel cells offer high efficiency and have only water vapor as a by-product, making them suitable for smaller, regional aircraft due to specific power and thermal management limitations, especially in PEMFC cells. PEMFC and SOFC cells are the most widely considered types for aeronautical applications, each with advantages and challenges regarding operating temperature, start-up time, and system requirements. Although PEMFC shows a great advantage in operational flexibility over SOFCs, they are hampered by low heat rejection capability and low operating temperatures, facing the risk of bulky and heavy installations. Multiple solutions to increase operating temperature are now being explored, and this is likely to improve, although the use of Perfluorosulfonic Acid (PFSA) polymers and the risk of PFAS emissions may set back development for a substantial time. The need to replace these membranes with hydrocarbon-based membranes may provide an alternative path, but the maturity and experience developing PEM around these materials are much less widespread.

Hybrid propulsion systems, combining gas turbines and electric systems powered by batteries or fuel cells, represent a transitional approach to reducing fuel consumption and emissions, especially in regional aircraft with short and medium ranges. Various hybrid configurations, such as parallel, series, and series/parallel, are being explored to optimize performance in different phases of flight. Fuel cell hybridization allows for more integrated and efficient architectures than conventional gas turbine propulsion.

Both the use of flexible combustion concepts and the design of multifuel aircraft can help to mitigate the challenge of the availability of a hydrogen infrastructure. These concepts simply introduce a variability that allows managing the geographical variation in the abundance of hydrogen. As hydrogen economies emerge, they are likely to develop quite differently in different markets, whereas new aircraft need to be economically feasible globally and, hence, need to manage the varying availability of hydrogen as a fuel.

The aeronautics and aerospace sector has shown a growing interest in hydrogen-powered aircraft, with various projects and flight tests, from the first hydrogen balloon in 1783 to recent prototypes of regional aircraft and UAVs. Companies like Airbus, Embraer, Universal Hydrogen, and ZeroAvia actively develop hydrogen aircraft concepts, exploring different configurations and propulsion technologies to introduce zero-emission commercial aircraft by 2035–2050. Projects such as HYLENA and Hy2PASS demonstrate innovative approaches to integrating fuel cells and gas turbines into more efficient hybrid propulsion systems. Despite hydrogen's great potential for sustainable aviation, challenges include efficiently storing gaseous or liquid hydrogen in optimal tank configurations, developing optimized engines and fuel systems, ensuring operational safety, and reducing production and infrastructure costs. However, continued advances in research and development, together with growing public and private investment, indicate that hydrogen-powered aircraft will play a crucial role in decarbonizing the aviation sector in the future and in contribute to mitigating the effects of climate change.

CRediT authorship contribution statement

Antonio Bruno de Vasconcelos Leitão: Writing – original draft, Investigation, Conceptualization. **Cleverson Bringhenti:** Writing – review & editing, Visualization, Supervision. **Jesuino Takachi Tomita:** Writing – review & editing, Visualization. **Franco Jefferds dos Santos Silva:** Visualization. **Carlos Xisto:** Writing – review & editing, Visualization. **Tomas Grönstedt:** Writing – review & editing, Visualization, Supervision, Conceptualization.

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Nomenclature

CO	Carbon Monoxide
CO_2	Carbon Dioxide
GH_2	Gaseous Hydrogen
LH_2	Liquid Hydrogen
H+	Proton Hydrogen
H_2	Hydrogen
H_2O	Water
NH_3	Ammonia
NO_x	Nitrogen Oxides
O_2	Oxygen
Abbreviations	
AIAA	American Institute of Aeronautics and Astronautics
APU	Auxiliary Power Unit
BLI	Boundary Layer Ingestion
BOP	Balance of Plant
BWB	Blended Wing Body
CAES	Cranfield Aerospace Solutions
CFD	Computational Fluid Dynamics
CINEA	European Climate, Infrastructure and Environment Executive Agency
DC	Direct Current
DLE	Dry Low Emissions
DLN	Dry Low NO_x
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DOE	Department of Energy
EECS	Electrical Environmental Control System
EEICE	Emission Index of Ice
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
FC	Fuel Cell
FC-APPU	Fuel Cell-based Auxiliary Power and Propulsion Unit
GE	General Electric
GMD	Gas Management System
GWP	Global Warming Potential
HHV	Higher Heating Value
HOPE	Hydrogen Optimized multi-fuel Propulsion system for clean and silEnt aircraft
HT-PEMFC	High Temperature Proton Exchange Membrane Fuel Cells
HY2PASS	Hydrogen Hybrid Power for Aviation Sustainable Systems
HYLENA	Hydrogen Electrical Engine Novel Architecture
HYSIITE	Hydrogen Steam-Injected, Intercooled Turbine Engine
ICAO	International Civil Aviation Organization
IT-PEMFC	Intermediate Temperature Proton Exchange Membrane Fuel Cells
KHI	Kawasaki Heavy Industries
LDI	Lean Direct Injection
LH2BB	Liquid Hydrogen Bread Board
LHV	Lower Heating Value

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LPT	Low Pressure Turbine
LT-PEMFC	Low Temperature Proton Exchange Membrane Fuel Cells
MCFC	Molten Carbonate Fuel Cell
MMX	Micromix
MSFC	Marshall Space Flight Center
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NMI	Nautical Mile
PAX	Passenger
PBI	Phosphoric Acid-doped Polybenzimidazole
PCS	Power Conditioning System
PFAS	Per and Polyfluoroalkyl Substances
PMAD	Power Management and Distribution
RAT	Ram Air Turbine
REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
SAF	Sustainable Aviation Fuel
SOFC	Solid Oxide Fuel Cell
SOFC-GT	Solid Oxide Fuel Cell Gas Turbine
TMS	Thermal Management System
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
UHBR	Ultra-High Bypass Ratio
UHS	Underground Hydrogen Storage
WGS	Water-Gas Shift
WMS	Water Management System

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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