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A review of liquid hydrogen aircraft and propulsion technologies

Saurav Tiwari, Michael J. Pekris *, John J. Doherty

Department of Mechanical Engineering Sciences, University of Surrey, Guildford, GU2 7XH, United Kingdom

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ABSTRACT

Sustainable aviation is a key part of achieving Net Zero by 2050, and is arguably one of the most challenging sectors to decarbonise. Hydrogen has gained unprecedented attention as a future fuel for aviation, for use within fuel cell or hydrogen gas turbine propulsion systems. This paper presents a survey of the literature and industrial projects on hydrogen aircraft and associated enabling technologies. The current and predicted technology capabilities are analysed to identify important trends and to assess the feasibility of hydrogen propulsion. Several key enabling technologies are discussed in detail and gaps in knowledge are identified. It is evident that hydrogen propelled aircraft are technologically viable by 2050. However, convergence of a number of critical factors is required, namely: the extent of industrial collaboration, the understanding of environmental science and contrails, green hydrogen production and its availability at the point of use, and the safety and certification of the aircraft and supporting infrastructure.

1. Introduction

The awareness of a sustainable/green economy and long-term energy security has given rise to substantial global momentum in the search for alternative energy sources. The carbon-free nature of green hydrogen production and use, and the versatility of both hydrogen production sources, as well as its end-use applications, have resulted in an unprecedented focus on hydrogen. In 2022, 26 countries have set national hydrogen strategies which forecast 145–190 GW total green hydrogen production capacity by 2030 [1]. The proliferation of hydrogen is evident in transportation [2], the energy sector [3] (including power generation and domestic applications), and high-power industrial applications (such as steel production and oil refining) with an opportunity for complete fossil fuel replacement.

For aviation, shifting to alternative energy sources is required to meet the net zero targets, and in order to avoid becoming the dominant CO_2 producer in future decades. The global aviation industry accounts for approximately 12 % of transport sector carbon dioxide (CO_2) emissions [4]. The continual improvement of technology and operational capabilities has led to a cumulative fleet fuel efficiency improvement of 54 % since 1990 and this trend is expected to continue [5]. A yearly passenger traffic growth of 3.6–3.8 % has been forecast between 2022 and 2024 by Airbus [6] and Boeing [7]. 'Clean Sky 2' and 'Fuel Cell and Hydrogen 2' joint undertakings, public-private partnerships initiated by the European Commission, performed a study to forecast how various scenarios impact net CO_2 emission of the aviation industry whose result is displayed in Fig. 1 [8]. CO_2 emissions are expected to double by 2050 even with an optimistic 2 % fuel efficiency improvement per annum. The results show that the adoption of both sustainable aviation fuel (SAF), by 2025, and a revolutionary green fuel, by 2030, is required to achieve the net-zero target.

A series of feasibility studies conducted in recent years (FlyZero [9], ENABLE-H2 [10], CHEETA [11], and others) have identified green hydrogen as a crucial step to bridge the decarbonisation gap for aviation, if not to become the future aviation fuel itself. Hydrogen can either be directly combusted in a gas turbine to generate thrust, or can be used in a gas turbine generator or within a fuel cell system to produce electricity and drive an electric propulsion powertrain. Its energy content is 2.8 times higher than kerosene allowing a corresponding reduction in the amount of fuel per mission [12]. However, hydrogen is four times less dense even when stored cryogenically in liquid form, requiring approximately four times larger storage volume than kerosene. Cryogenic storage is preferred for aerospace due to its lower storage pressure and higher density, hence the ability to carry a higher total mass of fuel on board [9]. The cryogenic conditions add design and integration

* Corresponding author.
E-mail addresses: st00913@surrey.ac.uk (S. Tiwari), m.pekris@surrey.ac.uk (M.J. Pekris), john.doherty@surrey.ac.uk (J.J. Doherty).

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Acronyms

BLI	Boundary Layer Ingestion
BWB	Blended Wing Body
CTE	Coefficient of Thermal Expansion
CTW	Conventional Tube and Wing
DOC	Direct Operating Cost
DP	Distributed Propulsion
DLR	German Aerospace Centre
EAS	Electrical Architecture System
EIS	Entry into Service
GH2	Gaseous Hydrogen
HEX	Heat Exchanger
LH2	Liquid Hydrogen
MLI	Multi-Layer Insulation
MTOW	Maximum Take-Off Mass
NMI	Nautical Miles
OEW	Operating Empty Weight
PAX	Passenger Capacity
PEMFC	Proton Exchange Membrane Fuel Cell
PMAD	Power Management and Distribution system
SAF	Sustainable Aviation Fuel
SFC	Specific Fuel Consumption
SOA	State of the Art
SOFC	Solid-Oxide Fuel Cell
TRL	Technology Readiness Level

complexity in storage, distribution, and fuel conditioning, but also create an opportunity to integrate this into the aircraft thermal management system achieving aircraft-level fuel burn benefits. Using hydrogen requires significant adaptation of the aircraft systems but offers carbon-free emission.

The idea of using hydrogen as a fuel in aviation is not a new concept and has been around for almost a century. Despite this, significant supply chain and technical challenges remain with the use of hydrogen as an aviation fuel, and uncertainties in the realisable benefits. Several reviews of hydrogen related technologies for aviation, and the challenges of using hydrogen, have previously been published. Haglind et al. [13] presented some environmental benefits of hydrogen combustion along with historical milestones in hydrogen aircraft development. Khandelwal et al. [14] further presented combustor designs for low emissions as well as requirements of cryogenic storage configuration and design. Cecere et al. [15] reviewed hydrogen uses in the whole aerospace sector including turbojet, ramjet, scramjet and rocket engines. Baroutaji et al. [16] reviewed the use of hydrogen fuel cell technology in aircraft auxiliary power units, ground support vehicles, unmanned air vehicles and space applications.

This study offers a critical comparison of the literature and prior work, and gives insight into the existing State of the Art (SOA) and future technology developments needed to achieve net zero by 2050. Hence, a comprehensive review of hydrogen aircraft and associated enabling technologies is presented based on the progress made over the last 50 years with a critical appraisal of previously published findings. The aim is to provide a holistic system-level view of hydrogen fuel cell as well as hydrogen combustion aircraft feasibility taking into account academic, industrial and market views of aviation research and development.

Section 2 briefly presents the future aviation energy landscape highlighting the case for hydrogen. Section 3 provides a brief historical overview of hydrogen aircraft technology development, followed by a summary of more recent initiatives. Section 4 describes potential aircraft configurations accommodating hydrogen. Sections 5, 6, and 7, analyse current research, technological status and future projections of the cryogenic fuel system, hydrogen gas turbine and fuel cell system respectively. Section 8 provides a brief review of safety and certification. Section 9 discusses the likely phases of hydrogen introduction in aviation. Note that green hydrogen production and distribution, novel airport infrastructure, and operational requirements are also vital for hydrogen aircraft commercialisation [17–20], but are outside of the

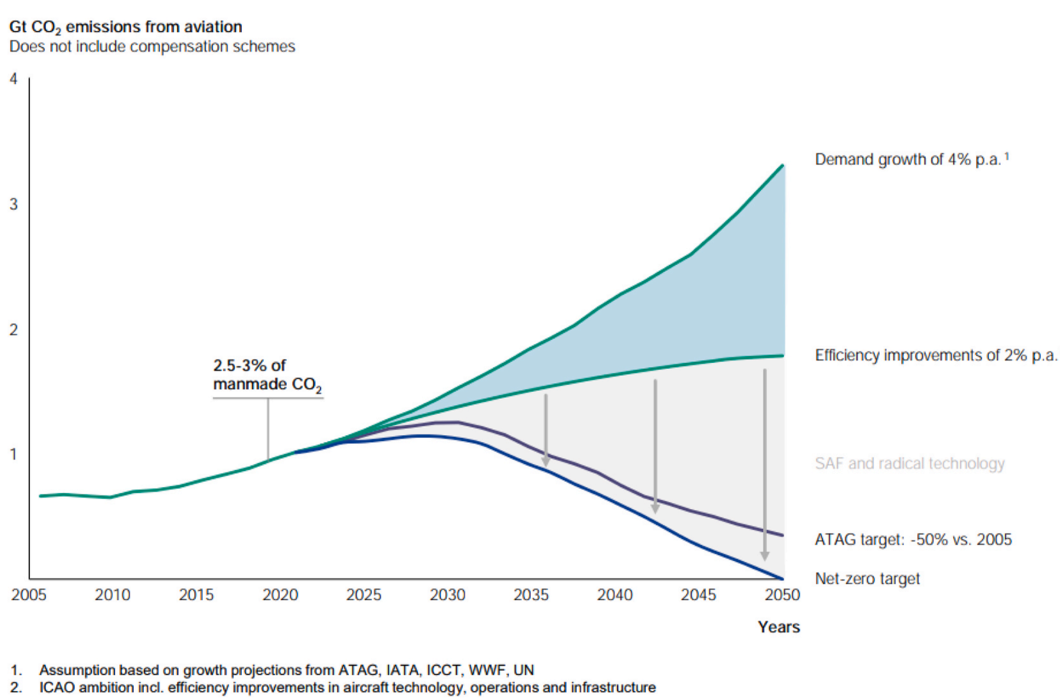

Fig. 1. Emission projection of the aviation industry [8].

scope of this study.

2. Future aviation energy mix: the case for hydrogen

Several concurrent decarbonisation strategies are required in the journey to net-zero by 2050, such as hybrid and full electrification for regional travel, the deployment of SAF and hydrogen solutions for medium and long-range aircraft missions, and carbon capture and storage. FlyZero investigated several potential alternative fuels to realise zero-carbon commercial aviation by 2030. Fig. 2 [21] presents the impact on design mission capability with the use of different fuels (indicating the proportion of fuel and storage system mass relative to aircraft mass). Considering the option of full electrification, a battery pack-specific energy of at least 800 Wh/kg is required for single-aisle size aircraft viability [22], while even the most optimistic projections forecast that this will reach 500 Wh/kg by 2030 [23]. Therefore, battery-powered aircraft would only be viable up to the sub-regional scale by 2035 [21, 24,25,26].

Hydrogen, if stored cryogenically in liquid form, could allow potential improvements in mission capability compared to kerosene at an expense of complexity in the design, integration and construction of fuel storage, distribution, and fuel conditioning systems. The use of liquid ammonia enables less complex fuel storage systems and high volumetric density, but its 6.7 times lower specific energy compared to hydrogen would cause severe limitations in aircraft-level mission and performance capabilities (See Fig. 2 [21]). Furthermore, alternative fuels such as liquid natural gas, methanol, ethanol and others have been investigated previously but none would provide a competitive advantage as liquid hydrogen in terms of aircraft-level performance as well as emissions [27, 28]. Liquid hydrogen and SAF (with capabilities equivalent to kerosene) seem more appealing options to bridge net-zero gaps for short to long-haul missions in the long term.

SAF is a fuel manufactured from sustainable feedstock and has comparable properties to kerosene requiring only minimal modification in the aircraft/engine (in contrast to hydrogen). It has the potential to reduce lifecycle CO_2 emission by up to 70 % depending on the feedstock [29] whereas hydrogen offers carbon-free emission at the cost of significant aircraft system adaptions. The EU has set targets to use up to 5 % SAF blend by 2030, 32 % by 2040 and 63 % by 2050 [30]. The current main feedstock of SAF includes oil from the biological origin and agriculture residue. A forecast shows that due to the complex supply chain, the feedstock supply capacity will be limited to only 20 % of what would be required to power the 2040 global aircraft fleet [31]. Synthetically produced hydrocarbon fuels (called Power to liquid SAF or synfuel), with carbon captured from the air and renewably produced hydrogen (H_2) as feedstocks, have the potential to meet aviation demand [31].

The emissions and the fuel price are the main drivers of fuel choices. Emissions include far more than just the CO_2. According to the German Aerospace Centre (DLR), the contrails cirrus cloud formation, nitrous oxides (NO_x) and soot emissions at altitude are far more damaging with almost twice the effect for global warming compared to CO_2 emissions [32]. Hydrogen combustion offers 50 %–70 % lower nitrogen oxides NO_x compared to kerosene/SAF fuelled gas turbines whereas the use of fuel cells offers zero NO_x [8]. Initial studies show that synfuel has fewer aromatics causing less soot formation during combustion changing the properties of the contrail, hence 10–40 % lower contrail formation. However, using hydrogen, water emission is 2.6 times more compared to kerosene/SAF but with no soot at all. The preliminary models show that direct H_2 combustion forms heavier ice crystals that precipitate faster which means contrails are optically thinner. This leads to a briefer radiative forcing effect (defined as *incoming energy – outgoing energy*), hence a 30–50 % reduction in contrails global warming impact compared to kerosene [8]. If a fuel cell is used, the exhaust water vapour can be conditioned depending on the atmospheric state to avoid contrails. Contrails are still a topic of huge uncertainty among the research community, so further research is required to conclude the overall environmental impact [33,34]. To understand contrails, Airbus and DLR have planned a project 'Blue Condor' to perform experimental flight tests with two Arcus-J gliders (one with a conventional engine and another with hydrogen modified engine) and a Grob Egrett to act as a chase aircraft with emission sensors [35]. The rate of decay of the contrails and the extent to which careful route planning can alleviate the radiative forcing effect have yet to be fully investigated.

With regards to cost, synfuel requires 22 % more hydrogen and 45 % more electricity than direct hydrogen usage [9]. Due to a more complex and less efficient production process of SAF and a carbon tax imposed on kerosene, hydrogen is expected to reach a cost-competitive point by the early 2030s [9]. Hence, hydrogen could be a long-term solution from economic and emissions perspectives, excluding the effect of contrails.

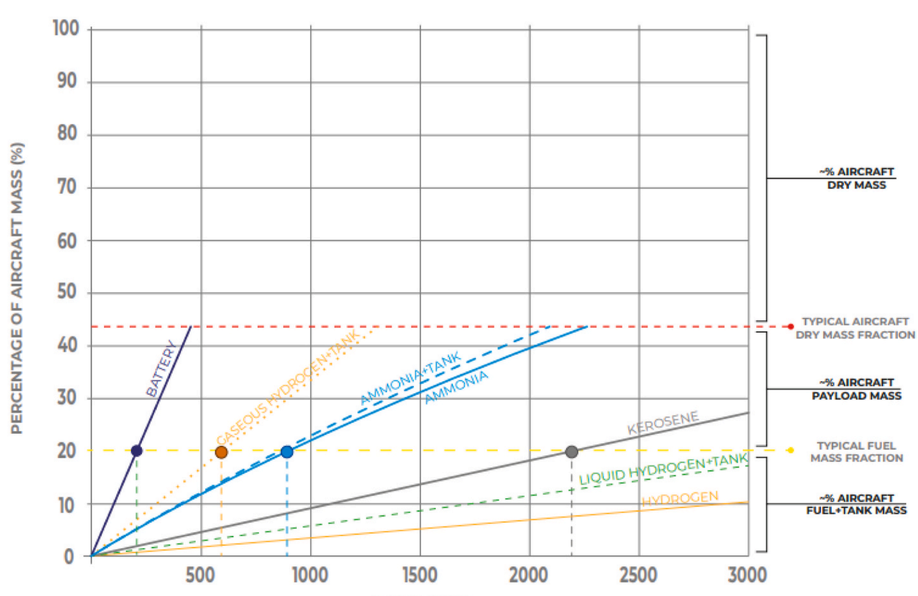

Fig. 2. The mass of fuel and containment system (2030 technological assumption) of different fuels relative to total aircraft mass against the design range in nautical miles [21].

3. Evolution of hydrogen research in aviation

Since, the demonstration of an aero-derivative hydrogen gas turbine in 1937 [36], several military projects assessed the potential of liquid hydrogen in the 1950s–60s. Project Bee [37] included a flight test of a modified B-57 bomber, shown in Fig. 3, and ground tests were carried out on the relatively short-lived concept of the Lockheed CL-400 spy plane [38]. The 1970s oil price shock sparked large-scale hydrogen feasibility projects for civil aviation. Lockheed's 1970s project in the US was concerned with preliminary designs of short-long range aircraft, and the TU-155 project in the Soviet Union [39,40] reported the flight test of a Tu-155 aircraft, shown in Fig. 3. Lockheed's hydrogen aircraft research reported in articles [41–45] and in Brewer's book '*Hydrogen Aircraft Technology*' (1991) [46] remain significant references in the area of hydrogen propulsion feasibility to the present day. After oil price stabilisation in the 1980s, these projects gained very limited attention in the industry. In the 1990s, '*Cryoplane'* project assessed the potential modification of A310 for hydrogen [47,48], while the EQHHPP Project investigated economic, certification and policy requirements [49]. In 2000, the European Commission initiated the '*Cryoplane – Liquid Hydrogen Fuelled Aircraft System Analysis*' project which produced conceptual designs of five aircraft for different mission capabilities [50,51, 52,53,54] (project referred as Cryoplane 2000s in this article). Even though all previous studies concluded technological viability, the cost of hydrogen production, storage and supply system, and the required aircraft infrastructure made hydrogen economically unattractive. Following Cryoplane, Cranfield University continued research on hydrogen engine performance and alternative engine cycles [55–60], environmental impact [13,61,62] and the effect of tank configuration on the aircraft level performance [63,12,64–68]. Inspired by previous research [46,69,70], NASA demonstrated a hydrogen-fuelled scramjet for their X-43 experimental hypersonic aircraft in 2004 [71] and Boeing demonstrated their 'Phantom Eye' UAV between 2010 and 2014 [72, 73]. In 2006, the potential of hydrogen in regional freighter aircraft was also investigated [74,77,75,76] showing superiority in terms of safety and energy efficiency compared to passenger aircraft.

The transition to greener propulsion technology has gained significant traction over the last decade. Fuel cell electric propulsion, deemed unlikely in the early 2000s [78,79], has been successfully demonstrated in regional-level aircraft such as the Dash8-300 by Universal Hydrogen [80], the Dornier 228 by ZeroAvia [81], and several others [82–88]. The UK Jet Zero Strategy [89], and the EU 'Fly the Green Deal' [90] have accelerated national-level efforts for green technologies. Plans for demonstration of both hydrogen combustion [91–96] and fuel cell technologies [97–102] are well underway at several engine manufacturers and startups. Embraer [103] have released sub-regional fuel cell and regional hydrogen turboprop concepts for 2035–2040. The Airbus ZEROe project released several concepts covering regional to short/mid-range for 2035 with plans to demonstrate both technologies by 2026–2028 on its A380MSN1 test aircraft [104]. ENABLE-H2 [10, 105–117] and the CHEETA project [11,118–123] are investigating the scalability and technology readiness level (TRL) of various hydrogen-enabling technologies. The Aviation Impact Accelerator (AIA) [124] has taken a system- and industry-level view in developing an environmental impact assessment tool and uncertainty analysis for a range of fuel choices. The NAPKIN project [125] investigated hydrogen demand and the required airport operation and infrastructure changes. In 2022, one of the largest zero-emission aviation feasibility projects called 'FlyZero' [126] was completed with 100+ technical reports [9, 127–132].

A supporting attachment, describing the major recent industrial and research projects, including their aim, and key findings, along with industry and academic partners, is presented in Appendix Table A 1.

To help to understand the findings of the three largest feasibility projects (Lockheed 1970s, Cryoplane 2000s, FlyZero 2020s) the main specifications of selected aircraft concepts, and their change in energy consumption compared to their kerosene counterpart, are presented in Table 1 and Fig. 4.

An interesting trend can be observed in Fig. 4. Hydrogen aircraft was deemed more energy efficient (5–12 %) compared to its kerosene counterpart in the 1970s for narrow-body size aircraft and larger (except regional), whereas in the 2000s energy efficiency projections were considerably worse no matter the design mission capability (9–15 % higher energy). However, the recent FlyZero study showed some agreement with 1970s projections. The Lockheed 1970s and FlyZero 2020s concepts had integral tanks utilising maximum volumetric efficiency within the fuselage whereas, Cryoplane 2000s concepts had overhead tanks. From Verstraete's [65] structural evaluation, top fuselage tanks create more drag and would be 28.1 % heavier than integral fuselage tanks, with a 5.3 % increase in MTOW and 6–19 % more aircraft

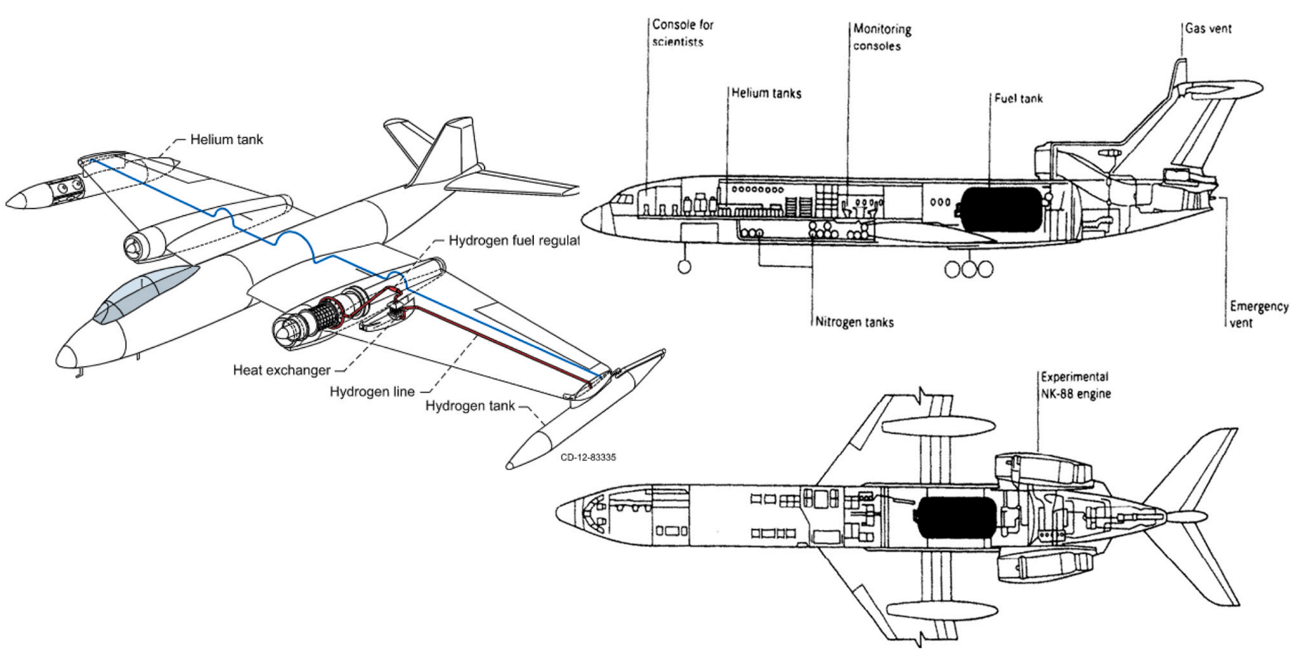

Fig. 3. (Left) B-57 bomber modified for hydrogen [265] (Right) TU-155 LH2 aircraft [47].

Table 1
Selected concepts of various feasibility projects [46,50,126,127] (EIS – Entry in Service).

Study	Regional	Short to Medium Haul	Medium to Long
Lockheed 1970s [46] EIS: 1990s	135PAX, 1500NMI Conventional M 0.85, Turbofan Tank: forward and aft cabin	200PAX, 3000NMI Conventional Aircraft M 0.85, Turbofan Tank: forward and aft cabin	400PAX, 5500NMI Conventional Aircraft M 0.85, Turbofan Tank: forward and aft cabin
Cryoplane 2000s [50] EIS: 2020s	70PAX, 2000NMI Conventional Both Turboprop/fan Tank: overhead PAX cabin	185PAX, 4000NMI Conventional Aircraft Turbofan Tank: Overhead and aft cabin	380PAX, 8500NMI Conventional Aircraft M 0.85, Turbofan Tank: forward and aft cabin
FlyZero 2020s [126] EIS: 2030s	75PAX, 800NMI Conventional Fuel Cell Prop Tank: aft PAX cabin	179PAX, 2400NMI Conventional canard Turbofan aft fuselage Tank: aft PAX cabin	279PAX, 5750 NMI Conventional Turbofan on Wings Tank aft PAX cabin

energy use. This could explain Fig. 4 observation, as FlyZero concepts had only a 9–15.7 % increase in OEW (except 32 % for regional aircraft where fuel cell and electrical systems added weight) whereas Cryoplane concepts had ~25 % increase in OEW compared to kerosene concepts. Fig. 4 also shows that hydrogen aircraft offers larger energy consumption benefits compared to kerosene aircraft for larger mission capability. This could be due to higher gravimetric (defined as the ratio of fuel mass to the total mass of the containment system plus fuel) and volumetric efficiency (defined as the ratio of the actual volume of storable fuel to the total volume of the containment system) of larger tanks. It is crucial to note that these studies were completed at different times and with different assumptions, technological understanding, and therefore resultant projections. Furthermore, all studies concluded hydrogen aircraft would be technologically feasible in their design timeframe. However, Lockheed and Cryoplane suggested only incremental improvements are required, whereas FlyZero concluded that several revolutionary breakthroughs in technology are needed.

The level of ambition within the above projects, and hence optimism in projections or the determination to achieve positive change, depend on a number of factors including fluctuating oil prices and observable changes to the natural habitat, air quality, local climates, and our way of life. As of the 2000s, even though environmental awareness was growing, there was uncertainty and scepticism about the predicted environmental impact, and low oil prices resulted in a lower motivation for change to alternative fuels. The global consensus on climate change, and major efforts to convene capabilities and resources since 2020, have given rise to the green fuel momentum and a push for a credible alternative fuel and energy vector. Investments in new technologies tend to be driven primarily by predicted economic returns over the short to medium term. Nevertheless, the landscape has shifted, and commercial entities are forced to adapt and take a longer-term view, including making strategic investments, to remain relevant and within stringent regulatory constraints around emissions and environmental impact over the product lifecycle.

4. Aircraft configuration

With approximately four times the volume compared to kerosene, the storage requirement of liquid hydrogen is the dominant driver of aircraft configuration. Bravo-Mosquera et al. [133] have reviewed research and development of unconventional configurations including their predicted benefits and level of fidelity of the design process. Regarding hydrogen aircraft, Lockheed 1970s [44–46] assessed eight airframe configurations based on fuel location in aircraft (fuselage, pods, or wings) and Cryoplane 2000s [51,63] assessed 21 concepts based on aero-structural benefits. Recent studies, however, focused on both aero-structural and aero-propulsive integration where ENABLE-H2 [10,106] investigated 31 airframe configurations with 21 propulsion system arrangements and FlyZero [127] investigated 27 integrated concepts. Interestingly, all studies concluded that a conventional tube and wing (CTW) aircraft with an evolutionary enhancement of fuselage, wings, and other components as the most promising configuration at the early stage. ENABLE-H2 presented a wing and tube with extended wing roots, distributed propulsion (DP), and boundary layer ingestion (BLI) for small/medium range aircraft, and a blended wing body (BWB) for long-range aircraft as maximum benefit concepts. However, the evolutionary CTW aircraft design (similar to Cryoplane) was identified as a low-risk design with earlier entry into service. The CHEETA project [119] developed a highly adapted fuselage, exploiting DP and BLI. Fig. 5 shows these concepts. The BWB has been researched significantly in the last decade by NASA [134], Boeing [135] and Airbus [136] and new generation designs [134,137] address most challenges previously identified with a ~15–16 % potential fuel burn reduction. However, the Airbus Annual Summit 2022 highlighted the CTW as a primary focus for

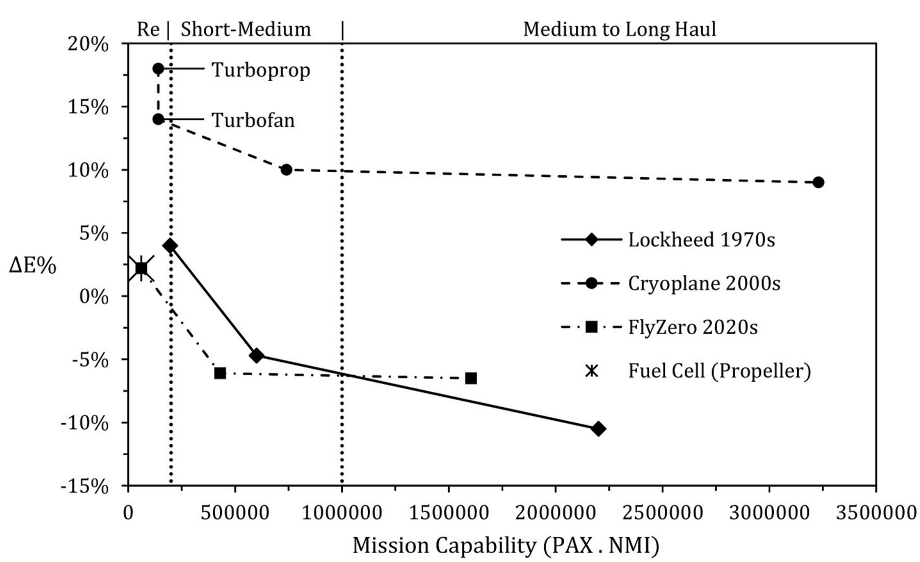

Fig. 4. Energy consumption change against mission capability for different studies.

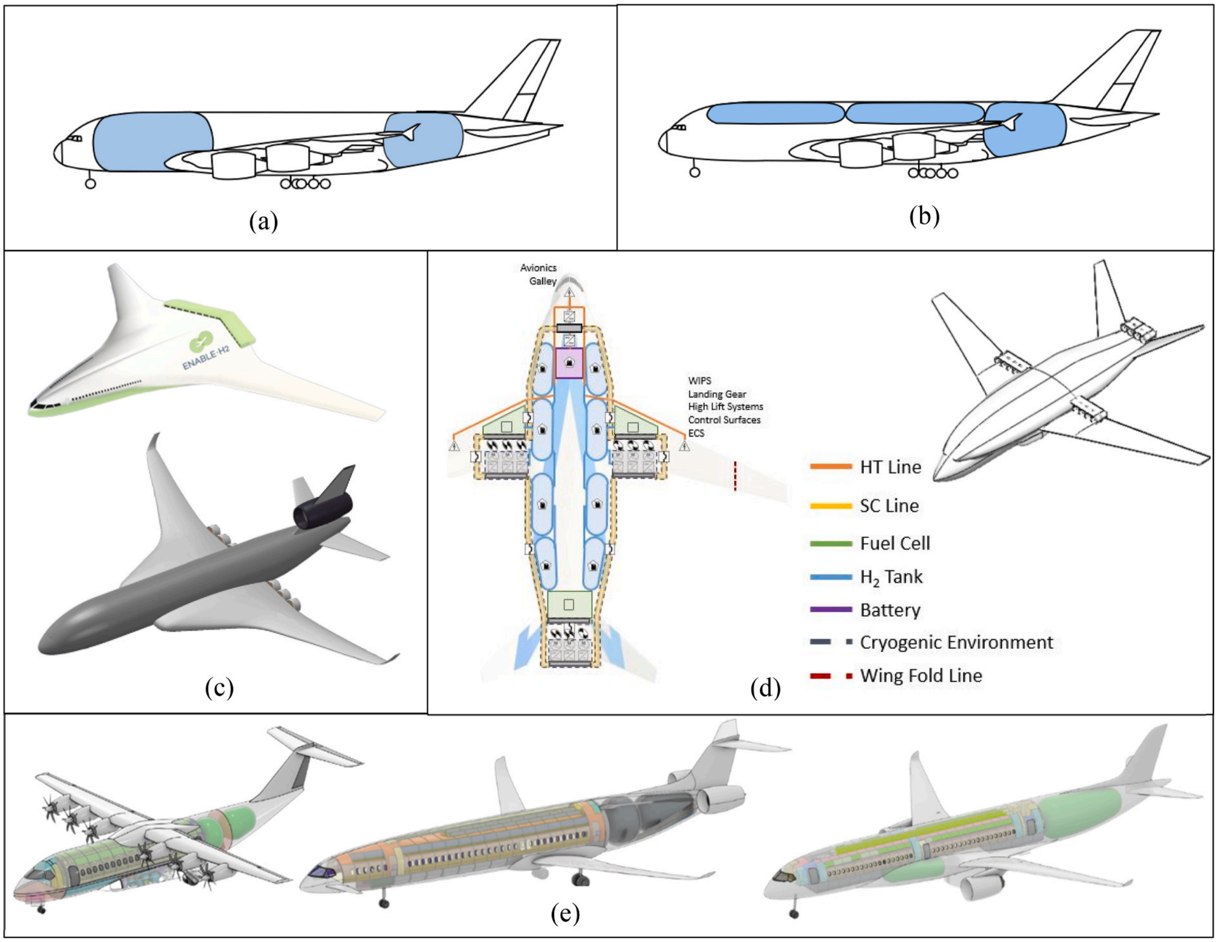

Fig. 5. Selected concepts. (a) LOCKHEED 1970s [44–46] (b) Cryoplane [51,63] (c) ENABLE-H2 [10,106] Long Range BWB and Short Range (d) CHEETA project [119] (e) FlyZero [127] Regional, Short and Medium Range.

its ZEROe concepts [104]. The use of hydrogen itself requires novel propulsion and fuel system architecture designs, and new airport infrastructure with significant investment. Hence given the additional investment and risk that would be associated with the BWB, the CTW with modifications to the fuselage and lifting surfaces is expected for 2030–2035 EIS, followed by more revolutionary concepts such as the box, strut-braced/truss-braced wings and possibly BWB designs for 2040–45 and beyond.

5. Cryogenic fuel system and storage

The design of the storage, control, and distribution systems for cryogenic fuel and its integration into the airframe could have a substantial impact on the overall aircraft weight and performance. Lockheed 1970s [46], Cranfield University publications [12,65,66,68,138] and ENABLE-H2 projects [112,113,139,140], have all investigated cryogenic storage requirements, configuration, and design in detail. Section 4 suggests that CTW aircraft with a tank inside the fuselage is the ideal solution for the first family of hydrogen aircraft. External tanks mounted as pods on wings or even twin-tail boom concept were reported favourable by Lockheed 1970s [46] and Cryoplane 2000s [63] respectively, but would create extra drag and weight causing 11–12 % higher MTOW and 32 % higher energy consumption [44,45].

Tanks can be arranged in various orientations inside an aircraft (Fig. 5). Winnefeld et al. [141] investigated the effect of various shapes and sizes of LH2 tanks on the gravimetric efficiency. This was developed further by Huete et al. [113], which investigated the effect of varying radius and length for a cylindrical tank with constant volume. Dannet [142] investigated the utilisation of all available aircraft empty spaces (wings, cargo space) with multiple small tanks but thick insulation requirements and mass penalty made it non-viable. All studies agree that a single tank at the rear fuselage bulkhead covering the entire cross-section (cylindrical) provides the highest gravimetric and volumetric efficiency [46,113] (FlyZero [127,129], Airbus [143] and Embraer [103] concepts). LOCKHEED 1970s [46] adopted two tanks, one front (with sidewalk passage for cockpit access) and one behind the passenger cabin. However, recent structural evaluation demonstrated a ~10 % decrease in gravimetric efficiency due to the sidewalk [139]. Cryoplane [51] and ENABLE-H2 [106] top fuselage tanks are another popular configuration but Verstraete [65] concluded significant aircraft level penalty (See Section 3). CHEETA [119] also adopted top tanks laterally outside of the passenger cabin for safety, and adapted the fuselage for lift enhancement. The tanks can either be structurally integrated into the airframe/fuselage (integral tanks) or simply attached to a conventional fuselage (non-integral). A non-integral tank can be retrofitted into any conventional fuselage structure (hence adopted by many studies [51,69,113,140,141]), whereas an integral tank requires adapting the structural design and manufacturing process of the fuselage ([139], and [12,144] both based on Brewer [46]). A comparison of integral and non-integral tanks based on structural analysis by Brewer [46] and Onorato et al. [144] concluded ~8–9% higher volumetric and gravimetric efficiency for integral tanks. To provide a full picture, a comparison of various tank configurations (external and internal) and integration techniques (integral and non-integral) at component as well as aircraft levels based on high-fidelity aerodynamic, structural, and thermal design analysis would be crucial for future aircraft optimisation.

5.1. Cryogenic storage: design philosophy

Hydrogen can be stored in many forms such as physical-based storage or material-based storage. A review of various storage options discussing storage requirements, technological maturity and viability at the aircraft level is provided in Refs. [145–147]. The material-based storage includes metal hydrides, metal-organic frameworks, metal borohydrides and chemical storage. Ammonia, methanol and formic acids can be considered as chemical storage of hydrogen as these compounds can be decomposed into hydrogen when required [146]. Chemical storage options allow less complex storage systems with ease of transport and storage for long periods of time. Although theoretical gravimetric efficiency and volumetric density are high, the requirement of additional systems for decomposition to hydrogen makes them less desirable. Other material-based storage techniques are still in the research phase and have low TRL. The physical-based storage includes compressed hydrogen gas (GH2), liquid hydrogen (LH2), a mixture of solid-liquid hydrogen (slush) and cryo-compressed hydrogen. These can be attained by maintaining the fuel container at different temperature and pressure conditions. The choice of storage mainly depends on storage density and gravimetric efficiency. Cryo-compressed hydrogen (storage at 50–700 bar, 25–110 K) offers extremely low boil-off but requires a heavier tank (SOA gravimetric efficiency ~28 %) and complex ground operations [146]. During Cryoplane [51], investigation of slush (at 13 K temperature conditions) showed 20 % higher density and heat capacity compared to LH2 but required 17 % higher production cost. The main challenges were, it contained 50 % solid matter which could affect the performance of cryogenic valves and pumps and, the storage requirement of subatomic pressure 7000Pa which could suffer from air ingress in case of leaks, requiring thicker tank walls.

Compressed GH2 (at 350 bar or 750 bar) and LH2 (at 20 K and 1–2 bar) are the most widely used forms of storage. GH2 storage was utilised in most of the demonstrator aircraft [78–85] but all feasibility studies [9,46,51] as well as industries suggest the requirement of cryogenic LH2 storage for scalability to larger aircraft. Even with the use of modern composites, only 5–10 % gravimetric efficiencies are achievable for GH2 storage technologies whereas more than 60 % could be attained for LH2 storage technologies [21]. LH2 storage is widely used in space applications. However, the aviation-specific requirements severely increase design complexity with ~0.1 % allowable boil-off and 1000s of operation cycles [148]. LH2 storage has been demonstrated on the ground (CL-400 [38]) as well in-flight (B-57 Bomber [38], TU-155 [39], Phantom Eye [73] and Universal Hydrogen [80]).

Storing hydrogen in a saturated form requires specific temperature (~20 K) and pressure combinations where liquid and gaseous hydrogen are in thermodynamic equilibrium. The pressure fluctuates during the flight due to heat leaks as well as fuel use, and if it exceeds the maximum allowable pressure, venting is required. The initial fill pressure and vent pressure also dictate the allowable fill level of the tank as a certain percentage of gas volume is required to meet venting requirements. Previously [12,65,66,68,112,139,141], tank design philosophy was based on allowing pressure fluctuation between fill and vent pressure, and designing the insulation with minimum or no venting criteria. Huete et al. [113] proposed a design philosophy, which was also adopted by FlyZero [129] in which optimisation is carried out based on dormancy time (fill pressure to vent pressure rise time). At least in the initial phase of hydrogen aircraft introduction, venting could be unsuitable due to aviation safety rules and airport constraints. In this case, tanks are designed for no venting for several hours of ground standing during adverse weather conditions, for the in-flight duration and an additional few hours on the ground after the flight. Rompokos et al. [112] compared venting and no-venting scenarios concluding venting some amount of fuel during flight allows lower vent pressure as well as lower insulation thickness with a potential of ~34 % reduction in tank weight. Considering the potential for significant weight saving, the safety and certification aspects of venting should be addressed.

5.2. Cryogenic storage: wall material

A review by Mital et al. [148] suggested high strength and stiffness, high fracture toughness, along with low density, low coefficient of thermal expansion (CTE), and low permeation and embrittlement (effect from hydrogen) properties are a must for cryogenic hydrogen containment. Various monolithic metals, polymer matrix as well as metallic composites could be viable choices. Among metals, aluminium alloys (Al 2219, Al 6061-T6) and pure titanium are the least susceptible to hydrogen embrittlement and permeation [149]. Lockheed 1970s [44] extensive fatigue lifecycle tests of Al 2219 alloy (5000hrs of service life) at cryogenic condition has led several studies [12,68,112,113,139,141,69] along with the Boeing Phantom Eye [73] to adopt aluminium alloys. Airbus ZEROe [104] tank manufacturing is also fully based on aluminium alloys with the use of composites potentially beyond 2030–2035. The use of composites offers improved gravimetric efficiency, but limited testing at cryogenic conditions and GH2 permeation susceptibility (requiring metallic liner) is still preventing its use. However, some research suggests the potential of even linerless composite tanks with new materials such as Spread Tow TeXtreme® [150]. FlyZero has presented optimistic projections of transitions to composites from aluminium as early as 2026 [129]. Gloyer-Taylor Laboratories has claimed a 75 % mass reduction with new cryogenic storage with composites (TRL 6+) compared to conventional metal tanks [151]. Overall, there is a critical need for the investigation of composite materials at cryogenic temperature to expand the materials library, as well as outstanding tasks in tank design based on composites.

5.3. Cryogenic storage insulation choice

For insulation, properties like low mass density, low thermal conductivity, and low thermal diffusivity are critical. Mital et al. [148] suggest various aerogels, foams and Multi-Layer Insulation (MLI) systems to be the most viable options for commercial aerospace applications. The properties of various insulation materials and their required operating pressure condition are presented in Appendix Table A 3 [152]. Aerogels offer superior performance than foams at low operating pressure but are brittle and fragile, hence cannot bear structural loads, unlike foams. In the case of foams, Rohacell foams have been widely used in ground applications. The Air Liquide investigation (Cryoplane 2000s) suggested the use of open-cell polyamide and closed-cell Rohacell foam [12]. However, Lockheed's 1990s [46] thermal cyclic test (4000 thermal cycles ~ 14 years of operation) found polyurethane superior with no degradation of the thermal and mechanical properties whereas Rohacell failed structurally. A recent comparative study of several foams highlighted polyvinylchloride (0.0046 W/mK) as the lightest solution (ENABLE-H2 [112]).

MLI offers two orders of magnitude smaller thermal conductivity and diffusivity than any foam insulation and is widely used in orbital spacecraft [153]. Research is underway into new insulation systems like variable density MLI coupled with vapour cool shields, showing superior insulation performance to MLI [154,155]. In MLI systems, a double-wall construction (an extra outer wall sustaining negative buckling pressure with a vacuum inside and the atmospheric pressure outside) is needed to maintain a vacuum. Hence, a heavy tank with stiffeners or a large tank wall thickness is required. In contrast, foam only requires inner wall or single wall construction [12]. Huete et al. [113] compared MLI and foam insulation for non-integral tanks. For a constant dormancy time, an optimum vent pressure and gravimetric efficiency exist for tanks with foam insulation because inner wall mass increases, but insulation thickness decreases with higher venting pressure. However, for tanks with MLI systems, increasing vent pressure always decreases the gravimetric efficiency, because inner wall mass increases, the mass of MLI insulation is relatively low/insignificant, and outer wall mass does not depend on vent pressure. Although MLI provides a large dormancy time, the foam insulation provides higher gravimetric efficiency for a larger range of vent pressures [113]. FlyZero [129] selected MLI for the regional concept but foam insulation for narrowbody and mid-size concepts.

5.4. Cryogenic storage summary

The gravimetric efficiency of the liquid hydrogen tank varies from 40 to 80 % in several previous studies. The literature survey suggests that an optimum tank with the highest gravimetric efficiency depends on many factors. Hence, cryogenic hydrogen storage must be designed for each specific mission with careful consideration of storage requirements (fill and vent pressure), mission requirements (hold time, venting requirements), tank configuration (integration and shape), volume and size, and insulation and tank material choices. Based on the design requirements, the maximum attainable gravimetric efficiency varies significantly but 70 % or above could be achievable by 2030–2035 [129].

5.5. Cryogenic fuel distribution system

The fuel distribution system includes cryogenic pumps, valves, fuel transfer lines to the engine and additional vent lines. For safety considerations, nitrogen or helium-purging fuel lines are also recommended [46] to prevent cryogenic hydrogen-air mixture which can lead to detonation. Lockheed 1990s [46] provided a preliminary design of a cryogenic fuel system for a large widebody aircraft with the same level of redundancy as the kerosene aircraft. Many ([65,66,74,76,141,156]) publications in hydrogen aircraft design only highlight the layout of fuel systems but include no information on mass and size, whereas some recent publications still use Lockheed 1990s results [144]. The understanding of 2-phase hydrogen flow and cryogenic pump/valve design is still limited. Hence, there is a requirement for detailed design, testing and experimentation of cryogenic fuel systems. A review of safety and certification issues in the distribution of cryogenic hydrogen around the aircraft is also required. If such systems are to be exploited as heat sinks, the development of compact heat exchangers is required that will be able to sustain the working fluid, low operating temperatures as well as relatively large temperature gradients across the metal parts. Airbus [104] claims it has completed a successful test of a prototype fuel system operating at cryogenic conditions and a complete fuel system is planned to be delivered by the end of 2024. Some top-level studies [8,157] have suggested a requirement of 35–40 % total hydrogen fuel system gravimetric efficiency (including fuel system mass) for hydrogen aircraft performance to be as competitive as their kerosene counterpart, while FlyZero [129] forecast 60–70 % total gravimetric efficiency could be achievable by 2030.

6. Hydrogen gas turbine

The introduction of hydrogen in gas turbines requires a new combustion system. The cryogenic fuel requires appropriate conditioning via an alternative engine cycle but also provides an opportunity to cool various engine parts enhancing overall engine performance. Hydrogen-modified conventional engines have been tested several times in the past: J57 turbojet modification for B-57 bomber [38], Model 304 engine development and 25hr of ground test for CL-400 project [46], and NK-88 engine modification for TU-155 [39,40]. Lockheed 1970s [46] and Cranfield University [55–60] have investigated engine changes with hydrogen and alternative engine cycles. Development of hydrogen-adapted engine codes for GasTurb (a commercial engine performance analysis tool [158]) and validation with TURBOMATCH (the Cranfield University engine analysis tool) during Cryoplane has led to these tools being widely used in research and industry today [57].

Due to the higher specific heat capacity and specific heat ratio of the hydrogen combustion products, it has the potential for engine-level benefits compared to kerosene. Jackson and Boggia [56,57] analysed the V2527-A5 engine in GasTurb with minimum change (same operating pressure ratio OPR and by-pass ratio BPR and a 250 K fuel inlet temperature with exhaust heat exchanger). For constant thrust at take-off, turbine entry temperature (TET) was 34 K lower for hydrogen whereas for the same TET, thrust increased by 2.97 %. Energy-specific fuel consumption (ESFC) was 1.6 % lower for both cases compared to kerosene. V2527-A5 engine analysis using TURBOMATCH reported similar findings [59]. Corchero and Montañés [159] suggested that a decrease in TET of 10 K would correspond to around 25 % improvement in turbine life. Hence, a hydrogen engine could enable mission fuel burn benefits as well as higher turbine life and lower NO_x. Exploiting all benefits, FlyZero [128] suggested that there is potential for a smaller engine core, larger bypass flow and increased on-wing life with almost 60 K lower peak temperature than a kerosene engine. However, some recent publications [160–162], assessing the exergetic performance of the state of art engines, show that the use of hydrogen would cause a small deterioration of overall engine exergy efficiency.

6.1. Hydrogen combustor design

An important design objective of hydrogen combustors is NO_x reduction. There are various processes of NO_x formations [60] but mainly the process is a strong function of temperature (proportional to T^5) and residence time [57]. With a conventional combustor, if operated at the same air-to-fuel ratio, the hydrogen flame temperature would be 100 K higher than kerosene (see Fig. 6). However, its wide flammability range allows operation at lean mixtures. Rapid kinetics (higher flame speed and reactivity) allow for a shorter combustor design and residence time. Although the techniques of hydrogen fuel injection are under development, gaseous fuel injection into the combustor enables more efficient diffusion/mixing with the air (than liquid droplets in case of kerosene) and a more uniform temperature distribution [57], hence lower NO_x.

In 1992 (EQHHPP project), analytical and experimental studies of pre-mix and non-premix combustor systems for lean hydrogen combustion were performed. Pre-mix combustors offered better performance in temperature uniformity and low NO_x emission than any non-premixing system [57], but were prone to flashback effect inducing uncontrollable combustion oscillation and potential hardware damage. An experimental test of a hydrogen modified PT6A-20 turboprop engine in premix mode found limitations in power due to flashback issues at high-pressure operating points [163,164]. Addressing the knowledge gaps in understanding pre-mix swirling flame characteristics and mechanisms of flame stabilisation [165], C-PARC at the University of Tennessee is currently working on the development of an injector and the stabilisation of hydrogen-premixed flames [166]. A novel aerodynamically trapped vortex pre-mix combustor has also been investigated recently (by Delft University and OPRA Turbines) for its potential of stabilised flow with no flashback issues [167].

At FH-Aachen research, Dahl and Suttrop [54] developed a non-premixing micro-mix combustor design to prevent flashback issues and premature combustion. This concept exploits the idea of minimizing the scale of the combustion zone by introducing thousands of uniformly distributed diffusing flames in the combustor injection system (see Fig. 7). The design also offers improved turbulent mixing thus reducing local residence time. This design achieved an almost 80 % reduction of NO_x emission compared to kerosene. Cranfield University [107–111] under ENABLE-H2 [105] has carried out extensive numerical studies (using RANS and LES) and has plans for experimental validation in a newly developed test rig. It has further planned a phase 2 full-size combustor configuration test and a phase 3 altitude relight test at sub-atmospheric conditions (target TRL 6 by 2030).

NASA studied a non-premix direct lean injection system (see Fig. 7) which exploited the use of fuel inlets smaller than fuel quenching diameter to avoid flashback problems [169]. However, only similar

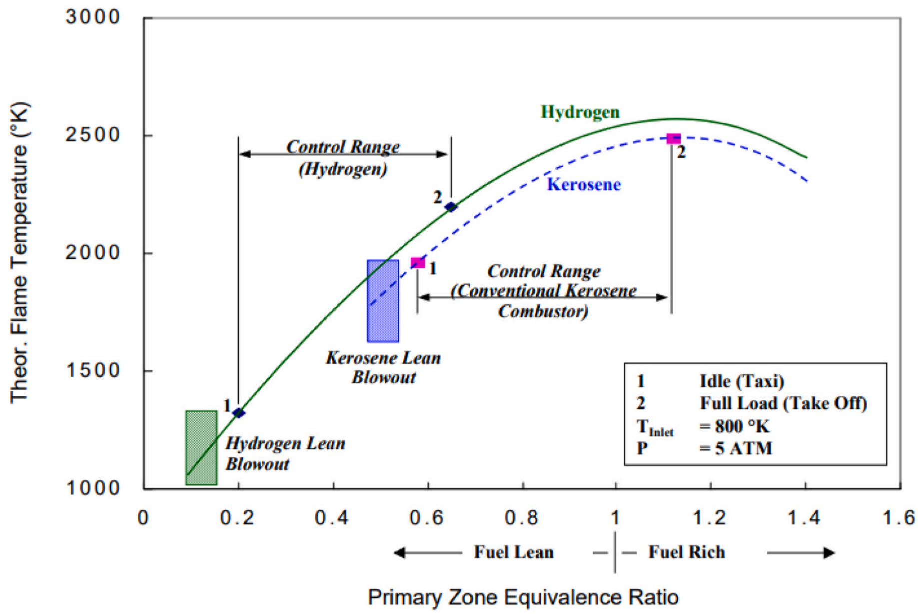

Fig. 6. Temperature characteristics of combustor primary zone [168].

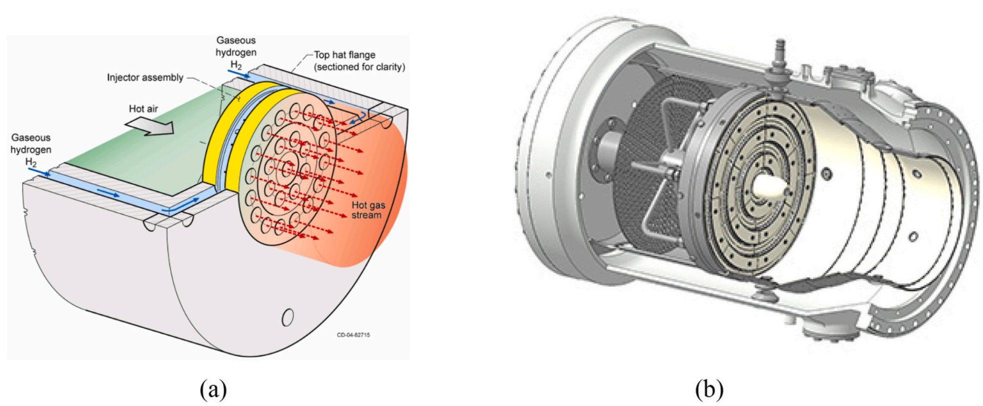

Fig. 7. Hydrogen injection systems and combustor technologies (a) NASA non-premix direct lean injector [169] (b) an example of micromix combustion system [266].

levels of NO_x emission as a kerosene counterpart was observed. A 100 % hydrogen operation on a novel combustor concept based on the Lean Azimuthal Flame has also been demonstrated recently and more research is ongoing under the Clean Sky 2 project LEAFINNOX [170].

6.2. Integrated thermal management (alternative engine cycles)

Introducing alternative engine cycles, engine-integrated heat exchangers (HEX) could be used for fuel conditioning as well as to recover the available waste heat in several parts of the engine exploiting the cryogenic nature and high specific heat capacity of hydrogen. At the expense of complex design and material choices, several engine-level performance benefits could be achieved. Regarding the expected temperature rise of LH2 between the storage tank and the combustor inlet, a minimum combustor inlet fuel temperature of 150 K was recommended by Brand et al. [168] to avoid large density and viscosity fluctuations and partial liquefaction during fuel expansion in the injector, whereas SNECMA (Cryoplane [51]) suggested 150–250 K as a reasonable range (which is significantly lower than the 823 K autoignition temperature [171,172]). In ideal conditions higher fuel temperatures allow lower specific fuel consumption [159]. In terms of fuel inlet pressure, for rapid fuel mixing with the air the fuel injection pressure must be higher than the combustion chamber air pressure. In the design of the heat exchangers that enable the above, a trade-off is required between fuel temperature rise and air-side pressure drop, particularly where these could impact engine thrust.

The five main cycles discussed in most literature for fuel conditioning were cooling of the engine oil, cooling of turbine cooling air, cooling of compressor air, cooling of the exhaust gases, and a hydrogen expander/topping cycle (see Fig. 8). Four of the alternative cycles were discussed in detail in Lockheed's 1970s [46] and Boggia and Jackson [55–57]. Table 2 summarises the predicted improvement in specific fuel consumption (SFC), direct operating cost (DOC) and engine weight (Wt) over their baseline engine.

In general, benefits in SFC and DOC are observed. However, direct comparison between these studies cannot be made due to different technological assumptions at different timescales and different baselines. Lockheed's 1970s [46] baseline was a hypothetical engine (take-off thrust of 127 kN) with no-fuel heating and fuel injection temperature of 50 K, and specific thrust, cycle pressure ratio and combustor outlet temperature were kept constant. However, Cryoplane [51] and Boggia and Jackson [55–57] adapted the V2527-A5 engine by increasing the combustor outlet temperature, by-pass ratio and operating pressure ratio whenever possible for each cycle to maximize the

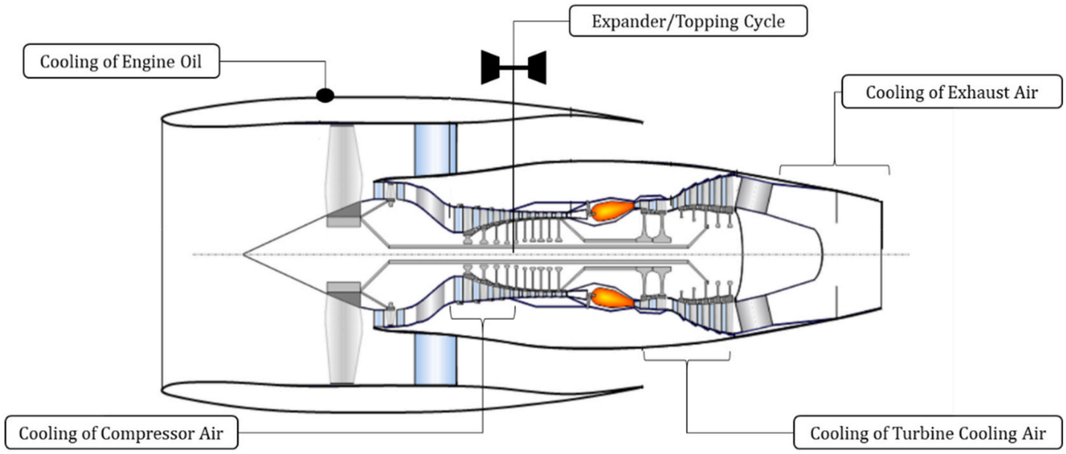

Fig. 8. Schematic of engine-integrated thermal management systems (created based on previous literatures).

Table 2
Benefits of Alternative Cycles [46,51,56,57].

Alternative Engine Cycles	LOCKHEED 1970s		Cryoplane 2000s		
	Δ SFC %	ΔDOC %	Δ SFC %	ΔDOC %	ΔWt %
Cooling of turbine cooling air	−0.53	−1.33	−2.11	−3.08	+18.1
Cooling the compressor air (Precoolers)	−1.86	−0.41	−5.70	−3.14	+5.44
Cooling of turbine exhaust	−4.31	−2.90	−3.88	−1.73	+0
Hydrogen expander and topping cycle	−4.31	−2.90	−1.10	−1.91	+5.49

engine performance. The baseline was a hydrogen V2527-A5 engine where fuel was heated to a minimum of 250 K using the residual heat in the exhaust gases. In terms of mass, Brewer [46] suggested only a minor increase for all concepts whereas Cryoplane [51] found a higher mass addition when cooling the turbine cooling air. Previous literature investigated the benefits of individual cycles, whereas recent research (Srinath et al. [173] and FlyZero [131]) have focused on the integration of multiple alternative cycles to achieve higher system-level benefits (also including cooling of engine oil). FlyZero outcomes with detailed engine cycle analysis are currently under restricted reports and not yet publicly available.

All studies [46,51,131] agree that exhaust heat recovery requires a minimum change in the hardware, and hence has potential for early adoption. SNECMA (Cryoplane [51]) concluded a tubular coil exhaust HEX as an optimum configuration which has been used before in the Tupolev-155 hydrogen aircraft engines heating the hydrogen fuel from 20 K to 83 K [39,40]. In an alternative configuration, Svensson [60] and Haglind et al. [59] presented a design to flow hydrogen through the exhaust struts behind turbine rotors. In 1956, the Pratt and Whitney hydrogen adapted model 304 utilised a complex involute pattern steel tube HEX in the exhaust [38] (hydrogen heated from 20 to 1000 K at 72 million Btu/hr). This concept was developed further by researchers at Bristol University ([174]) and is under development at Reaction Engines in the UK. Pre-cooling/inter-cooling of compressor air was concluded unfeasible by Lockheed [46] and Cryoplane [51] due to practical issues of airside freezing (also excluded by FlyZero [131]). However, research of Chalmers University [175–177] under ENABLE-H2 suggested this cycle allows performance benefits and engine size reduction, and experiments are planned for the near future in a new low-speed compressor facility [178–181]. With the current technological status, the FlyZero [131] findings highlight that the oil-to-fuel heat exchangers and exhaust heat recovery could be integrated into the engine as early as 2026, with the addition of cooling of turbine cooling air by 2030 and further addition of the expander cycle by 2040–50.

Previous performance evaluation studies of exhaust heat recovery, intercoolers, and pre-coolers assumed a specific air-side pressure loss (core flow) and heat exchanger effectiveness. These quantities depend on the design, and configuration of the selected heat exchanger. However, there exists no publication with a detailed comparative study of various HEX configurations. Hence, an evaluation of various engine-integrated heat exchanger configurations is required to verify these findings.

6.3. *Summary and industry outlook of hydrogen gas turbines*

Prior research over several decades has identified a number of modifications that are required to adapt turbines for use with hydrogen. System-level evaluations indicate significant promise, and this has led to an acceleration in research and development within the aerospace industry. Further detailed design studies are required to inform the performance predictions, including the simulation and testing of different combustor technologies and heat exchanger configurations that enable novel fuel and thermal management systems and alternative engine cycles. The development of advanced materials and manufacturing processes is also required [182]. Research, analysis and testing of cryogenic and hydrogen tolerant materials as well as systems which can withstand very high temperature gradients are critical for engine-integrated heat exchanger development.

The aviation industry has responded in an effort to achieve the above target with various hydrogen gas turbine design projects ongoing in industry. Rolls Royce has completed the first phase of a demonstrator programme with a successful ground test of a hydrogen-adapted AE 2100 engine. A ground test of the Pearl 15 jet engine is expected in the second phase [91,92]. It is also leading Clean Aviation Programme-funded projects HEAVEN and CAVENDISH to integrate the LH2 system into its engines including the UltraFan®. Pratt and Whitney (2022) has initiated the HySIITE project to develop hydrogen combustion with a steam injection into a compressor, combustor, and turbine to cut NO_x emission by 80 % [93]. GKN Aerospace is leading the H2JET project to develop hydrogen gas turbines for single-aisle size aircraft by 2035 [94]. CFM International has a partnership with Airbus to modify the combustor, fuel, and control system of the GE Passport turbofan for the demonstrator programme [95]. MTU Aero Engines is working on Project 'WET Engine' to develop a SAF and hydrogen-compatible engine by 2030 [96].

7. Fuel cell propulsion system

The drive for true net zero has given rise to extensive research and development of aviation-scale fuel cell technologies that are targeted at short and regional missions based on their projected capability. Fuel cell propulsion systems require a novel electrical architecture system to distribute and control considerable power which drives electrical machines or propulsors (see Fig. 9). It has the potential for higher reliability, lower noise, higher chain efficiency [183] (less mechanical moving parts) and ease of scalability (independent energy storage and power output unlike batteries). The following sections discuss various competing fuel cell technologies and their potential to achieve the required energy densities and overall specific power for future commercial flight.

7.1. Fuel cell system design and types

A detailed understanding of fuel cell, stack and system with thermodynamic and electrochemical analysis is presented in Refs. [184,185] whereas [186,187] further review the recent developments and gaps. Multiple cells are connected to construct a stack whereas multiple stacks along with a balance of plant (BoP) form a complete fuel cell system (Fig. 9). The BoP is comprised of the following: i) a gas management system (GMS), including fuel and air conditioning with heat exchangers and a compressor to prevent altitude performance deterioration [186], ii) a water management system (WMS) to balance water production and removal inside cells [187,188], iii) a power conditioning system (PCS), and iv) a thermal management system (TMS) to maintain the correct operating temperature and to enhance system efficiency. An additional exhaust conditioning system could be an extra aviation-specific requirement which may help to avoid contrails formation.

Various fuel cell technologies are reviewed in Ref. [186,187,189, 184]. For aviation-specific requirements, Kazula et al. [190] suggested that proton exchange membrane (PEMFC) and solid oxide fuel cell (SOFC) have the highest potential. High specific power and short start-up time have made PEMFC popular in the automotive industry ([191–198]) and have been used in recent aircraft demonstrators [81, 84,86,199]. High-temperature operation of the SOFC exploits waste heat utilisation and higher system efficiency, and these have found applications in ground power generation [200]. Extensive studies on SOFC adoption in aircraft auxiliary power units (APU) were conducted in past [201] and due to its fuel flexibility (and uncertainty of future fuel of aviation), SOFC-gas turbine hybrid engines with various fuels (such as hydrogen, natural gas, ammonia, methanol, etc.) is a topic of increasing interest [28,202–205]. The high operating temperature requirement of SOFC also makes it best suited for integration within a gas turbine in a hybrid propulsion architecture utilising the engine heat [202,206]. A NASA patent claims a SOFC with high stack specific power and density (2.5 kW/kg and 7.5 kW/l) but no demonstration has yet been published [207]. Both technologies show potential and could suit different aviation applications. However, PEMFC has high TRL and is favoured by most feasibility studies [119,208,130,79].

PEM fuel cells can be categorized into two types: low-temperature LT-PEMFC and high-temperature HT-PEMFC. Due to operation below 100 °C, the LT-PEMFC has a faster start time and rapid dynamic response to load changes. It does, nevertheless, require a complex WMS (susceptibility to overhydration and electrode flooding [209]) and complex TMS/large heat exchangers (low-grade heat). Hence, higher system weight and drag. Using new materials for electrode membranes, HT-PEMFC enables operability up to 200 °C with better tolerance to contaminants (*CO*, H_2S), and notably a simpler water and thermal management system [186,210]. The LT-PEMFC has high TRL with wide use in the automotive industry [191–198] and in a number of aircraft demonstrators [80,81,84,86,88]. Airbus [104] and GKN Aerospace [99] (Table A 1) have partnerships with ElringKlinger and Intelligent Energy, both with considerable experience in automotive LT-PEMFC technology. The LT-PEMC is expected to be the dominant technology for at least 15 years according to FlyZero [130].

The HT-PEMFC is still at a very low technology readiness level, but significant development has taken place over the past decade, as reviewed in Refs. [210–212]. There is the potential to reduce cost and start-up time by up to 40 min compared to the current SOA [211], which may prove to be critical. HyPoint (recently acquired by Zero Avia) have demonstrated the potential for BoP mass fraction improvement from 75 % for the LTPEMFC to 40 % for the HTPEMFC system [213]. Models based on experimental data (>5000 cycles of operation of cells) show the possibility of 1.8 kW/kg HT-PEMFC with state of art technology [214]. The HT-PEMFC is envisioned as the next step in fuel cell technology development in the aviation sector according to FlyZero [130], AIA [34], CHEETA [119], ZeroAvia [81] etc.

7.2. Thermal management system

Heat energy of the same order of magnitude as the output power is rejected in the SOA fuel cells due to entropy changes in the electrochemical reaction (~30 % heat), irreversibility of the reaction (~60 % heat), and ionic and electric resistance (~10 % heat) [215]. Heat is mainly produced on the microscopic catalyst layer on each cell where the reaction takes place [186], requiring an internally integrated heating/cooling mechanism at least between every 2–4 cells. There are two available heat removal techniques, active cooling (using air, liquid, and phase change), and passive cooling (using heat pipes and heat spreaders). A generic fuel cell system level architecture for these

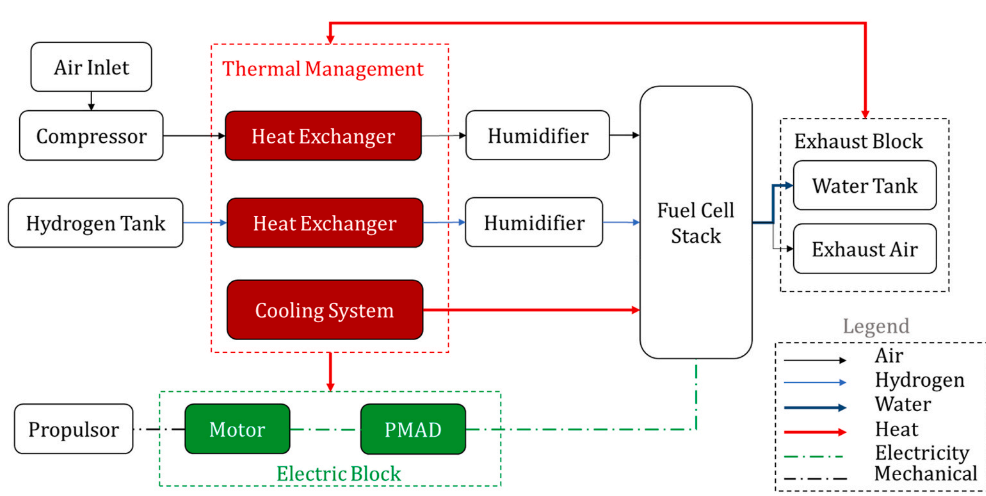

Fig. 9. Fuel cell system architecture (adapted from Ref. [146]) where PMAD is a power management and distribution system.

techniques is presented by Tomažič [216] whereas a cell level integration strategy to maintain cell temperature gradient below $10°C/\ cm$ is presented by Srinath et al. [173]. A comprehensive review of PEMFC thermal analysis, recent progress, and research gaps in these techniques is reported by Chen et al. [215] and Zhang et al. [217]. From a literature survey, Choi et al. [218] presented a chart indicating the suitability of various cooling methods based on the power level (see Fig. 10). Air cooling ([184,219]) and passive cooling (as reviewed in Ref. [209]) were previously used for power levels <10 kW and liquid and phase change cooling were desired for higher power levels. A numerical study of a 60 kW fuel cell system demonstrated a more compact system with evaporative cooling compared to liquid cooling (27 % reduction of radiator frontal area), integrating the water and thermal management systems [220]. Two-phase cooling with boiling is another technique with large heat rejection capability and a rapid dynamic response but requires a relatively complex system [218].

Future aviation requirements are expected to be in MW scales (CHEETA ~28 MW [221]), so liquid and phase change cooling may be a feasible choice. A two-phase cooling with boiling method (using a coolant like HFE-7100) may be necessary for LT-PEMFC with low-grade heat (a low-temperature gap to ambient conditions) whereas both liquid and phase change cooling could be applicable for the relatively high-grade heat of the HT-PEMFC. Nevertheless, HyPoint has demonstrated the potential of air cooling for MW-scale HT-PEMFC with compressed air circulation between stacks [214]. Air-cooled 16 kW HT-PEMFC and liquid-cooled 30 kW LT-PEMFC systems have been previously tested on Antares DLR-H2 [85]. Therefore, it must be noted that different TMS techniques may be best suited for different fuel cell technologies and different overall system architectures (design/integration).

Heerden et al. [222] presented a comprehensive review of the thermal management systems of a conventional aircraft. For maximum benefit at an aircraft system level, the TMS of the fuel cell system must be highly integrated (to achieve low mass and volume) with existing aircraft systems and with waste heat utilisation in place. The concept of utilising thermoelectric generators integrated with fuel cells for waste heat recovery is highlighted in Ref. [223]. Heat is normally rejected into the atmosphere with air-cooling systems. However, with liquid and phase change cooling, it can be utilised for in-aircraft practical uses including hot water availability or fuel heating with extra heat exchangers (eliminating cooling drag) [216]. However, some literature suggests only 15 % of heat can be dissipated into LH2 fuel and entrance air [29]. Some level of drag accounting from each component of a hybrid LT-PEMFC jet engine with phase change heat pump cooling is presented in Ref. [224]. In summary, waste heat utilisation and design of integrated TMS with minimum mass and drag impact is a research gap that needs significant future work.

7.3. Fuel cell evolution and projection

To develop a top-level understanding of whether fuel cell technology is a viable option for aviation, it is crucial to know the weight, volume, and performance impact of the fuel cell system in an aircraft. These can be characterized by specific power (SP), power density (PD), and efficiency of the system. These three quantities will be different for a fuel cell, stack, and system. For example, the LT-PEMFC stack level specific power of 5.5 kW/kg is demonstrated at a laboratory scale [123] but only 0.75–1 kW/kg is achievable with state-of-the-art technology when the additional mass of balance of plant (BoP) is accounted for a system level [213].

From an extensive survey [8,34,78,79,130,191–199,203,207,214, 219,225–230], a collection of fuel cell system level-specific power, power density, peak efficiency, and BoP mass fraction is provided in Table A 2 (of Appendix). BoP mass fraction is the mass of additional GMS, PCS, WMS and TMS as a proportion of the whole fuel cell system. The state-of-the-art peak efficiency of fuel cell systems is currently 45–50 % for aviation designed systems compared to already achieved 60 % for automotive. (Note that efficiency is a transient phenomenon and varies at each operating condition [186]).

Substantial discrepancies exist in most literature on the BoP mass fraction varying from 37 to 75 % for the LT-PEMFC while some literature only provides stack-level quantities, not including any information on BoP. To establish a comparison of fuel cell-specific power progress at a system level, a median data point has been assumed for the BoP (60 %) for converting from stack to system-level specific power for the LT-PEMFC where only stack-level quantities were provided (highlighted

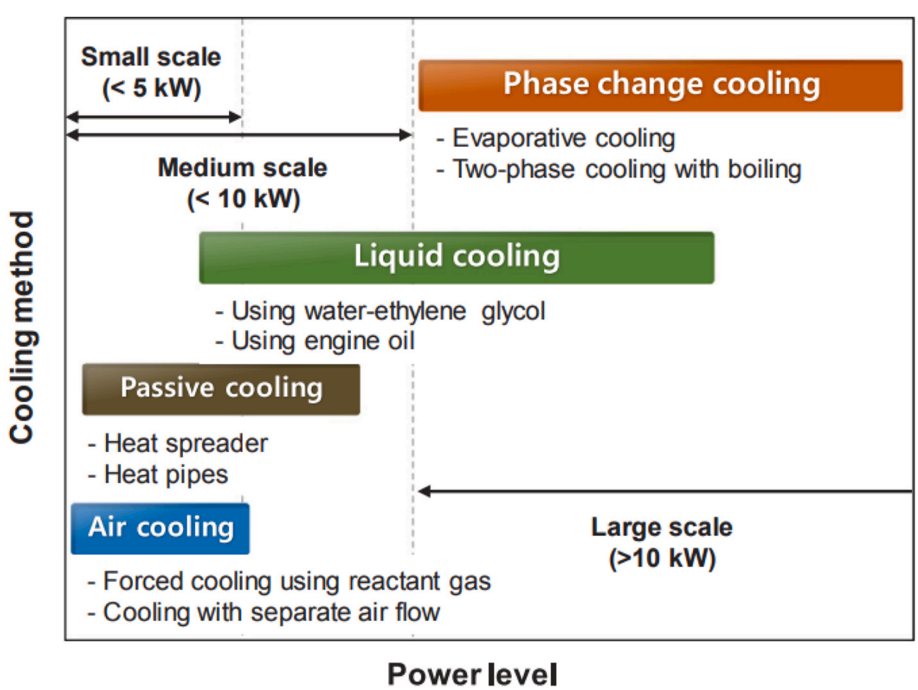

Fig. 10. Suitability of Various cooling methods based on power level [218].

in gold in Table A 2). Significant BoP proportion improvement (33–45 %) is observed for high-temperature fuel cells like HT-PEMFC and SOFC (40 % BoP assumed for conversion).

The power density, defined as the power output of the fuel cell system per unit volume, was hardly reported in any literature despite the significance of volume constraints in aviation. The stack level power density of the state-of-the-art automotive fuel cells varied from 1 to 4.7 kW/l for LT-PEMFC. Only Horizon Fuel Cell Technologies [191] provided the system level power density of 0.87 kW/l for an LT-PEMFC (4.7 kW/l stack level) which signifies the BoP makes up almost 80 % volume of a fuel cell system. This shows that significant work is required to develop a compact BoP as well as to improve the power density of the fuel cell stack and system.

To visualise the technological trend, the specific power evolution of the fuel cell system is presented in Fig. 11 (with auto for automotive and aero for aerospace). There is a clear trend that the specific power of the fuel cell has continually improved since 2000. The growth was comparatively slower up to 2015 because fuel cell technology was gradually being tested for application in the automotive sector (car, bus, and trains) in early 2010. With new inventions in electrolyte material and cell membrane structure, a rapid increase in specific power was possible after 2015 [194]. This led to commercialisation in the automotive sector which further enhanced research and development. This trend is expected to continue given the transfer of this technology into aviation, and with system specific power expected to reach 3 kW/kg. Note that in Fig. 11 several specific power predictions reported in aerospace-related literature are still based on the development trend of commercially available automotive fuel cells. Focusing on the future projection to the right of the dashed vertical line, in 2009 NASA [79] projected 1.7 kW/kg for 2035 LT-PEM fuel cells, whereas recently in 2022 FlyZero projected 3 kW/kg for both LT-PEM and HT-PEM fuel cells [130]. The difference in fuel cell capability before and after 2015, as highlighted above, is the reason behind this. Some extremely optimistic projections have been made by Unifier19 [228] which is highly uncertain because it has not specified the fuel cell technology type and has not discussed any evidence supporting the prediction. Kadyk et al. [227] even estimated 8 kW/kg for fuel cell systems without evidence and projection date (not in Fig. 11). HyPoint also provided an optimistic projection for HT-PEMFC achieving 3 kW/kg as early as 2025 predicted from modelling tools validated with an experimental test of a novel kind of HT-PEMFC [214].

AIA findings suggest that for a 2035 level aircraft design, a fuel cell system with a specific power of at least 1.5 kW/kg (above dashed horizontal line) is required to design 50PAX, 800NMI hydrogen fuel cell powered aircraft with 20 % higher energy consumption than a kerosene counterpart [34]. Therefore, if this trend of fuel cell-specific power is successfully sustained, hydrogen fuel cell-powered aircraft at least at a regional level will be feasible. In summary, substantial discrepancies have been observed between studies in specific power and the balance of plant mass fraction projections. Some aviation-related system design articles still lack fuel cell power density information. This shows that the fuel cell system is still a new topic for the aerospace research community and a reliable and consistent understanding of fuel cell systems is yet to be fully established.

7.4. Electrical architecture system (EAS)

A novel electrical architecture system is required to manage the considerable power produced by fuel cells up to MW scale, and to distribute this to each propulsor, flight sub-systems and avionics. The EAS includes motors and the power management distribution system (PMAD) which consists of converters, cables, inverters, buses, and switches. Battery electric research has achieved significant developments in these electrical components in the past decade. A comprehensive review of the electric aircraft powertrain including recent findings, challenges and future projections is provided in Ref. [231]. The US Department of Energy has funded 10 projects under the ASCEND program (2021–2024) to develop an all-electric powertrain for a Boeing 737 equivalent aircraft with a power density ≥12 kW/kg and with an efficiency of ≥93 % [232].

The EAS can be characterized by three different technologies: conventional non-cryogenic, hyperconducting and superconducting technology. Conventional non-cryogenic technology includes electrical machines, cables and other components based on conducting materials (copper or copper/aluminium alloys) at ambient temperature. Utilising non-cryogenic technology, the electrical components require air or liquid cooling to maintain near ambient temperature. In 2015, NASA [233] published an assessment of non-cryogenic electrical technology. With the current research trend [234], it projected a MW scale 13 kW/kg non-cryogenic electrical machine with >96 % efficiency by 2030. Power converters and inverters target of 19 kW/kg with 99 % efficiency has been set for 2030 [234]. A lab demonstration of a 13 kW/kg specific power permanent magnet synchronous machine has already been completed by Collins Aerospace and the University of Illinois Urbana-Champaign [235]. Hinetics is commercialising this concept with 1 MW, 10 kW/kg, ~98 % efficiency product currently at TRL 6 [236].

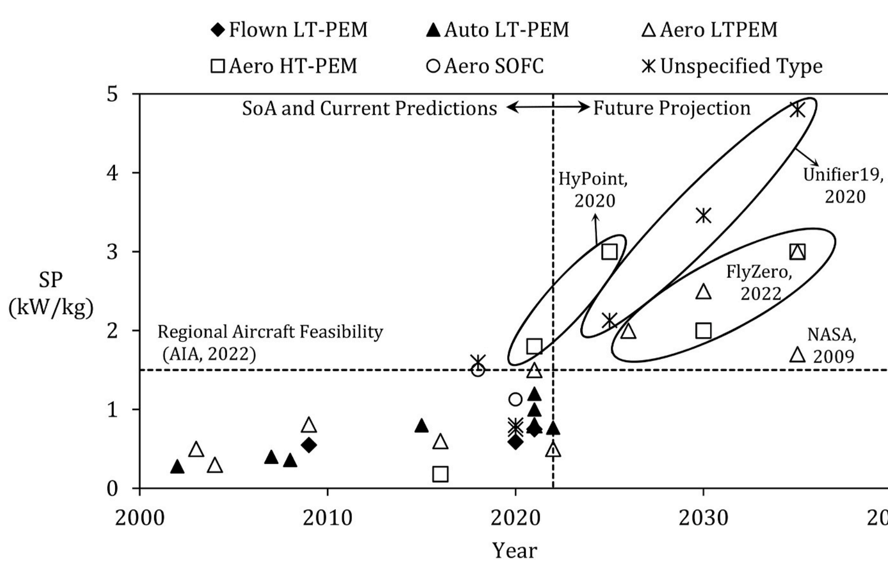

Fig. 11. Fuel cell system specific power evolution and projection (from Table A 2).

There is increasing start-up activity in this area. For example, magniX has supplied its ~600 kW non-cryogenic electrical machines to power battery electric (Eviation Alice) and fuel cell aircraft demonstrators (Universal Hydrogen) [237].

Superconducting technology utilizes superconducting materials (MgB2, YBaCuO) with almost no ohmic losses in cryogenic conditions (20–65 K). This technology can exploit onboard LH2 as a cryogen to cool electrical systems which have the potential of attaining significant system-level mass benefits. However, this requires a complex and highly integrated hydrogen fuel distribution system and EAS (see CHEETA concept Fig. 5). Since 2019, the CHEETA project has been working to mature such technologies [11]. Within CHEETA, Balachandran et al. [121] explored fully superconducting air-core machine designs with a potential of achieving 50 kW/kg specific power and 99 % efficiency, whereas Sirimanna et al. [120] provided a comparison of state of art conventional and superconducting electrical machines. Sirimanna et al. [120] also identified the major heat loads in superconducting machines and discussed potential cryogenic cooling techniques. Ansell [119] presented the power system architecture and temperature requirements of each superconducting electrical component along with the integration of fuel cell, EAS, and hydrogen distribution into the CHEETA aircraft concept [119]. ARPA-E in 2021, funded 6 projects under the Connecting Aviation by Lighter Electrical Systems (CABLES) programme to develop superconducting high-power density cables and dielectrics, and to investigate partial discharge issues at high altitudes [238]. In 2021, Airbus initiated its 3 years ASCEND ground demonstrator project to develop a 500 kW advanced superconducting and cryogenic experimental powertrain utilising LH2 as a cryogen [239].

Hyperconducting technology includes electrical components based on normally conducting materials with high chemical purity (Al 99.999 %, 20 K) which have a much lower specific resistivity for cryogenic temperatures (≤100 K). It has recently attracted some attention due to its potential to achieve significant mass savings when compared to non-cryogenic technologies but also not requiring rare and expensive superconducting materials. GKN Aerospace [98] is currently working on this technology within the H2GEAR project with an initial trade-off study indicating hydrogen electric aircraft viability could be pushed to 98PAX and beyond, in contrast to the sub-regional scale limitation previously assumed.

Sebastian et al. [240] presented a weight and efficiency comparison between conventional, hyperconducting and superconducting cable technologies for 40 MW class power transmission. Hyperconducting (Al 99.999 % at 20 K, TRL 4) wire produced a 5.4-time smaller heat load and weighed ~23 times smaller than conventional (Cupanol™ at 294 K, TRL 9) whereas superconducting (CORC™ at 20 K, TRL 4) cable produced 7.7 times further smaller heat load and weighed 1.15 times smaller than hyperconducting cable. However, the mass of extra components required to control, regulate, and distribute hydrogen was not included in this study.

Having high TRL, non-cryogenic systems have been utilised on demonstrators (ZeroAvia [81], Universal Hydrogen [80], CAeS [241], HAPPS [100], H2FLY [86]) whereas research and development of cryogenic technologies are ongoing and are expected to be adopted in near future. FlyZero suggests the potential utilisation of cryogenic technologies as early as 2030 [132].

It is noteworthy that the technologies discussed in this section are largely transferable to other systems including hybrid hydrogen propulsion systems (parallel/series hybrid or turbo-electric concepts with hydrogen burning turbines as a generator, fuel cell/gas turbine hybrid, fuel cell/battery etc. [204,242–247]). Cardone et al. [248], Bradly [249] and Rendon et al. [250] reviewed various hybrid propulsion architectures applicable to various fuels highlighting previous research, demonstrator projects, recent developments as well as challenges for technological adoption. For earlier EIS 2030–2040, the low specific power of the fuel cell limits its use to only regional aircraft. However, its use in hybrid propulsion architecture with gas turbines could enable higher propulsion system efficiency (up to 70 % [202,251]) and lower NO_x emissions compared to conventional gas turbine engines and could be viable for short to long-haul aircraft. CHEETA concept includes full electric (hydrogen fuel cell – battery) hybrid systems for short to medium-haul aircraft [123]. Seyam et al. [28] investigated a hybrid system with SOFC incorporated before the combustion chamber stage within a gas turbine, whereas Rupiper et al. [202] investigated flame-assisted SOFC incorporated between two combustion stages (fuel-rich and lean fuel combustion stages) which enabled a much simpler configuration requiring no external heating (or heat exchangers) for SOFC which significantly reduced their startup time. For hydrogen fuel, Rupiper et al. [202] found 24.5 % higher system efficiency with the integrated hybrid system compared to the conventional gas turbine baseline. Seitz et al. [206] although utilising a parallel hybrid architecture (SOFC system not integrated within the gas turbine cycle, and powering separate propulsors or other aircraft subsystems), still injected the water vapours produced by SOFC into the gas turbine core to enhance efficiency and reduce NO_x emissions. The NO_x emissions reduction of up to 62 % relative to the baseline engine and up to a 7.1 % block fuel burn improvement was possible with hybrid architecture. Liu et al. [205] and Collins et al. [251] investigated the potentials of turbo-electric hybrid systems (SOFC – battery – turbine generators) demonstrating potentials of up to 65–70 % system efficiency. The key challenge of a hybrid propulsion system is the complexity of the integration of two different energy conversion systems/propulsion topologies which require highly integrated and compact thermal management system design.

7.5. Fuel cell aircraft research and industrial progress

The investigation of fuel cells for aircraft propulsion started in 1984 [252], but this technology was not developed further until 2000. In 2004 [78] and 2009 [79], NASA completed a series of zero-emission aircraft studies, showing that fuel cell (hydrogen electric) propulsion was not feasible for any regional-mid haul aircraft (2004 SOA fuel cell system specific power ~ 0.3 kW/kg) despite aggressive assumptions on the advancement of fuel cell and novel aircraft designs over 30 years. In the meantime, several small fuel cell aircraft demonstrators were flown to prove the technology including the Global Observer [82] in 2005, the Boeing modified Diamond DA20 in 2008 [84], the Antares DLR-H2 (2009) [84], and the H2FLY (2016) [86]. After the revolutionary improvement in fuel cell specific power in 2015, fuel cell demonstrators reached the sub-regional scale. The HyFlyer I 6-seater Piper Malibu M350 [87] (2020), the 2023 ZeroAvia [81] demonstration of a modified 19-seat Dornier (one engine replaced with 600 kW LT-PEMFC system), and the 2023 Universal Hydrogen [80] demonstration of Dash8-300 aircraft (one engine replaced) are important milestones. ZeroAvia [81], Universal Hydrogen [80] and Cranfield Aerospace Solutions (CAeS) [241] have plans to commercialise MW scale propulsion system retrofit kits for ATR/Dash 8 (40-90PAX, 500-1000NMI) size aircraft as early as 2025. Airbus [253] and Embraer [103] are also targeting the regional market with fuel-cell aircraft concepts for 2035. Airbus has planned to perform a flight demonstration of a megawatt-class fuel cell propulsion system by 2026 on its test aircraft A380MSN1 which, if successful, would power a 100PAX, 1000NMI concept [254]. Fig. 12 presents some demonstrators' fuel cell propulsion systems and aircraft concepts.

Predictions from alternative fuel feasibility projects are in line with the plans of these demonstrators and manufacturers. The FlyZero [127] concluded that with 3 kW/kg LT/HT-PEMFC, a regional 75PAX, 800NMI aircraft is feasible by 2035 with 2.21 % higher energy requirement and 26 % higher MTOW compared to its conventional counterpart. The concept utilizes a 6-propeller system, fuel cell stacks, and BoP in the underside of the fuselage of the aircraft [127], whereas the Airbus concept [253] has 6 self-contained fuel cell propulsion system pods on the wing, each acting as a standalone turboprop. The AIA programme

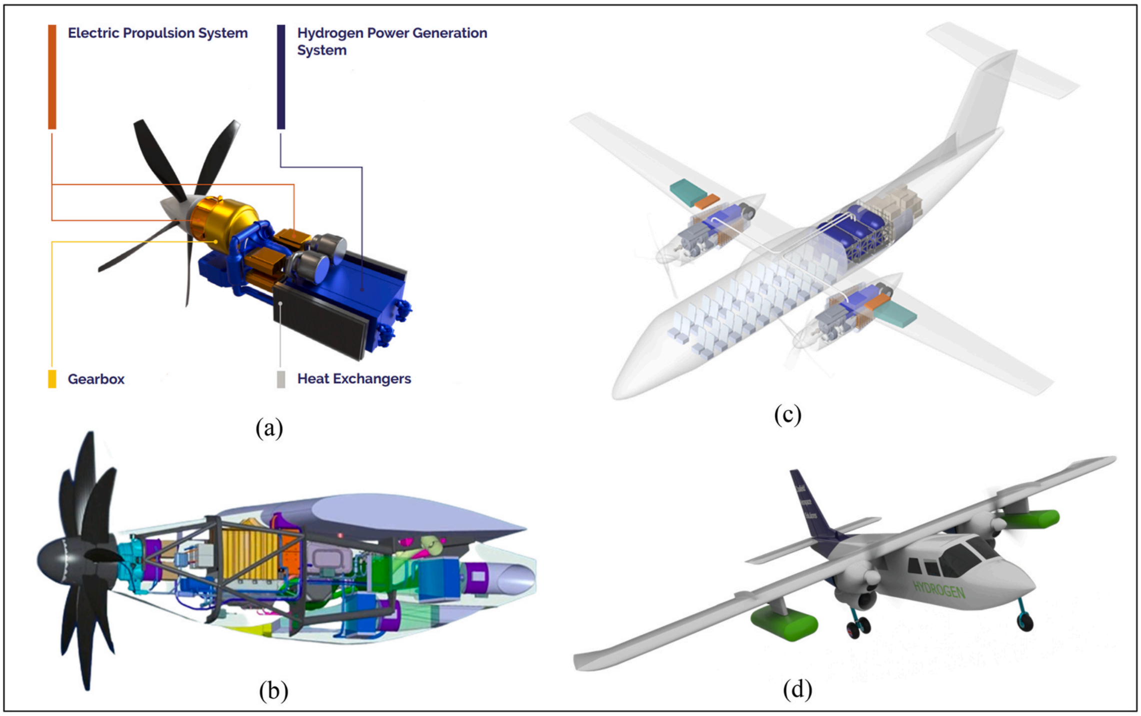

Fig. 12. Demonstrators fuel cell propulsion system and aircraft concepts (a) ZeroAvia [81], (b) Airbus [104], (c) Universal Hydrogen [80] and (d) CAeS [241].

showed the potential of 50PAX, 800NMI regional propeller aircraft with just 1.5 kW/kg specific power [34], and further publication of findings and disclosure of important assumptions in the key enabling technologies are expected in the near future. Considering 2050 timescales, the CHEETA project shows that fuel cell potential will extend to electrifying short haul 160PAX, 3750NMI aircraft using a 2.73 kW/kg HT-PEMFC, a revolutionary superconducting power system, and highly integrated airframe with DP and BLI [119].

The choice of the EAS will have a crucial impact on aircraft-level integration and hence could demand different aircraft configurations. For cryogenic systems, a highly integrated fuel and electrical system is required. A highly distributed propulsion system might be beneficial for higher aerodynamic efficiency, but this would require large lengths of integrated cables and hydrogen fuel supply pipes routing around the whole aircraft with negative effects on mass and safety. Localised propulsion pods each acting as a standalone turboprop (like retrofit demonstrators and Airbus concept) could therefore be an effective solution. An investigation of various aircraft-integrated thermal management strategies for both fuel cell stacks and required electrical systems, identifying the design and integration challenges and quantifying aircraft level mass and performance comparisons, will be required in future. It is also noteworthy that current fuel cell aircraft plans for 2034 are only based on low-altitude and low-speed propeller-powered aircraft hence significant research and development of ducted fans or open rotor concepts are necessary to enable high-altitude and high-speed flights.

In summary, while considered unattainable before 2010, the developments in fuel cell system technology, electrical system architecture and airframe developments have made fuel cell electric aircraft commercialisation highly likely by 2035 in the regional market of 50–70PAX and 800NMI. In the context of hybrid systems, the integrated use of fuel cell electric architecture as well as gas turbines would enable higher propulsion system efficiency, lower NO_x emissions and ultimately could achieve system-level fuel burn benefits compared to conventional gas turbine engines.

8. Safety and certification

Safety remains a controversial topic when it comes to hydrogen-associated technologies. The lower end of the flammability limit is 4 % for hydrogen compared to 1.4 % for kerosene, so a fire can only start if the concentration of hydrogen is more than 4 %, 3 times larger than for kerosene [57]. The auto-ignition temperature of hydrogen (550 °C) is also much higher than kerosene (220 °C) [172]. However, the minimum ignition energy of hydrogen (0.02 mJ compared to 0.25 mJ for kerosene) is extremely low which makes hydrogen prone to ignition even with a weak spark. The hydrogen-exposed systems (fuel system, storage, and engine parts) are susceptible to material embrittlement and hydrogen permeations, so careful material selection is crucial [148]. Hydrogen is a flammable and odourless gas, and any leaks are difficult to detect. This requires novel gas leakage detection and fire detection devices as well as prevention techniques to ensure aircraft safety. Due to the cryogenic storage, any large spillage can quickly condense the air before getting dispersed forming cold clouds drifting to large areas [171]. Also, any oxygen-enriched solidified air with hydrogen can lead to an explosion if there is ignition [172]. Most current findings based on experiments and modelling suggest that hydrogen could be as safe as kerosene if robust systems for fuel storage, fire detection/containment and ventilation are in place. However, previous accidents like the Hindenburg disaster in 1937 and the 1986 Space Shuttle Challenger launch have adversely affected public perception of the safety of hydrogen. Public surveys show that only 49.5 % of the population think hydrogen is a safe fuel to use in transportation [255].

To assess the safety of LH2 aircraft, the Lockheed 1970s study developed modelling tools evaluating four accident scenarios [43,46] from small internal leaks due to cracks in fuel lines to non-survivable crashes. These modelling tools were validated using the previous experiments of a LH2 detonability test by Lockheed in 1956–1957, and a spill test by the US Air Force in 1958 and NASA in 1980. The results showed that purge air and drain holes are required in the fuel system compartments to prevent the formation of a combustible mixture. The LH2 spill had a shorter vaporisation time and a smaller spill area on the ground compared to kerosene. The ignition further increased the vaporisation rate and decreased the spill spread. LH2 spill fuel burnout time was found to be shorter than the fuselage collapse time from hydrogen flames, suggesting that passengers could remain seated in case of fire for hydrogen aircraft but for kerosene, immediate evacuation is necessary (Assumption: no failure of internal cabin isolation systems until fuselage collapse). However, the effect of the window was not included which could fail first. Lockheed's 1970s [43,46] study concluded that in consideration of spill release, spreading, vaporisation, dispersion and burning in different scenarios, LH2 offers "*many advantages when compared to JetA*". The EQHHPP project discussed basic airport safety considerations of integrating hydrogen production, liquefaction, storage, and distribution [48]. Experiments with the ground release of LH2 between two buildings were conducted to understand the dispersion behaviour in a residential area. Cryoplane 2000s cites two technical publications on safety relating to tank location, fuel system, fire protection and emergency landing, but these are not publicly available [51]. It concluded that from a safety perspective, there is "*no fundamental problem*", preventing the successful operation of LH2 aircraft. Imitating an LH2 hose line failure during tanker refuelling, the UK Health and Safety Laboratory [256] did some unignited tests with 0.071 kg/s spill on the ground and spill from 1 m above ground. The results showed a 9 m downwind ground distance of the flammable gas cloud and the cloud stayed close to the ground for wind speed > 5 m/s whereas it was buoyant for windspeed < 3 m/s.

More recently, ENABLE-H2 [10] has conducted extensive work on hydrogen safety in aviation. Reviewing existing industrial safety standards, and previous experimental and research work Benson et al. [114] presented a preliminary hazard analysis for hydrogen storage, fuel distribution, heat management and combustion systems. A gap analysis is provided with future work identified for each hazard category. Addressing the lack of knowledge of the altitude effect (low pressure and temperature) on flammability and ignition [115], an experimental rig has been developed (up to 150 mbar and −50 °C operation). Investigating hazards related to liquid hydrogen in airports, Benson et al. [115] suggest that firefighting had the highest risk factor highlighting a need for new techniques, devices, and regulations for firefighting. Reviewing previous modelling work, Holborn et al. [117] presented the FLACS computational fluid dynamics model for explosion and atmospheric dispersion modelling in the investigation of a large-scale LH2 pool release. It was shown that higher wind speeds resulted in a larger ground flammable distance for a vaporising and dispersing LH2 pool [115]. Comparison of the model with the NASA 1980 spill test showed a consistent prediction of pool size and similar trends with wind speed and spill rate, although the magnitudes were underpredicted. Holborn et al. [116] simulated various accident scenarios for small leaks to tank rupture, and LH2 spill resulted in rapid vaporisation, and high-intensity flames but for shorter periods, lower total thermal radiation dose and smaller hazardous distance (similar to Lockheed 1970s).

The literature review suggests certification is the most critical and yet least considered aspect. However, most studies have highlighted aspects of aircraft to airport-level requirements for safe operation with hydrogen, which could form a starting point for system certification. Reviewing current CS25 certification based on kerosene, Spencer [257] identified which existing certification requirements and compliance could be applicable and which ones require modification by defining a special case for liquid hydrogen. The study highlighted the requirement of a complete 'Functional Hazard Analysis' along with preliminary-level aircraft design with hazard mitigation for proper certification development, a process which needs to be considered from the research and development and preliminary design phases.

9. Phases of hydrogen introduction in aviation

The survey of the literature and market shows that aviation is heading for three stepwise stages for hydrogen introduction: technical demonstration and certification (2025–2030), system-level optimisation (2030–2040) and aircraft fleet development (2040–2050). During the first phase, fuel cell powered sub-regional and regional retrofit aircraft are expected to be operated from very few experimental regional airports with hydrogen delivery by road. Research and experimentation on enhancing TRL of enabling technologies will be prioritised in academic and industrial sectors. Investments in airport and hydrogen distribution infrastructure planning must be accelerated at this stage. In the second phase, system-level optimised regional aircraft powered by fuel cells and narrow-body aircraft powered by hydrogen combustion engines such as FlyZero, ZEROe and Embraer concepts are expected to enter the market by 2035. Some large international airports are likely to adapt for hydrogen operation after 2035. NAPKIN [125] findings suggest that due to low demand, hydrogen delivery by road will be sufficient till 2040 with no permanent airport infrastructure requirement. In the final stage, rolling out a family of aircraft fleets along with the introduction of the combustion engine-powered mid and long-haul aircraft is expected by 2040–2050. Highly integrated concepts exploiting novel airframes, propulsion configurations and superconducting electrical systems such as the CHEETA and ENABLE-H2 concept could be rolled out. Permanent liquid hydrogen storage and pipeline infrastructure will be needed at major airports. However, on-site production with electrolysis and liquefaction is still unlikely till 2050 due to the high-power demand of up to 3–4 GW required for electrolysis [125]. Fig. 13 presents these three phases with timelines.

Hydrogen aircraft and infrastructure network development might take several decades, so even with the current substantial momentum of hydrogen research and development, a net zero target by 2050 is extremely unlikely. Hence, both SAF and carbon capture and storage will also play critical roles in narrowing the net zero gap. Some studies suggest an optimistic and aggressive approach for rapid development of a global hydrogen network. Huete et al. [140,258,259], suggested utilising existing manufacturing capability to create a family of very large aircraft (A380 and A350 type) with different hydrogen tank arrangements within fuselage capable of covering the whole globe with a single stop. At the expense of performance and cost inefficiencies in the early stages of adoption and operation, this could incentivise a ramp up in global investment allowing faster creation of a global hydrogen network. FlyZero [127,9] also recommended the introduction of mid-size aircraft first by 2030, so investments are focused on large international airports' hydrogen infrastructure development at an early stage (rather than experimental regional airports).

Considering the risk and uncertainty in hydrogen infrastructure development, aircraft using both hydrogen and kerosene (or SAF replacement) in dual-fuel adapted combustion engines or hybrid electric systems is also a new topic of interest in aviation. Some literature on experimental and numerical studies of hydrogen and conventional dual-fuel combustion systems were recently published [260–262]. Diamond Aircraft, a subsidiary of Austro Engine, plans for dual-fuel combustion engine EIS for General Aviation by 2025 [263]. Smith and Mastorakos [264] present an energy system analysis and comparison of a LH2 aircraft and a LH2 dual fuel combination with kerosene and natural gas for 2050 timescales, indicating an increasing interest in a dual-fuel capability for commercial flight.

10. Conclusion

Growing awareness of the environmental crisis and the resultant net zero policies from governments and corporate entities have fuelled the global momentum of hydrogen aircraft research and development. Even with differences in technological assumptions, Lockheed 1970s, Tupolev 1970s, Cryoplane 2000s and FlyZero 2020s have concluded the technological feasibility of hydrogen powered aircraft. Reviewing current developments, aviation is paving its path to commercialise hydrogen electric sub-regional and regional aircraft, and hydrogen combustion short-mid haul aircraft, by 2035. Whether or not net zero is achievable by 2050 is inconclusive owing to the large uncertainties and

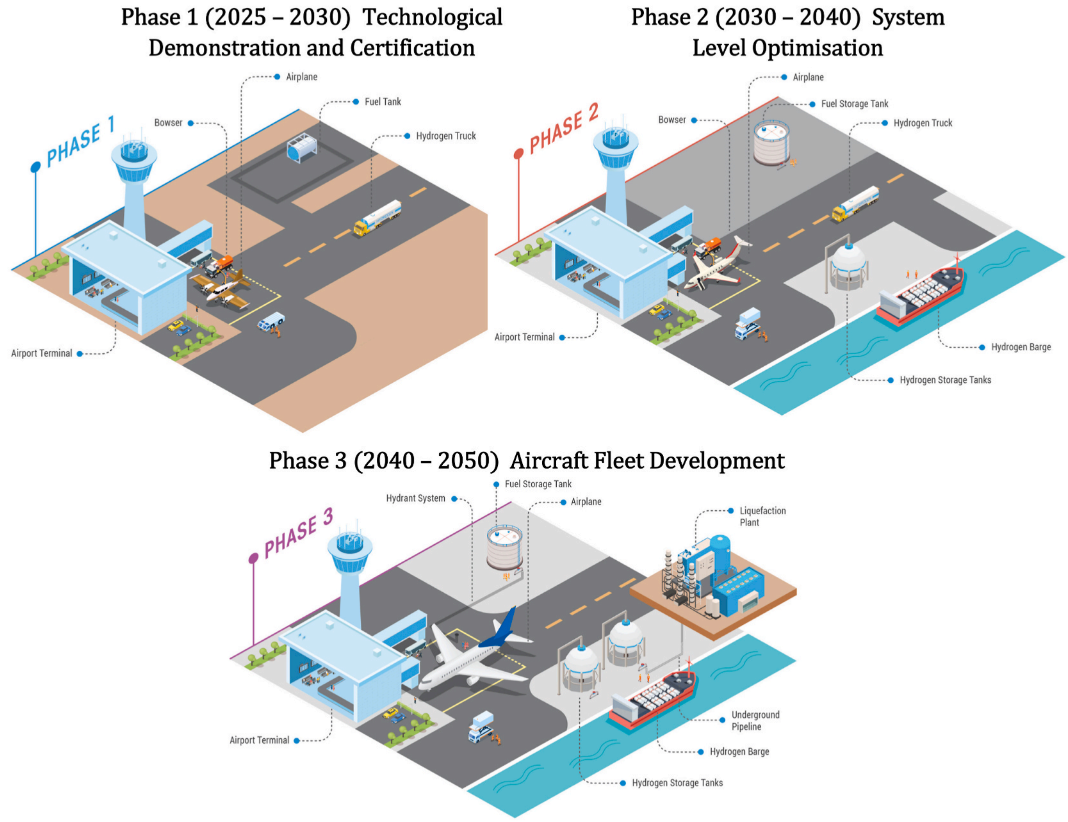

Fig. 13. Phases of hydrogen introduction in aviation (three images from NAPKIN [125,20]).

assumptions required on the enabling technologies and their impact. Certification and legislation, infrastructure development and integration into the airports, and financial commitments also remain barriers to achieving this objective.

Conventional aircraft configurations with storage inside the fuselage are the most favourable short-to medium-term solutions in terms of complexity as well as performance. Given the research and development cost of hydrogen propulsion, fuel systems and hydrogen supply chains, and the ambition to achieve a substantial reduction in carbon output by 2050, the aviation community is unlikely to adopt a more revolutionary change in aircraft design such as the BWB over this timescale. There is a need for a high-fidelity aero-thermal and structural work to assess tank placements and different integration techniques. Aluminium-based tanks, due to their high TRL, are likely to be prevalent in the initial stages. Composite tanks have the potential for gravimetric efficiency improvements, so investigation of composites at cryogenic temperature and new manufacturing techniques will be important. Foam and MLI both show good potential for tank insulation. A cryogenic fuel tank gravimetric efficiency of 70 % or above is expected by 2035. Tank design depends on many factors and requires careful optimisation based on mission and aircraft requirements. A review of safety and certification on venting is also necessary. Substantial work is required for the detailed design and test of cryogenic fuel system architectures for aircraft.

Hydrogen burning gas turbine engines are relatively more mature than other technologies, as indicated by previous records of ground and flight testing, and in light of the more recent developments from several engine and airframe manufacturers. Research on the effect of altitude on flammability and ignition of hydrogen and detailed combustor designs are ongoing. Engine-integrated heat exchangers for fuel conditioning and thermal management are important requirements. Previous research indicates that using a heat exchanger at the engine exhaust is the most straightforward and impactful measure of improving system efficiency, and thus is expected to be exploited in early engines. Full waste heat utilisation with integrated engine oil cooling, turbine blade cooling, compressor pre/inter-cooling and a fuel expander cycle is expected to be implemented in future. Detail design and testing of heat exchanger configurations for potential alternative engine cycles are required at this stage.

Fuel cell technology has developed rapidly in the past decade and is a popular powerplant choice in recent demonstrator aircraft. The projections show that the system-level specific power of fuel cells will reach around 3 kW/kg in 2035, unlocking the potential for all-electric regional hydrogen aircraft of up to 75PAX and 800NMI. However, there are substantial discrepancies between studies in fuel cell-specific power and power density projections, and the balance of plant mass fraction. Research on fuel cell technologies, including the design of compact BoP is required. With fuel cell efficiencies around 50–70 %, thermal management and waste heat recovery are critical in determining overall system efficiency. At the time of writing, 60 % of the weight of a LT-PEMFC system is attributed to the BoP, but a transition to HT-PEMFC (with an associated 40 % BoP) is expected as the technology develops. In terms of electrical architecture systems, the super-conducting and hyperconducting technologies integrate both the liquid hydrogen fuel system and electrical distribution system achieving significant mass savings. To date, these technologies have only been demonstrated in a laboratory, and the heat loads on the fuel line require careful management if fuel system efficiency and operating integrity are to be maintained. Therefore, scaling fuel cell propulsion systems for regional aircraft or beyond would require a revolutionary change in integrated thermal management system design.

In the context of safety, extensive modelling has been used to conclude that hydrogen fuel is safer than kerosene. These tools are mostly validated with experimental observations from 1957 to 1980. Hence there is a requirement for new experimentation, particularly concerning large liquid hydrogen spillages with and without ignition scenarios. Research on certification is also limited, and collaborative projects involving stakeholders from certification boards and the industrial and academic communities are urgently required as these projects continue to move at pace.

In terms of environmental emissions, the fuel cell propulsion system could achieve true zero emissions with exhaust conditioning. On the other hand, hydrogen combusting systems would still produce NO_x and contrails. Hydrogen-burning turbines are anticipated to be needed for mid to long-haul aircraft. New combustor technologies show potential for NO_x reduction by 80 %. Regarding the impact of contrails, there is significant uncertainty about their impact within individual studies as well as among researchers and industry experts, requiring an urgent need for experimental tests for the quantification of their greenhouse effect, considering the particulate content of the exhaust gases, and the option of implementing careful route planning as a mitigation.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2023.12.263.

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