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Hydrogen propulsion systems for aircraft, a review on recent advances and ongoing challenges

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A B S T R A C T

Air transportation contributes significantly to harmful and greenhouse gas emissions. To combat these issues, there has been a recent emergence of aircraft electrification as a potential solution to mitigate environmental concerns and address fuel shortages. However, current technologies related to batteries, electric machinery, and power systems are still in the developmental phase to meet the requirements for power and energy density, weight, safety, and reliability. In the interim, there is a focus on the more electric and hybrid electric propulsion systems for aircraft. Hydrogen, with its high specific energy and carbon-free characteristics, stands out as a promising alternative fuel for aviation. This paper is centred on the application of hydrogen in aircraft propulsion, mainly fuel cell hybrid electric (FCHE) propulsion systems. Furthermore, application of hydrogen as a fuel for the aircraft propulsion systems is considered. A comprehensive overview of the hydrogen propulsion systems in aviation is presented with an emphasis on the technical aspects crucial for creating a more sustainable and efficient air transportation sector. Additionally, the paper acknowledges the technical and regulatory challenges that must be addressed to attain these goals.

1. Introduction

Fuel shortage is the other principal concern which has been addressed for the transportation systems. Considering an anticipated 20% increase in the aviation industry growth rate by 2040, a surge in fuel demand of up to 38% or 120 billion litres is expected just in the U.S [1,2]. This growth, in turn, is expected to cause a 12% increase in emissions in this sector [3]. As a result, the industry has set challenging targets for reducing CO_2 content per passenger by 75% and nitrogen oxide emissions by 90% before 2050 [4].

To achieve these goals, some efforts have been made to control the emitted CO_2 in the aviation sector. The decrease can be achieved by advancements in technology (T), enhancements in operations and infrastructure (O), utilization of sustainable aviation fuels (F), and implementation of offsets and other carbon mitigation strategies (M), as illustrated in Fig. 1. Source: Adapted from Refs. [5,6]. Over the past 30 years, there has been a 54% reduction in CO_2 emissions per passenger per kilometre due to successful measures.

Electrification of aircraft systems is considered one of the principal approaches to suppress environmental concerns. Depending on the degree of electrification, electric propulsion systems for aircraft may be classified as more electric, hybrid electric, and fully electric. In the more electric propulsion systems, mainly aircraft actuation systems are targeted and are replaced with electric versions. This can enhance the efficiency of the propulsion system owing to the better efficiency and reliability of the electric actuators. As a result, less fuel consumption and exhaust emissions for the aircraft as well as larger reliability in its actuation systems are expected.

The fundamental principle of electric propulsion lies in utilizing one or more electric motors to drive some propellers to generate the necessary thrust force. These electric motors are powered by an onboard energy storage system (ESS), mainly a battery system.

Despite the immense potential, several challenges must be addressed to fully embrace aircraft electrification. One major hurdle involves the development of high-energy density batteries that can deliver sufficient power and energy for commercial aircraft while maintaining the total weight and volume reasonable. Although batteries have made significant advancements in recent years, they still lack the energy density of traditional jet fuel. Consequently, electric aircraft will have a shorter range, restricting their commercial viability. Accommodation of the battery system is the other challenge from the safety point of view, incorporating high-voltage electrical systems in aircraft raises safety

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concerns that demand careful consideration to ensure passengers and crew's safety and advanced power management and protection systems need to be developed for this purpose.

Alongside the electrification and until the development of fully-electric propulsion systems for aircraft, utilizing alternative low-carbon, high-energy-density alternative fuels is viewed as another solution to meet the target emission reduction requirements [8].

Hydrogen, owing to its carbon-free content can considerably contribute to reducing air transportation carbon footprint when burned as a fuel in the combustion chamber. Moreover, it might be used to use FC systems in hybrid electric FC propulsion systems [9,10]. In this case, the high specific energy of hydrogen (33.3 kWh/kg) is viewed as a substantial advantage for aircraft where weight is a main concern [11]. Fig. 2 compares the specific energy and the volumetric energy density of hydrogen fuel with batteries and some conventional fuels. As seen in this figure, hydrogen has a significant specific energy implying its high potential for being used as an ideal fuel for aircraft. However, it is very low volumetric energy is challenging and should be considered in the on-board H_2 energy in aircraft.

Fig. 3 shows the required specific energy to produce 50 kW of electricity in four different propulsion systems: a direct hydrogen FC, an indirect hydrogen FC (which extracts H_2 from kerosene via onboard reforming), a system coupling a kerosene-fueled internal combustion engine with an electric generator, and an electrochemical battery system. As illustrated in the figure, the battery system displays a lower specific energy requirement than all other systems, while the kerosene internal combustion engine/generator system delivers superior performance in this regard. Meanwhile, the FC system, particularly when paired with an onboard reformer, exhibits specific energy like the kerosene engine/generator configuration, implying that FC systems outperform electrochemical battery systems in terms of specific energy. This is an important factor in the aircraft propulsion systems implying the effectiveness of FC systems for aircraft propulsion.

Table 1 summarizes the technologies that may be used for aircraft propulsion to decrease harmful emissions and CO_2. As seen in this table, FC propulsion technology could be imagined to be implemented in aircraft only after the year 2045 when Li-air battery technology and H_2 cryogenic tank technologies are well developed. Meanwhile, using Li–S battery technology and pressurized H_2 tank technology would be viable to incorporate a hybrid proton exchange membrane (PEM) FC/battery propulsion system in aircraft after the year 2035.

Very limited reviews have been done on aircraft hydrogen propulsion systems. For instance, recently, a review of the technologies employed for liquid hydrogen propulsion systems was carried out [17]. However, ongoing research in this field and challenges were not addressed in the review. In another work, a review of the chronological progress of hydrogen technology in aircraft highlighted major obstacles to its application, including low pressure and temperature [18]. Current key technologies for hydrogen-powered aircraft were examined in a recent study [22], which concluded that, except for economic costs requiring more study, hydrogen propulsion could be a promising alternative to conventional propulsion systems.

Although some works have been reported on applying hydrogen for aircraft propulsion, a comprehensive review on this subject is missing in the literature. This paper follows a comprehensive review methodology, primarily focusing on existing research related to hydrogen propulsion systems in aviation. A systematic search was conducted across various scientific databases and journals to identify relevant studies and papers. Selection criteria were based on their relevance to hydrogen use in aircraft propulsion, either as a fuel or in fuel cell systems such as Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC).

Once the literature was collected, the studies were organized thematically, covering key aspects such as the configuration, structure, balance of plant, and multi-stack FC systems. The narrative approach was employed to synthesize these findings and critically evaluate the advancements in hydrogen technologies, including energy management strategies and the challenges of hydrogen storage, water management, and fuel cell degradation. The review also highlights the future potential of these technologies, incorporating both technical insights and regulatory considerations.

In section two application of H_2 as a fuel for aircraft propulsion is explored. In this section first, the alternative fuels for aviation including H_2 are explored and H_2 production methods on an industrial scale are discussed. Furthermore, a cost analysis of the conventional and the H_2 fuel is presented. Finally, a survey on the application of H_2 fuel as a fuel in aviation is conducted.

Section three is devoted to the FC propulsion systems for aviation where various FC systems that could be employed for aviation propulsion are introduced and their characteristics are discussed and compared with those of the ESSs. Moreover, various hybrid electric configurations that employ FC systems and their corresponding structures including passive and active systems are presented and their applications in various-size aircraft are discussed. Furthermore, the history of the commercial implementation of FC systems in aircraft is presented. In continue, special focus is put on the PEMFC and SOFC systems as the most common types of aviation FC systems and the application of these systems in UAVs, regional, and large aircraft propulsion systems as well APU systems are explored. are explored. Finally, other FC systems employed in aviation are discussed.

The challenges for H_2 application in aviation and the future perspective are discussed in section four where on-board H_2 storage methods including compressed H_2, liquified H_2, cryo-compressed H_2, and material-based H_2 storage methods and their corresponding challenges are discussed. Furthermore, contrail formation and balance of plants are explored in the H_2 propulsion systems for aircraft.

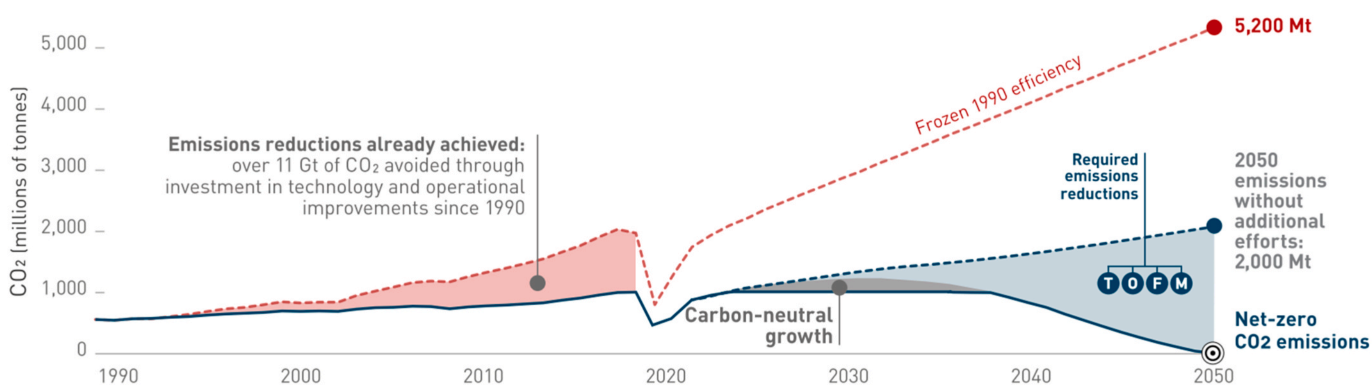

Fig. 1. Comparison between CO_2 emissions prediction with and without additional measures [7].

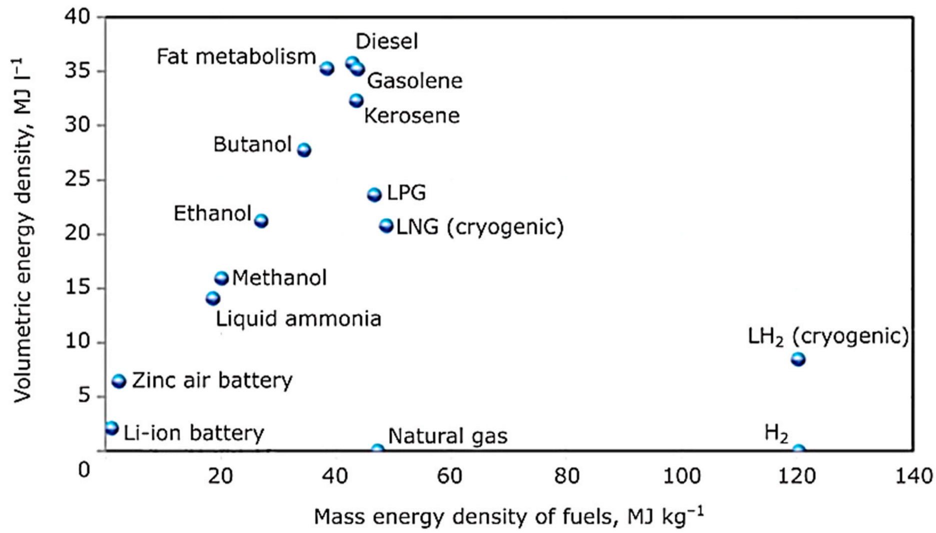

Fig. 2. Volumetric and mass-energy density for some fossil fuels vs electrochemical batteries [14].

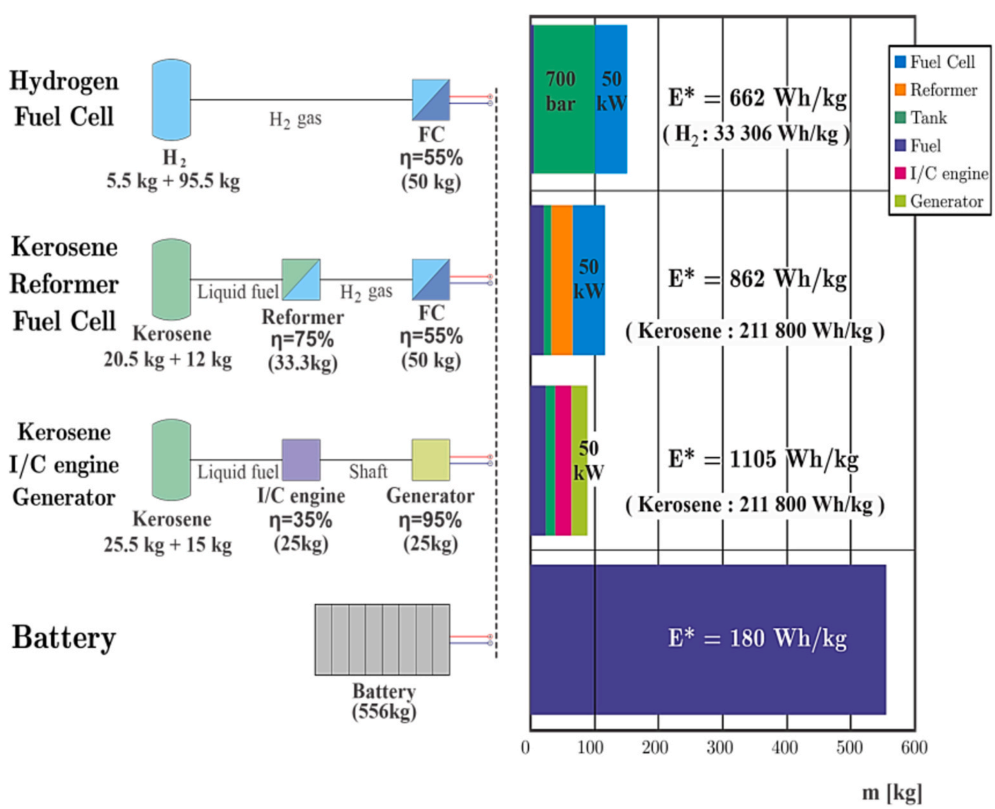

Fig. 3. Comparison of the specific energy density for 50 kW output power at various configurations [15].

2. Hydrogen as aircraft fuel

At present, kerosene is the most commonly utilized aviation fuel due to its superior combustion and ability to lower flight costs in comparison to other fuels [12].

The other aircraft fuels [21] maybe categorized as bio-jet, electro, and synthetic fuels, as seen in Fig. 4. The primary energy sources come from various origins including fossil fuel, renewable energy, vegetable oils, etc.

The significant energy content of liquid jet fuel, in terms of both specific energy per unit mass and energy density per unit volume, poses difficulties in seeking alternatives. However, hydrogen fuel shows promise in outperforming traditional fuels due to its lower carbon footprint [10]. Cryogenic fuel, which denotes fuels in a liquefied state at extremely low temperatures, typically below −150° Celsius, may prove advantageous for aircraft applications due to its condensed volume. Initial research indicates that utilizing cryogenic fuels like LH_2, LNG, and liquefied bio-methane has the potential to decrease the overall CO_2 emissions of upcoming electric aircraft [8]. Using hydrogen as a fuel for aircraft propulsion is preferable to fuel cells plus electric motors due to volume and mass concerns in hybrid electric fuel cell systems [19]. A study on using hydrogen as a fuel for aircraft gas turbines considered aspects like hydrogen storage, fuel flexibility, flame stability, and emissions. It concluded that hydrogen has the potential to replace

Table 1
Overview of the prospected technologies to be implemented in aircraft propulsion [16].

Time Interval	(2025–2035)		(2035–2045)		(2045–2050)	
Powertrain	ICE	ICE + Battery	ICE + Battery	PEMFC + Battery	SOFC + Battery	PEMFC + Battery
Electrochemical batteries	–	*Li – ion*	*Li − S/SSB*	*Li − S/SSB*	*Li − S/SSB*	*Li − S/SSB*
Fuel cells	–	–	–	PEMFC	SOFC	PEMFC
Main electric machines	–	Liquid Cooled PMSM	Halbach Array PMSM	Halbach Array PMSM	Halbach Array PMSM	Halbach Array PMSM
Complementary electric machines	–	Liquid Cooled PMSM	Liquid Cooled PMSM	Halbach Array PMSM	Halbach Array PMSM	Halbach Array PMSM
Fuel	Kerosene (jet A-1)	SAF (HEFA-SPK)	SAF (HEFA-SPK)	Hydrogen	Hydrogen	Hydrogen
Hydrogen storage	–	–	–	Pressurized Tanks	Cryogenic Tanks	Cryogenic Tanks
Converters	–	Sic converters	Sic converters	SiC Converters	GaN converters	GaN Converters

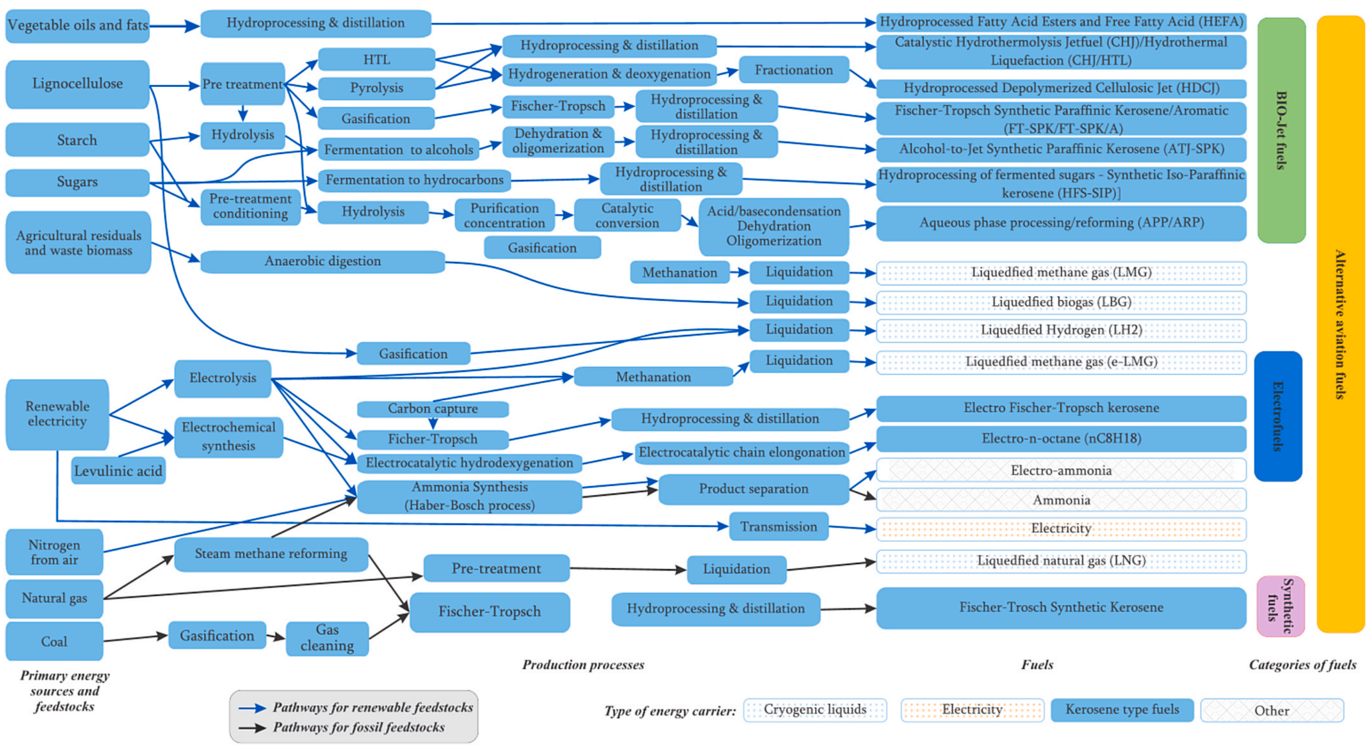

Fig. 4. Schematic diagram for aircraft fuel production [20].

conventional fuels in aircraft propulsion systems [23].

Depending on its production method, H_2 can be fit in either electro-fuel or synthetic fuel. Electro-fuel H_2 is generated through water electrolysis, while synthetic H_2 is predominantly derived from fossil fuels through chemical processes.

Most of the hydrogen production worldwide is currently derived from reforming using fossil fuels, primarily natural gas (CH_4) and coal [24]. When natural gas is utilized, it can be processed through three different methods: steam reforming, auto-thermal reforming, and partial oxidation. Steam reforming involves a reaction in which methane and water vapor (H_2O) are converted into hydrogen and undesired carbon monoxide (CO), which is emitted into the atmosphere. The process occurs within a temperature range of 700–850 °C and at a pressure range of 3–25 bar. The reaction can be represented by Equation (1) [11].

$$CH_4 + H_2O + \text{heat}\ CO + 3H_2 \tag{1}$$

In the course of partial oxidation reactions, methane is partially burned in the presence of oxygen gas, leading to the formation of carbon monoxide and hydrogen (Eq. (2)) [11].

$$CH_4 + 1/2O_2\ CO + 2H_2 + \text{heat} \tag{2}$$

The thermal auto-reform process combines steam reforming and partial oxidation, operating at temperatures between 950 and 1100 °C and pressures up to 100 bar. This integrated method allows for the simultaneous reactions of steam reforming and partial oxidation to take place (Eqs. (1) and (3)).

$$CH_4 + H_2O + heat\ CO + 3H_2 \quad (3)$$

$$CO + H_2O\ CO_2 + H_2 + heat \quad (4)$$

Coal has the capability to undergo conversion into hydrogen by means of gasification methods like fixed bed, fluidized bed, and entrained flow. During a standard gasification reaction, both the coal (fuel) and the gasification agent experience changes, leading to a blend that includes carbon monoxide and hydrogen, as illustrated in Equation (5).

$$C(s) + H_2O + heat\ CO_2 + H_2 + heat \quad (5)$$

Fig. 5 provides a more detailed understanding of one of the synthetic methods for H_2 production, specifically power-to-liquid fuel (PtL) conversion. In this process, renewable energy is initially employed to generate hydrogen from water through electrolysis. The produced hydrogen is subsequently combined with carbon dioxide (CO_2) captured from the atmosphere or other sources, including industrial emissions, to synthesize hydrocarbon fuels.

Table 2 [10] poses the thermodynamic properties of gaseous and liquid hydrogen fuels with those of E-kerosene and jet A fuels. Notably, the specific energy of hydrogen is three times larger than that of kerosene and jet fuel. Additionally, the energy density and fuel density of liquid hydrogen are 4 and 10 times greater than those of kerosene, respectively, necessitating significantly more space for a hydrogen reservoir. The feature distinguishes LH_2 as a top choice for increasing payload capacity and expanding the range of possible aircraft configurations [3,10]. In a study conducted by Ref. [27], the possibility of using hydrogen as a fuel for aviation propulsion was discussed, and concluded although hydrogen doesn't eliminate nitrogen oxides completely, it is highly effective at reducing carbon oxides. However, the main challenges for using hydrogen as a fuel are its weight and storage requirements. In another study [28]. historical progress and future of hydrogen aircraft as well as the challenges in this regard were examined and it is shown that hydrogen production is not cost-effective yet. Moreover, most of the produced hydrogen is gray rather green and this intensifies environmental concerns. However, it is predicted by 2030 renewable hydrogen would be available for aircraft propulsion.

Hydrogen has a much higher specific energy compared to Jet A, but its volumetric energy density is lower than that of Jet A. At standard temperature and pressure (STP) conditions, which are 0 °C at 100 kPa, hydrogen is in a gaseous state with a density of 0.899 kg/m^3 [10,29]. However, when comparing the mass and volumetric specific energy of hydrogen fuels with those in battery systems as shown in Fig. 6, hydrogen fuel receives commendation for its high energy density. This suggests its suitability for aircraft applications where weight and mass are constant concerns.

Table 2
Specifications of H_2 fuel vs conventional aircraft fuels [10].

	Jet A	E-Kerosene	Compressed Gaseous H_2	Liquid H_2
Specific energy (MJ/kg)	43	43	120	
Density (kg/m^3)	808	808	42	71
Energy density (GJ/m^3)	34.7	34.7	5	8.5

Cost is a key determinant influencing the adoption of H_2 fuel as an alternative in aviation. The estimated costs of H_2 production are derived from various pathways [30], including electrolysis, gasification of biomass, and steam methane-reforming [31] of natural gas.

Estimates of conventional and hydrogen fuel costs for aircraft in the years 2035 and 2050 in the US and Europe are provided in Fig. 7, based on 2019 airline route data. The figure illustrates that the fuel cost for LH_2-powered aircraft using green hydrogen is expected to be higher than that for Jet A-fueled aircraft. However, it is projected to be more cost-effective compared with LH_2 derived from fossil fuels with carbon sequestration or synthetic e-kerosene (ES 2). To ensure the competitiveness of green LH_2 emissions versus fossil jet fuel, it will be crucial to implement taxes on CO_2 emissions, as shown by the hatched bars. The estimates indicate that a carbon price of around \$250/tonne-CO_2 will be required for LH_2-powered aircraft to achieve fuel price parity in the United States by 2035, gradually decreasing to \$100/tonne-CO_2 by 2050. In Europe, where renewable hydrogen is anticipated to be pricier, a higher CO_2 price might be necessary to reach cost parity with Jet A fuel. It is important to highlight that this calculation does not consider the assessment of other benefits linked to hydrogen usage, such as decreased air pollution and non-CO_2 climate impacts.

The exploration of hydrogen fuel application in aircraft propulsion traces back to the 1950s, primarily in the context of military aircraft. However, its limited density posed challenges, requiring substantial space, and adding extra weight to the aircraft. Consequently, the use of hydrogen fuel for commercial aircraft was not deemed practical until recent years where the development of cryogenic technology for hydrogen fuel has significantly improved its commercial viability. Recent technological breakthroughs have enabled the storage of hydrogen in a liquid state, providing the dual benefits of high energy density and a more manageable volume, making it conducive for storage in smaller reservoirs.

The Cryoplane project is a significant illustration, as emphasized in

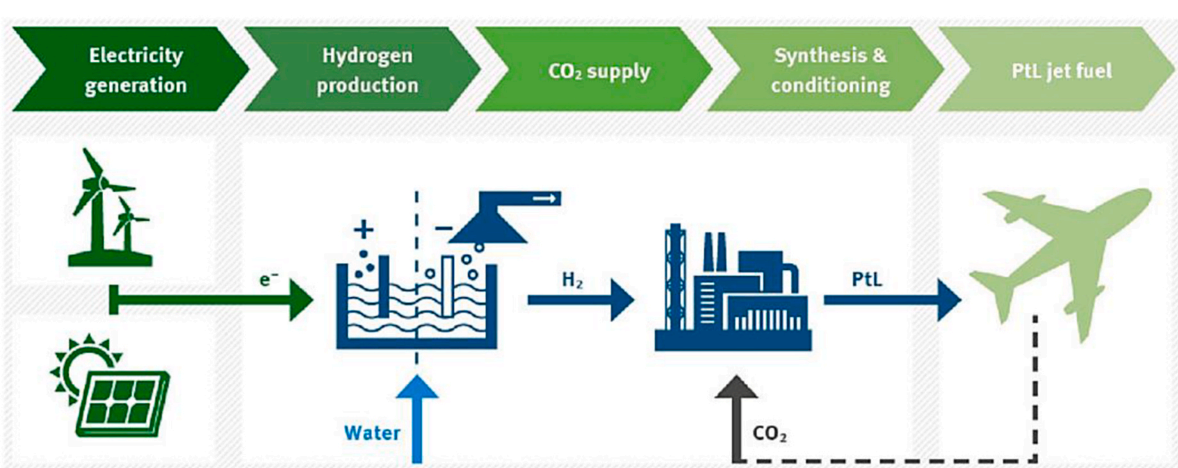

Fig. 5. Schematic diagram for PtL fuel production from renewable energy [26]. Source: LBST GmbH (2016). All rights reserved.

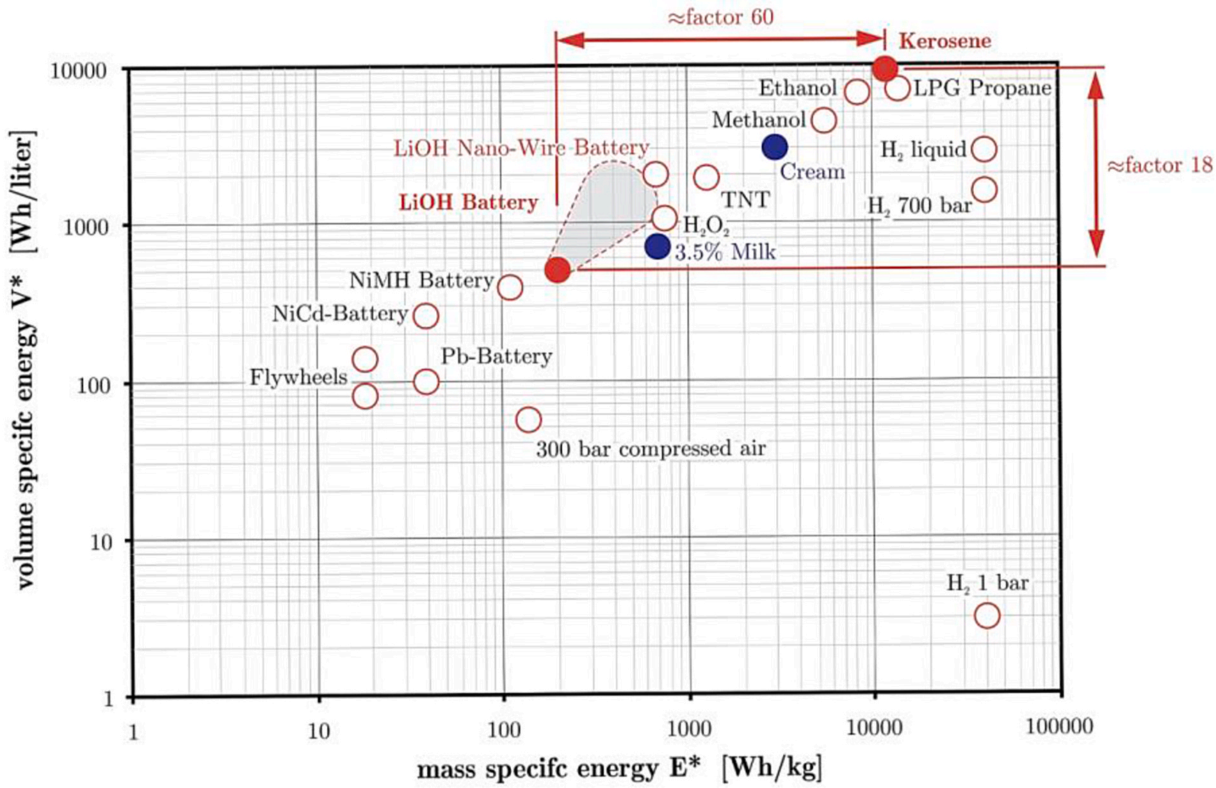

Fig. 6. Volumetric and mass-energy density of various energy storage systems [15].

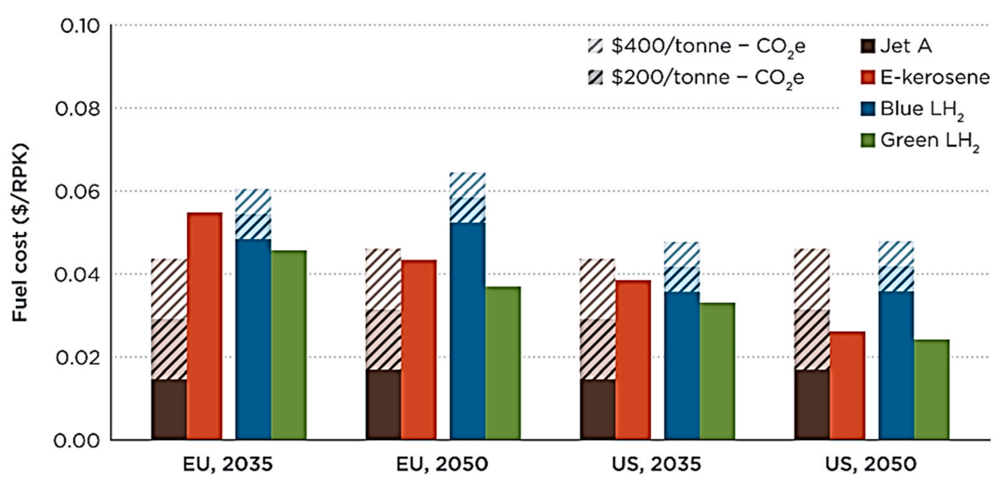

Fig. 7. Fuel cost prediction in the US and EUE excluding carbon price [10].

recent research [35,36]. This endeavour utilizes a 'minimal change' strategy for wing platform and engine design in hydrogen-powered aircraft. Studies show that optimizing both airframe and engine design for hydrogen propulsion can result in energy savings of up to 12% on long-distance flights when compared to a kerosene standard.

Nevertheless, it is crucial to recognize the existence of trade-offs. While long-haul flights gain from the energy-saving advantages of hydrogen, short-haul flights incur a penalty in terms of energy consumption when transitioning to hydrogen as a fuel source. Thoughtful consideration of flight distances and usage patterns is imperative to ascertain the most efficient and sustainable application of hydrogen technology in the aviation industry [37].

Major aircraft manufacturers, such as Airbus and Boeing, have also recognized its potential and have committed to exploring hydrogen propulsion systems further. These industry leaders have invested in ambitious research and development projects aimed at harnessing the full potential of hydrogen as a viable and eco-friendly alternative for aviation.

These collective efforts and breakthroughs in hydrogen propulsion signify a promising step towards a greener and more sustainable future for the aviation sector. As technology continues to advance and mature, we can look forward to witnessing even greater strides in reducing the environmental impact of air travel [10].

Various organizations and countries have acknowledged the favourable combustion properties and high specific energy of hydrogen over the years. For instance, Hans von Ohain introduced the hydrogen-powered turbojet engine HeS 1 in 1937. NACA recognized these benefits in 1955 [38,39], followed by the US Air Force with the B-57 on hydrogen fuel in 1957. Lockheed also joined the trend with the Lockheed CL-400 Suntan in the 1950s. The Soviet Union showcased its interest with the Tupolev Tu-155 Laboratory aircraft in 1988 [8]. Additionally, projects in Europe in the 1990s [40] further highlighted the potential of hydrogen. In a more recent development, Airbus announced in September 2020 its intention to create three new aircraft concepts that utilize direct combustion of hydrogen through a modified gas turbine with an embedded electric motor powered by FCs.

Several studies have been carried out regarding the utilization of H_2 fuel in commercial aeroplanes. For example, there have been a number of investigations on the effectiveness of hydrogen fuel for aircraft propulsion in recent times. Akdeniz et al. [41] delved into the effects of various fuel applications on the thermodynamic capabilities of a high bypass turbofan engine utilized in commercial aircraft. The research revealed that the fuel mass flow of hydrogen fuel (1.03 kg/s) is lower than that of kerosene fuel (2.85 kg/s), and the exhaust gases mass flow of hydrogen fuel (117.14 kg/s) is lower than that of kerosene fuel (118.96 kg/s). Conversely, when hydrogen fuel is used, the exergy efficiency of the overall engine was observed to decrease from 26.9% to 24.3%, indicating that the thermodynamic performance of hydrogen fuel is relatively comparable to that of traditional kerosene fuel.

Verstraete [35] contrasted aircraft using hydrogen fuel with kerosene and concluded that by utilizing hydrogen as a fuel, instead of traditional kerosene in aviation, a greater thrust can be achieved by reducing the turbine pressure [13].

Airbus's Zero-Emission initiative is focused on developing hydrogen-powered aircraft by 2035, with plans for utilizing hydrogen as a fuel source for jet engines or propellers in a twin-engine setup. The ultimate objective of this endeavour is to create aircraft featuring a blended wing body design equipped with two sets of turbo engines to produce thrust [42]. Recently, ARPA-E allocated $10 million in funding for 6 projects under the Connecting Aviation by Lighter Electrical Systems project (CABLES) [20]. These projects aim to develop high-power density cables using various materials, ancillary vacuum or cryogenic technologies, lightweight electrical insulating materials with favourable dielectric and thermal properties, connectors, circuit breakers, and to tackle the issue of partial discharge at high altitudes caused by Paschen's curve. Additionally, NASA is supporting the Center for Cryogenic High-efficiency Electrical Technologies for Aircraft (CHEETA) to explore the use of liquid hydrogen (LH_2) in fuel cells for generating electric power, in conjunction with cryogenic hybrid aluminium cables to enhance the potential of electric propulsion [3,25].

The application of hydrogen as an aviation fuel faces several challenges, with hydrogen embrittlement being a prominent concern. Hydrogen embrittlement occurs when atomic hydrogen infiltrates the structure of high-strength metals, causing them to become brittle and prone to fracture. This phenomenon poses a significant risk to the structural integrity of aircraft components, especially in critical areas such as fuel tanks and pipelines. Additionally, the storage and distribution of hydrogen present logistical challenges due to its low density and high flammability, necessitating specialized infrastructure and safety measures. Despite these challenges, ongoing research and development efforts aim to address these issues and unlock the potential of hydrogen as a cleaner and more sustainable fuel option for aviation.

A study was conducted on anticipating hydrogen demand in aircraft by 2050 [43]. It was shown that demand for liquid hydrogen could reach 17 million tons by 2050. Moreover, to meet aviation's full demand, hydrogen fuel costs must be lower than 70 EUR/MWh by that time. However, the anticipated hydrogen price is more than twice the needed price by 2050.Maintenance and safety requirements for hydrogen storage and distribution in aircraft were examined, concluding that this application could significantly increase maintenance costs and requires special safety considerations [44].To avoid combustion chamber modification, adding hydrogen to conventional aircraft fuel was proposed and studied [45] and it was concluded that hydrogen causes unburnt hydrocarbons and increased NOx emissions, necessitating an advanced ignition system to address these issues.

3. FC propulsion systems for aircraft

3.1. Aircraft FC systems

FCs have emerged as an innovative technology that has attracted considerable attention in the aviation industry for its potential to transform aircraft propulsion systems. Essentially, FCs are electrochemical devices that convert chemical energy directly into electrical energy through a controlled reaction between hydrogen and oxygen. In the context of aircraft, FCs offer a promising alternative to combustion engines by providing a cleaner and more efficient power source. The aviation sector is exploring the integration of FCs as a means of reducing environmental impact, enhancing energy efficiency, and mitigating the challenges associated with conventional fossil fuel use. This technology holds the promise of not only reducing greenhouse gas emissions but also addressing issues related to noise pollution and fuel consumption in the aviation sector.

Table 3 provides a comprehensive summary of various FC systems, encompassing their distinctive chemical reactions, operating conditions, and application domain. Within this table, notable attention is given to the PEMFC and SOFC systems, both of which have emerged as promising choices for aircraft propulsion. Each system presents unique advantages and considerations, highlighting their potential significance for this purpose.

When it comes to operating conditions, PEMFCs have gained preference in aviation primarily because of their capability to swift warmup and start and function optimally at comparatively lower temperatures, typically ranging from 80 to 100° Celsius. Furthermore, PEMFCs exhibit a short response time implying their fast response to power demand, enabling quick adaptations in power output as required during flight.

Conversely, SOFCs operate at elevated temperatures, typically ranging from 600 to 1000° Celsius. Although their high-temperature operation presents integration challenges in aircraft, SOFCs offer superior overall efficiency and the potential to utilize a broader spectrum of fuels, including jet fuel. When employed alongside aircraft gas turbines in hybrid systems, the high temperature of the gas turbine exhaust gases can be advantageous for these FCs. Moreover, their solid-state design imparts inherent durability and vibration resistance, which can prove advantageous in the demanding aviation environment.

Regarding power range, PEMFC's power is generally confined to a few hundred Kilowatts, making them well-suited for small aircraft, drones, UAVs, and auxiliary power units (APUs) applications like supplying electricity to onboard equipment. On the other hand, SOFCs, due to their higher operating temperatures and larger physical size, possess the capacity to achieve power ranges on the scale of mega-Watts. This characteristic makes SOFCs more appropriate for larger aircraft propulsion.

As illustrated in Fig. 8, FCs, when compared to electrochemical batteries, demonstrate lower power density but notably higher energy density. To enhance the response performance of FCs, a promising strategy involves integrating batteries or supercapacitors (SC) into a hybrid system, ensuring a more efficient and reliable power supply for aircraft operations [30,47].

3.1.1. Hybrid electric FC configurations

Hybrid electric powertrain systems are typically categorized into two major architectures: series and parallel. Fig. 9 illustrates schematic diagrams for hybrid electric powertrain systems designed for aircraft propulsion. In the parallel configuration depicted, both the combustive and electric power sources work in tandem to deliver the necessary propulsion power. In contrast, the series configuration involves the combustive power source charging a battery system through generators, which, in turn, powers propellers to generate the required propulsion force. In the series-parallel configuration, a combination of two major

Table 3
Various fuel cells and their specifications [46].

Types of FC	Chemical reactions		*Overall reaction*	*Working temperature*	Applications
	Anode	Cathode			
Proton Exchange FC (PEMFC)	$2H_2$ $4H^+$ $4e^-$	O_2^+ $4H^+$ $4e^-$ $2H_2O$	$2H_2$ O_2 $2H_2O$	10–100 °C	Space, Public bus, military, aircraft
Alkaline FC (AFC)	2H2 $4OH^-$ 4H2O $+4e^-$	$O2^+$ $2H_2O^+$ $4e^-$ $4OH^-$	$2H_2^+$ O_2 $2H_2O$	20–120 °C	Space, military
Solid Oxide FC (SOFC)	$2O_2^-$ $2H_2$ $2H_2O^+$ $4e^-$	O_2^+ $4e^-$ $2O_2^-$	$2H_2^+$ O_2 $2H_2O$	600–1000 °C	Utility, vehicles, aircraft
Direct Methanol FC (DMFC)	CH_3OH $+H_2O$ $6H^+$ $+6e^- +$ CO_2	$6H^+$ $6e^- +3/$ $2O_2$ 3H2O	CH_3OH $+3/2O_2$ $2H_2O$ $+CO_2$	50–120 °C	Transportation, Portable devices
Phosphoric Acid FC (PAFC)	$2H_2$ $4H^+ +$ $4e^-$	$O_2 +$ $4H^+ +$ $4e^-$ $2H_2O$	$2H_2 +$ O_2 $2H_2O$	~200 °C	Distributed generation
Molten Carbonate FC (MCFC)	$2H_2 +$ $2CO_{2/3}$ $2H_2O$ $2CO_2$ $4e^-$	$O_2 +$ $2CO_2 +$ $4e^-$ $2CO_{2/3}$		600–700 °C	Utility, distributed generation

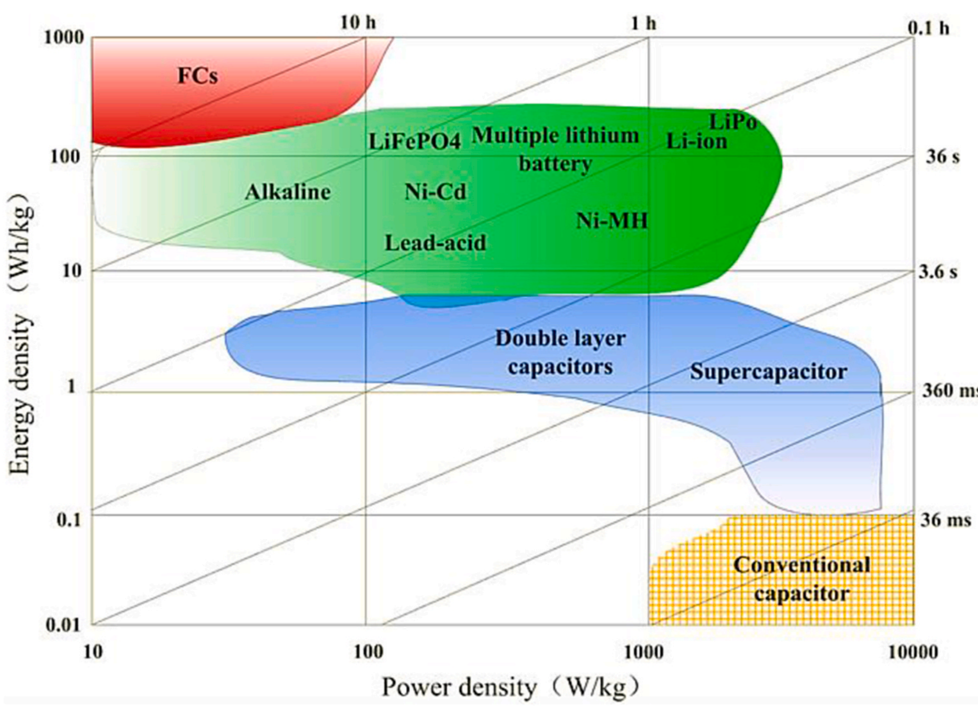

Fig. 8. A comparison between energy and power density in Fcs with those in the other electrical power sources [48].

types, the performance of the parallel configuration is enhanced by integrating a generator to charge the battery system. In the FC hybrid electric context, the combustion power source may be replaced with FC.

Table 4 compares the performance of various FC configurations in the context of aircraft propulsion.

The table clearly demonstrates that the parallel setup surpasses series setups in efficiency, fault tolerance, dynamic performance, and weight. Xie et al. [51] conducted a comprehensive study on the conceptual design and energy management strategies of hybrid electric-powered aircraft.

3.1.2. FC systems' structures

The architecture of the parallel FC/battery configuration can be of passive or active type, depending on their interconnections.

In the passive configuration, as depicted in Fig. 10, no converter is used to connect the power sources. This passive setup can have different versions. In the first type, a single diode is used to connect/disconnect the FC power flow. In the second type, one diode is used for each of the

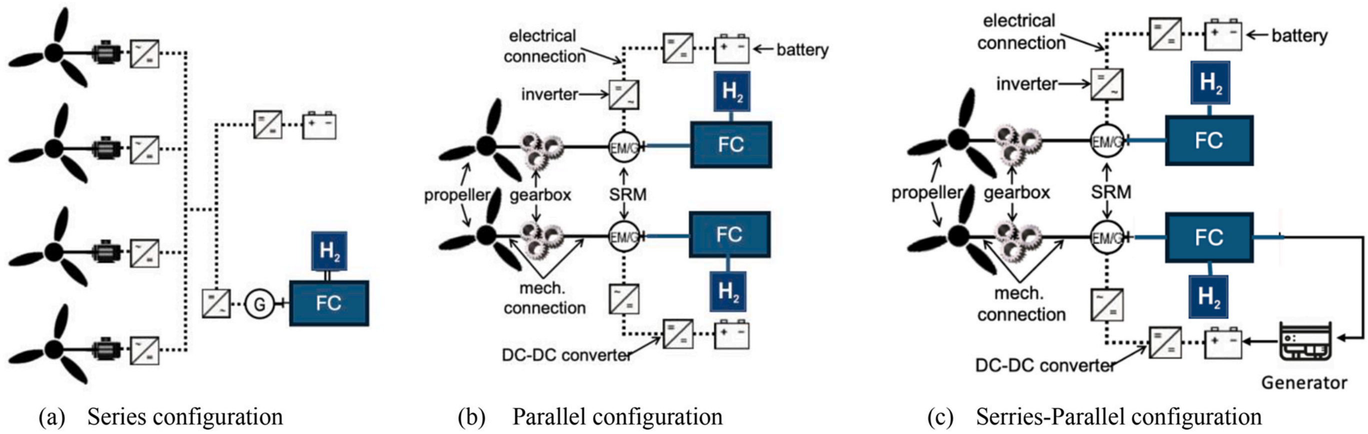

Fig. 9. *Conventional and hybrid electric configurations for H_2 aircraft powertrain* [49].

Table 4
Comparison between Pure, Series Hybrid, and Parallel System [50].

Configuration	Simplicity	*Efficiency at low power*	*Efficiency at high power*	Robustness	Response Speed	Mass
FC only	High	Low	Medium	Medium	Low	Medium
FC series hybrid electric	Medium	Medium	Low	Low	Medium	High
FC parallel hybrid electric	Low	High	High	High	High	Low

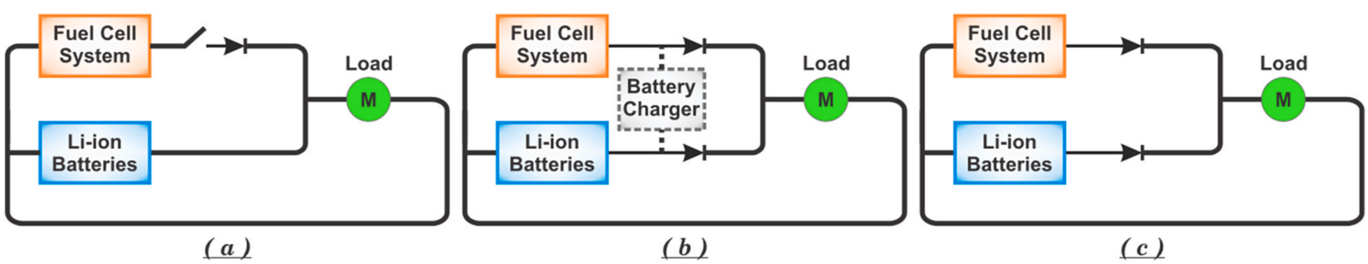

Fig. 10. Passive hybrid FC/batteries power system configuration [50,52].

power sources. Additionally, a battery charger is provided to charge the battery using the FC power, all managed by the energy management system (EMS). Finally, in the third type, the battery charger is absent, and the battery is directly connected to the FC without any charging control.

Fig. 11 shows the active configurations for the parallel architecture in which some DC/DC and DC/AC converters are used to connect the FC and battery systems to the load.

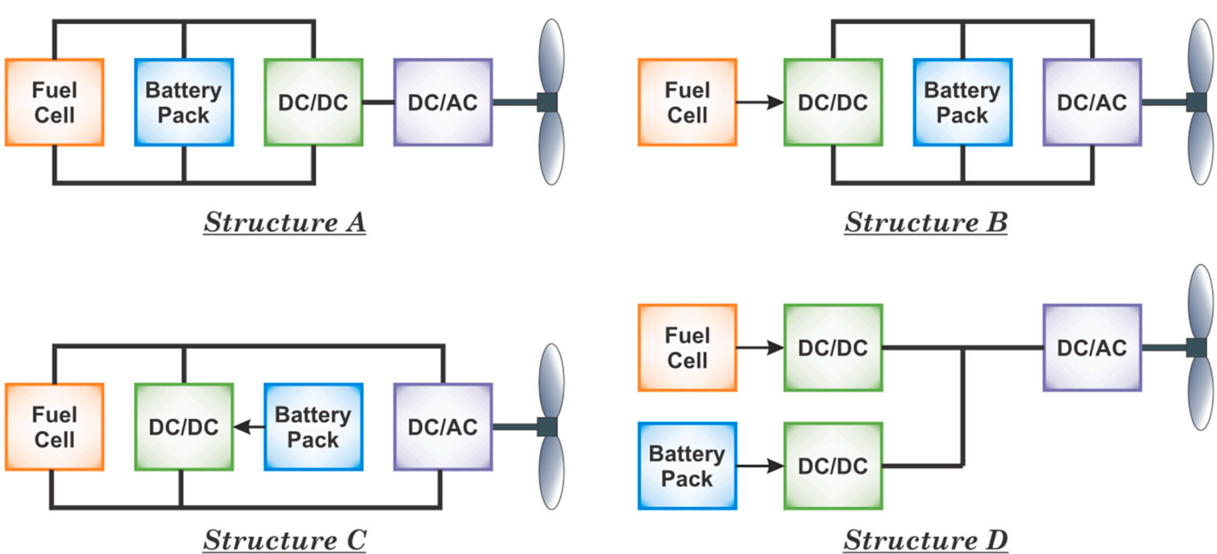

Fig. 11. Various active FC parallel hybrid power system structures [50,53].

In Configuration A, the battery connects directly to the FC system, while the DC-DC converter is located between the DC-bus and the load (i.e., the DC-AC converter in the diagram). The battery acts as an energy buffer, handling transient loads and functioning as part of the steady-state load. The unregulated output power of the FC system causes the battery to charge whenever its voltage drops below that of the FC. As a result, the DC-DC converter must manage power from both sources, requiring a robust current design.

Structure B involves the connection of the FC system to the battery through a DC-DC converter, which requires aligning the high-voltage battery with the DC-bus voltage. Similar to Structure A, the direct coupling of batteries to the DC bus allows for a quick response to load transients. However, this design presents challenges with uncontrollable battery discharge and charging, posing risks of overcharging, over-discharging, and accelerating battery ageing. Additionally, selecting a suitable battery pack for UAVs becomes challenging due to the DC bus voltage dependence on the battery output voltage.

In contrast, Structure C situates the DC-DC converter at the battery's end, with the FC system directly connecting in parallel to the front-end DC-DC converter. This configuration enables controlled battery discharge and charging, extending battery life and eliminating FC current ripple. However, the power response of the FC system is compromised, limiting the overall system's dynamic performance. Applying this hybrid power system to high-voltage conditions requires an additional DC-DC converter, resulting in additional costs.

Structure D features both the FC system and the battery linked through a DC-DC converter, allowing precise control of power-sharing. Controlled discharge and charging ensure the battery operates optimally. This structure offers greater convenience in selecting the FC system and battery compared to the other three. Nevertheless, as the battery is not directly connected to the DC bus, there may be a degradation in the overall system's dynamic performance to some extent. Table 5 provides a summary of the advantages and disadvantages of the mentioned configurations.

In a hybrid powertrain system, the EMS assumes a crucial role in efficiently distributing power from various sources to attain optimal performance and lifespan. Fig. 12 depicts the EMS system in a lightweight manned hybrid FC aircraft with a parallel configuration [37]. In this illustration, the EMS controller dictates the operational points of the FC and battery systems by considering the total power demand and feedback from the power sources. This feedback encompasses critical parameters such as State of Charge (SOC), State of Health (SOH), and optimal operating points, allowing the EMS to make informed decisions for effective power allocation.

The use of FC systems in the hybrid electric propulsion systems for aviation can be traced back to their early incorporation into spacecraft propulsion, particularly notable in the Apollo program by Pratt & Whitney in 1959. General Electric further advanced FC technology in the 1960s, culminating in the development of the first PEMFC for NASA's Gemini missions [55]. A significant contribution to the field came from Mitlitsky et al. in the 1990s, with the publication of various reports on Ultra-Reliable PEMFC (UR-PEMFC) for aerospace applications [32,56]. Since then, numerous studies have focused on UR-PEMFC, particularly for applications in space energy and transportation.

A significant breakthrough took place in 2006 when NASA Glenn Research Center successfully demonstrated closed-cycle operation at rated power for multiple charge/discharge cycles using a Regenerative FC (RFC) device. This RFC device exhibited the capability to store input electrical energy and consistently provide a power output of 5 kW for around 8 h. The study emphasized the potential use of URFC as an energy storage device for aerospace solar power systems, including solar electric aircraft and lunar/planetary surface installations [57].

Further noteworthy advancements include the collaboration between IHI and Boeing in 2010 [58], which led to an aircraft incorporating RFC as an auxiliary energy source. In 2011, the Japan Aerospace Exploration Agency (JAXA) unveiled a 560 W UR-PEMFC system designed for operation in isolated low-gravity and closed environments [59]. With the support of the European Space Agency, Barbera et al. developed a 1 kW pure hydrogen and oxygen PEMFC stack, demonstrating its suitability for potential use in lunar human exploration missions [60]. Recently, Barbera's research team showcased a 2 kW Modular PEMFC stack for simulated lunar surface missions [61].

Pu et al. proposed a regenerative FC system for space application, as illustrated in Fig. 13 [46]. This approach employs an FC system for generating propulsion power, with hydrogen fuel produced through electrolysis, powered by photovoltaic elements. The water generated by the FC system is collected and stored in a tank for recycling back to the electrolysis section for further processing.

Together, these studies collectively underscore the feasibility and promise of FC systems for space missions, marking significant progress in advancing sustainable and efficient power solutions for aerospace exploration [46]. However, as the scope of this paper is confined to aircraft propulsion systems, in continue the application of FC systems for aircraft propulsion is discussed.

The following sections provide a continuation of the survey, focusing on research related to the application of FC systems in aircraft propulsion. The discussion encompasses the most prevalent types of FC systems, along with an exploration of the aircraft systems in which these propulsion systems have been employed.

3.1.3. *Balance of plant*

Balance of plant refers to all required equipment to control and condition of fuel, air, temperature, water, and electrical output. Design of balance of plant for aircraft faces due to the certain operating conditions including variable altitude and weight and space limitations.

Fig. 14 also provides an overview of the FC architecture, which includes the BOP.

Very little research has been done on the design of BOP for FC propulsion systems. For instance, Schroter [63] studied the pressure loss on the compressor performance in an air supply of a FC powertrain system for an aircraft application. The findings indicate that lowering ambient pressures and minimizing pressure losses before and after the compressor lead to a 33% decrease in maximum pressure and a 24% decrease in maximum power [62].

A fuel cell propulsion system was proposed for regional and mid-range aircraft [64]. In this design, special focus is put on the air supply system by considering various operating ranges of the system and showing that, through optimal design, both fuel consumption and component sizes can decrease considerably.

In another research, performance targets for fuel cell systems and on-board hydrogen storage for regional aircraft were examined [65]. and it was concluded that the minimum requirement to achieve 1000 nautical miles in regional aircraft is 2 kW/kg for fuel cell system specific power and a tank gravimetric index of 5%.

Table 5
Advantages vs disadvantages for passive and active FC/Battery Power Systems [50].

	Advantage	Disadvantage
Active	Separation of battery and fuel cell sizing from operational parameters	Complicated system configuration Power loss in the DC-DC converters.
	Improved regulation of the power system to achieve greater precision	Increased system expenses Greater mass and size.
Passive	Enhanced efficiency decreased expenses streamlined design, minimizing chances of malfunction diminished size and mass	It is not feasible to control active power. The FC functions at the voltage determined by the batteries. It is essential to carefully plan and integrate the FC system and batteries to meet the load requirements.

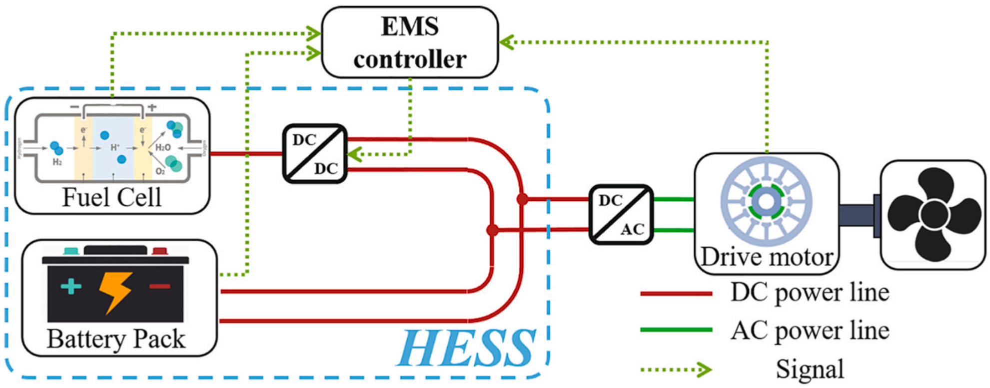

Fig. 12. Schematic diagram for a parallel FC/battery propulsion system for a light aircraft [54].

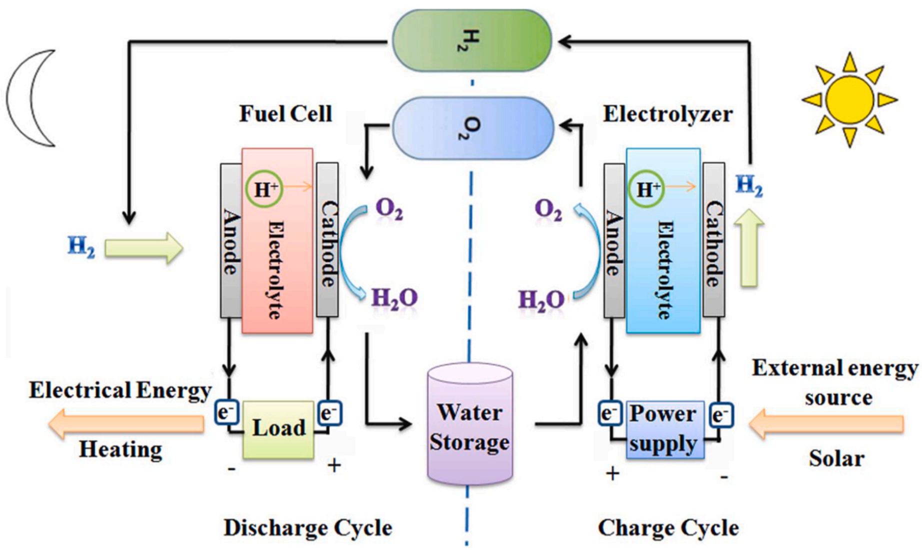

Fig. 13. Schematic diagram for a regenerative FC system for space application [46].

The influence of low pressure, typical for aircraft operating at high altitudes, on the performance of direct hybrid fuel cell systems was studied in Ref. [66]. and found to negatively impact the output voltage of the fuel cell system.

3.1.4. Multi-stack FC systems

Multi-stack FC system (MFCS) refers to a system in which more than one FC is employed to deliver the required power. This provides more flexibility in the power allocation between the FCs and consequently it would be possible to operate each FC in its optimal operating regions. As a result of utilizing multi-stack FC systems, overall efficiency, reliability, and durability can be improved. For aircraft propulsion that efficiency, reliability, durability are key factors, MFCSs could be a proper match and have been considered in recent years [8].

Fig. 15 illustrates the schematic diagram for a parallel MFCS. As seen in this figure, MFCs may increase the complexity of the system and increase the cost.

3.2. PEMFC systems for aircraft propulsion

The predominant FC systems employed in small and regional aircraft belong to the PEM type. This selection is influenced not only by the limited power density of PEMFCs, rendering them well-suited for low-power aircraft, but also by their lack of a requirement for high temperatures during start-up. Typically, the elevated temperatures necessary for initiation can be supplied by gas turbines, which are notably absent in small and regional aircraft.

The application of PEMFC in UAVs, as well as regional and large aircraft, is examined separately in the following section.

3.2.1. PEMFC for UAVs

Unmanned Aerial Vehicles (UAVs) present significant advantages, including heightened safety, reduced costs, and suitability for perilous missions [50]. Given the distinctive challenges in aviation, particularly the substantial energy demands, recent endeavours primarily focus on the development of light, small-scale UAVs, and passenger aeroplanes tailored for fewer than five passengers.

Based on a market research report from 2019, the global commercial UAV market is forecasted to achieve a value of up to 17 billion dollars by the year 2024 [35]. In military settings, UAVs are essential for various tactical missions like artillery guidance, drone combat, communication disruption, and defense against anti-ship missiles [68]. UAVs, whether in civilian or military applications, provide benefits such as improved fuel efficiency, greater reliability, and enhanced safety when compared to traditional piloted helicopters [70].

Ahluwalia et al. [71] conducted a study on the performance and cost of FCs for air mobility using UAVs, determining that FCs are the most feasible option for powering multi-rotor electric vertical take-off and landing (eVTOLs) in urban environments requiring a 60-mile range. The research also found that hybrid FCs outperform batteries as powertrains for tiltrotor eVTOLs. This investigation included a techno-economic assessment of eVTOL air taxis with different powertrains, focusing on

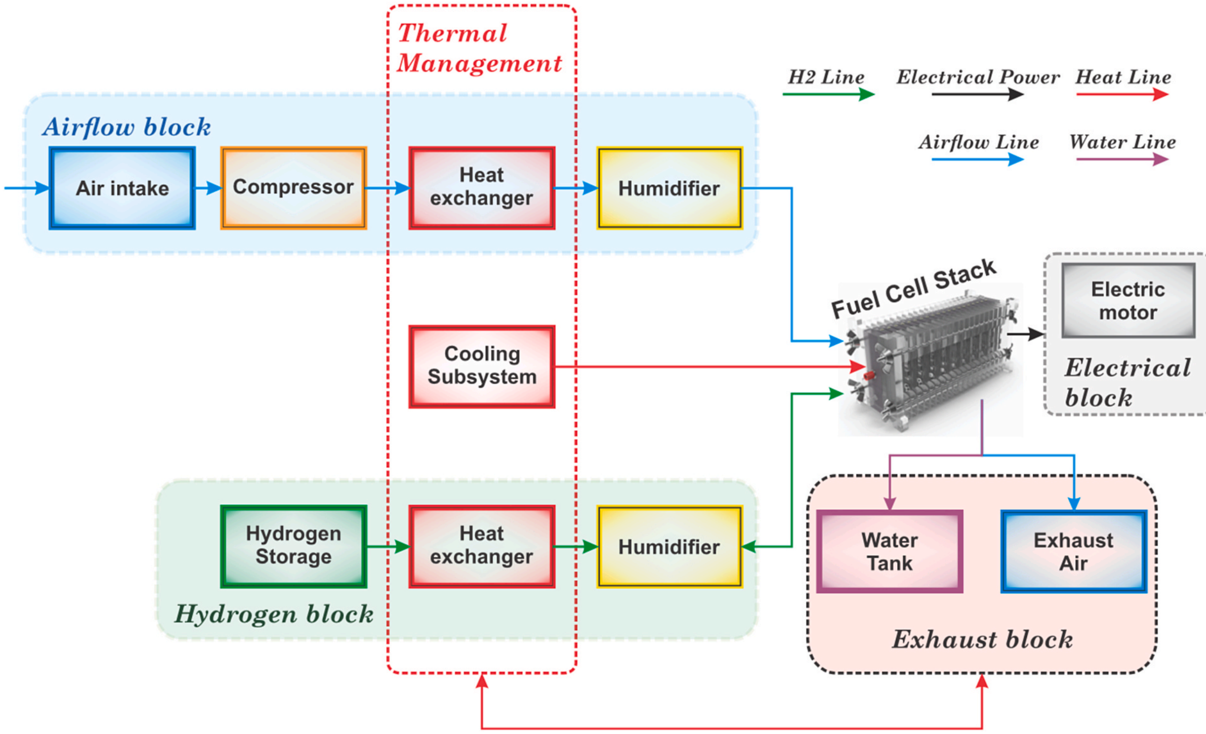

Fig. 14. FC system architecture [62].

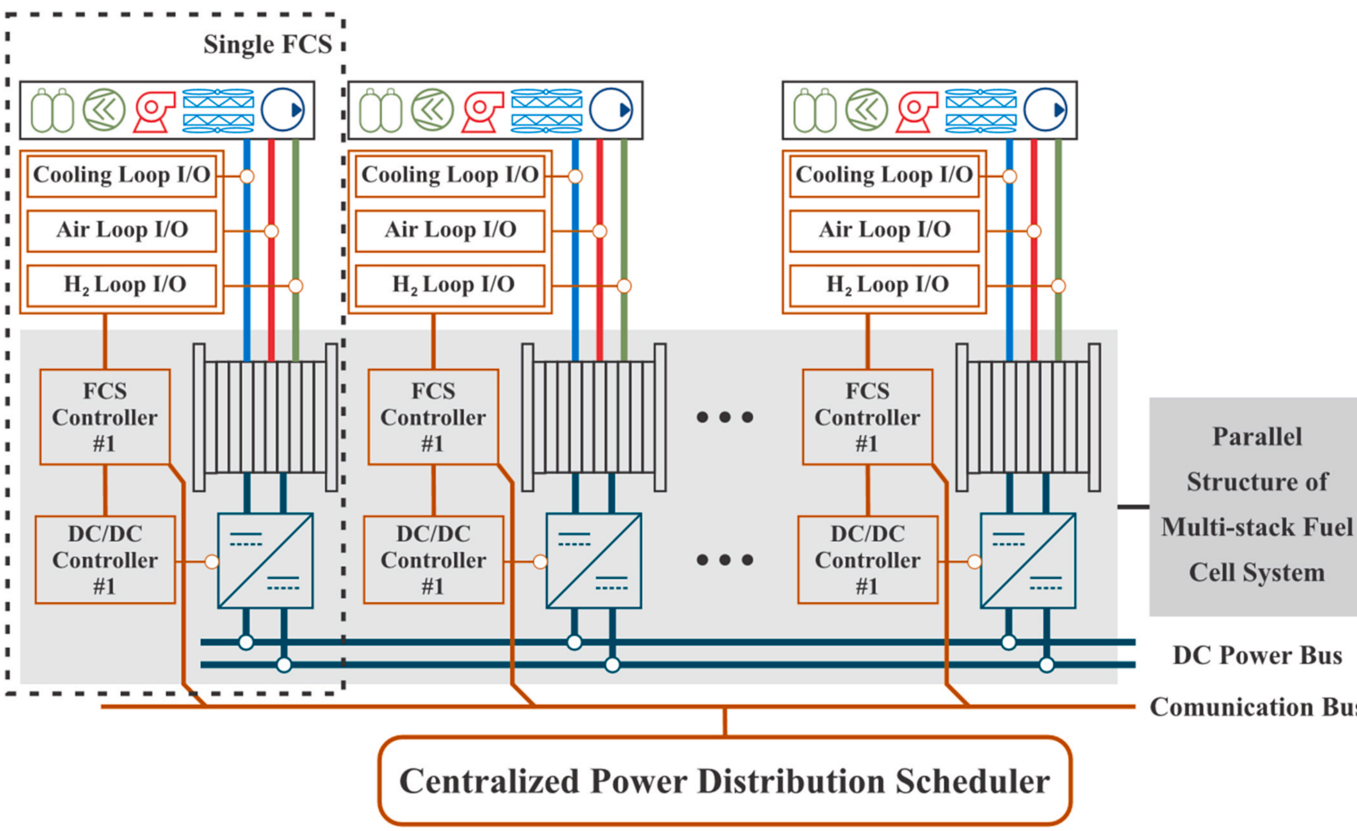

Fig. 15. Schematic diagram for a parallel multi-stack FC system [67].

hydrogen FC systems designed for both light-duty and heavy-duty vehicles.

There are three primary categories of FCs used in UAV applications: PEMFC, SOFC, and DMFC. Among these, the PEMFC is the most widely used in current UAV applications due to its unique advantages. The PEMFC operates within a safe and reliable temperature range of

30∼110 °C, ensuring mechanical and chemical compatibility [72]. Additionally, the PEMFC utilizes hydrogen as fuel, with only water produced as a by-product, making it environmentally friendly. The energy density of compressed hydrogen gas in the PEMFC can reach up to 1000 Wh/kg, surpassing that of Lithium-based batteries [73].

However, obstacles related to PEMFC continue to exist, particularly the expensive nature of the PEM and the catalyst made of noble metal. As a result, there is continuous industrial and academic research focused on finding different membrane materials and catalysts [74]. The storage of hydrogen remains a significant challenge for UAVs, influenced by limitations concerning size, weight, and flight conditions [46].

In Fig. 16, various powertrain options for a UAV are explored, where a consistent 1.9 kg mass limit is put on the powertrain system [75].

Several research have been conducted on the application of FC systems in UAVs in recent years. Husemann et al. [76] assessed potential influences on flight operations for small air taxis operating in urban areas, with a specific focus on the implementation of FCs instead of batteries as the primary energy source. Their findings demonstrated that the incorporation of FCs enables significantly extended flight ranges when compared to battery-powered alternatives. Moreover, technological maturity, evaluated in terms of individual energy density and powertrain unit weight, emerges as a key factor in shaping the overall cost structure.

Bradley et al. [77] introduced a proposal for a powertrain powered exclusively by FC for the propulsion of Unmanned Aerial Vehicles (UAVs) (refer to Fig. 17). They confirmed the viability of the FC aircraft concept, demonstrating acceptable operational intricacy and system weight. Nevertheless, obstacles such as reduced efficiency, inadequate dynamic performance, and restricted fault-tolerant capability have hindered the advancement of UAVs that depend entirely on FC systems.

Nevertheless, the implementation of pure FC systems in aircraft encounters certain obstacles. In order to improve the viability of pure FC

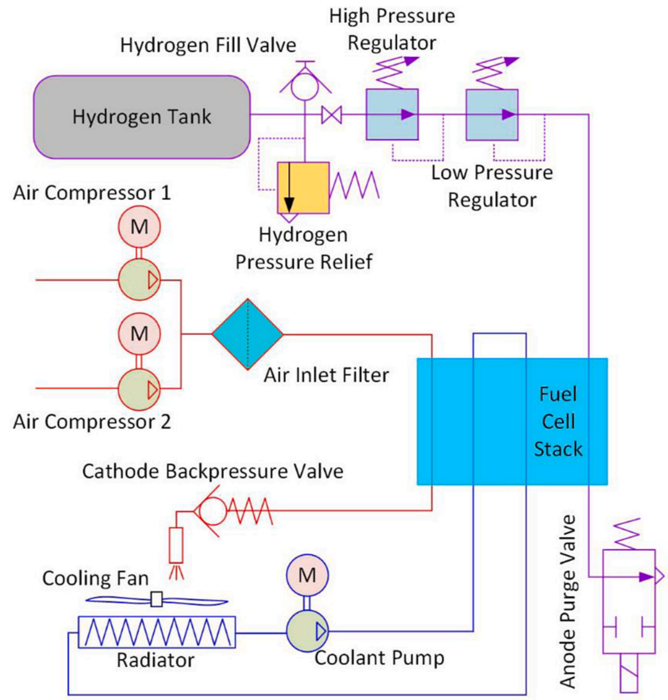

Fig. 17. Powertrain diagram for an FC-only powered employed for UAVs [50,77].

systems for UAVs, several researchers have dedicated their efforts to tackling these challenges. These initiatives involve investigating advanced hydrogen storage methods [78], alternative onboard

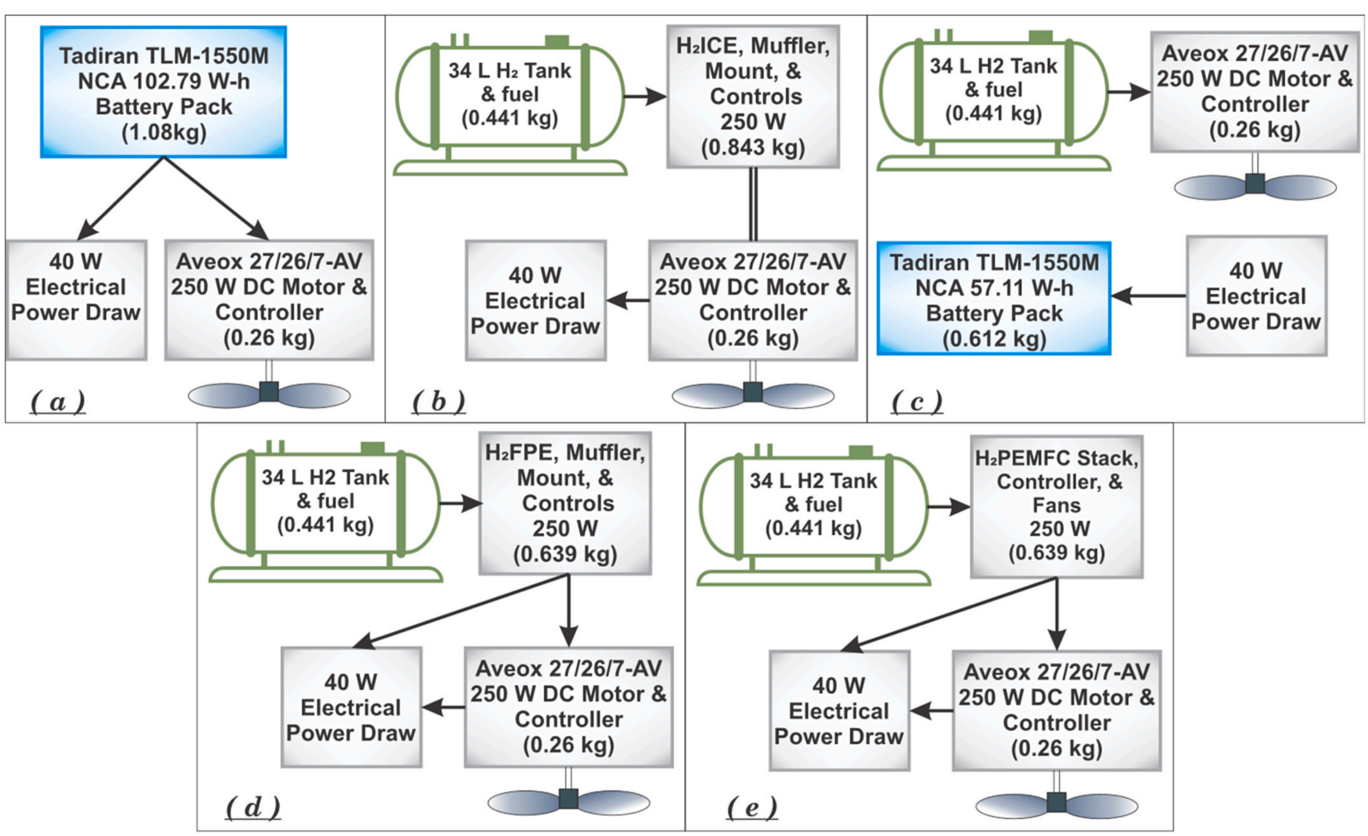

Fig. 16. Various powertrain: (a) Sole use of a battery pack, (b) Internal combustion engine with integrated generator, (c) Parallel hybrid internal combustion engine, (d) Fuel-powered engine with integrated linear generator, and (e) Proton Exchange Membrane fuel cell [75].

hydrogen generator approaches [76], high-power density FC stacks with metal bipolar plates [47], designing high-efficiency power plant architectures [30], and creating a more compact Balance of Plant (BoP) [54].

In the realm of UAVs, utilizing a hybrid power system with both a FC and a battery running simultaneously offers benefits over a solely FC-powered system. This setup not only minimizes hydrogen waste but also boosts efficiency when FC UAVs are not in use [32]. Table 6 outlines UAVs that are powered by hybrid FC-battery systems, showcasing the incorporation of Lithium-Polymer (Li–Po) batteries as the secondary energy storage system (ESS), mainly due to their lightweight characteristics.

The series configuration, as demonstrated in Ref. [87], is found to increase weight due to the inclusion of a generator and larger electric motor, yet it streamlines operational complexity. This results in enhanced dynamic performance and fault-tolerant capability. Moreover, given the high-speed requirements of UAV propulsion motors, series hybrid systems may not be the most suitable choice [61]. The FC and battery series hybrid electric propulsion configuration is better suited for low-speed, high-torque applications such as buses [59] and aircraft tractors [60].

The challenges identified in studies by Refs. [79,88] for fuel cell-powered UAVs include issues such as onboard hydrogen storage limitations, insufficient power output, slow response times, and inefficiency in both low and high power modes.

It is imperative to tackle these issues in order to improve the overall performance of UAVs in real-world scenarios. For example, Wagter et al. [89] suggests a hybrid transitioning UAV design that prioritizes the integration of a hydrogen tank and FC in a Vertical Take-Off and Landing UAV configuration, utilizing 12 redundant propellers for hover capability.

Numerous studies have been conducted regarding the development and integration of FC propulsion systems for UAVs. Calicir et al. [72] examined the environmental impact of hybridizing a UAV using PEM FC and battery, comparing it to a fully electric version of the aircraft powered by a lithium polymer battery. As a result of transitioning from a lithium-polymer power system to a hybrid hydrogen FC system, there is a 6.95% reduction in global warming, a 6.35% decrease in terrestrial ecotoxicity, a 1.23% decrease in photochemical oxidation, and a 12.44% increase in ozone layer depletion. In today's world where environmental issues are at the forefront, the implications of UAVs hybridized with FCs, considered a clean energy source, in relation to environmental concerns are the focus of this study.

Ozbek et al. [79] developed a hybrid powertrain system for an UAV by combining a PEM FC with a Li–Po battery. They examined three different configuration scenarios by evaluating various architecture models. The required power was estimated from an air test of a full-electric version, while the proposed hybrid version was tested on the ground. Song et al. studied the impact of high-altitude operation on PEMFC systems, considering mechanical vibrations and harsh operating environments such as low pressure, cathode air starvation, and low ambient temperatures at high altitudes [90]. Ji et al. [91] conducted research on determining the safe operation zone for a turbine-less SOFC hybrid electric jet engine, where the compressor is operated by the SOFC on the UAV. They focused on matching the compressor's required power with the power produced by the SOFC to prevent compressor power shortages. The safe operating zone of the hybrid engine is not limited by turbine inlet temperature. Under low fuel flow rate and low air flow rate, there are zones with either too low reforming temperature or too low SOFC open voltage. In the safe zone, the hybrid engine exhibits high specific thrust (837.6 N/(kg.s)) and high thermal efficiency (70.4%) at high fuel and air flow rates. Arat et al. [92] conducted an experimental investigation on FC usage in a quadrotor drone. This hybrid propulsion system mainly consists of a 30 W PEMFC, a compressed hydrogen tank, a lithium-polymer battery, and 4 brushless motors that drive the propeller. As a result, using the FC led to an improvement of approximately 2 min in a total of 12 flight tests.

Table 6
FC hybrid electric powertrain systems employed for UAVs.

Study	FC Type	Battery Type	Validation with Flight Test
Ozbek et al. … [79].	PEMFC 250W	Li–Po battery	Yes
Dudek et al., 2013 [80]	PEMFC 250 W	Li–Po battery	Yes
Zhang et al., 2018 [81]	EOS 600 PEMFC	Li–Po battery	No
Mobariz et al., 2015 [82]	Concept PEMFC	Li–Po battery	No
Chiang et al., 2008 [83]	PEMFC 150 W	Li–Po battery	Yes
Gong et al., 2018 [84]	PEMFC 150 W	Li–Po battery and supercapacitor	No
Savvaris et al., 2016 [85]	PEMFC 500 W	Li–Po battery	No
Bayrak et al., 2020 [86]	PEMFC 200 W	Li-Ion, Ni-Mh battery Comparaison	No

Ozbek et al. [93] presented the development stages of a mini-UAV created for Hybrid FC flight. Additionally, they constructed and tested a prototype of their design and compared the detailed design estimates of power consumption with the final power consumption data collected from flight tests of the aircraft to provide valuable information for future power consumption limited aircraft design studies. In 2013, UTRC successfully tested a FC rotorcraft for a 20-min flight duration using 5000-psi compressed hydrogen stored in a carbon/aluminum pressure vessel in 2009 [94,95]. Geiss et al. [31] examined power reserves failure in light hybrid electric cell (FC)-powered and internal combustion engine (ICE)-powered UAVs. Furthermore, based on size, they can be classified as nano, micro, mini, medium, and large UAVs [5]. Atanasov et al. [33] carried out a conceptual design of a parallel hybrid FC + gas turbine and demonstrated that the proposed hybrid powertrain system results in a 9% efficiency improvement compared to the conventional powertrain in an assumed aircraft. Apeland et al. conducted a sensitivity analysis that quantifies the impact of central system parameters for an X8 multirotor drone with a 2 kW FC hybrid system [34].

Limited research has been conducted on integrated gas turbine-FC powertrain systems for aircraft. For example, Bahari et al. presented a hybrid PEMFC + turbine propulsion system developed for an Unmanned Aerial Vehicle (UAV). This novel hybrid setup aims to utilize the strengths of both PEMFC and turbine technologies to enhance the overall performance and efficiency of the UAV's propulsion system [96]. The schematic diagram of the proposed hybrid system is illustrated in Fig. 18. They achieved an impressive thermal efficiency of 62.41% for the newly designed hybrid PEMFC + turbine propulsion system, signifying significant enhancements in efficiency.

Furthermore, there have been recent reports of various commercial applications of FC systems in UAVs. For instance, The Blue Bird Aero System developed one of the first commercial FC-powered UAVs [88], while Inha University created a light-weight UAV with a 200-W stack that achieved a 14-min flight time [97]. Additionally, H3 Dynamics introduced HYWINGS, a FC powered fixed-wing drone capable of flying 500 km and 10 h [98,99]. Protonex, a subsidiary company of Ballard, has also entered the market by selling its FC system for UAVs [100,101]. Lastly, Energy or Technologies, a Canadian-based PEM FC company, showcased the long-endurance flight capabilities of its FC UAV, FAUCON H_2 aircraft, which successfully executed a predetermined flight plan for 10 h and 4 min [102].

3.2.2. Energy management systems for FC UAVs

Given that UAVs represent a highly promising application of FC systems for propulsion, numerous studies have delved into the design and implementation of energy management systems (EMS) for these aircraft. EMS is the heart of a hybrid FC/battery propulsion system by

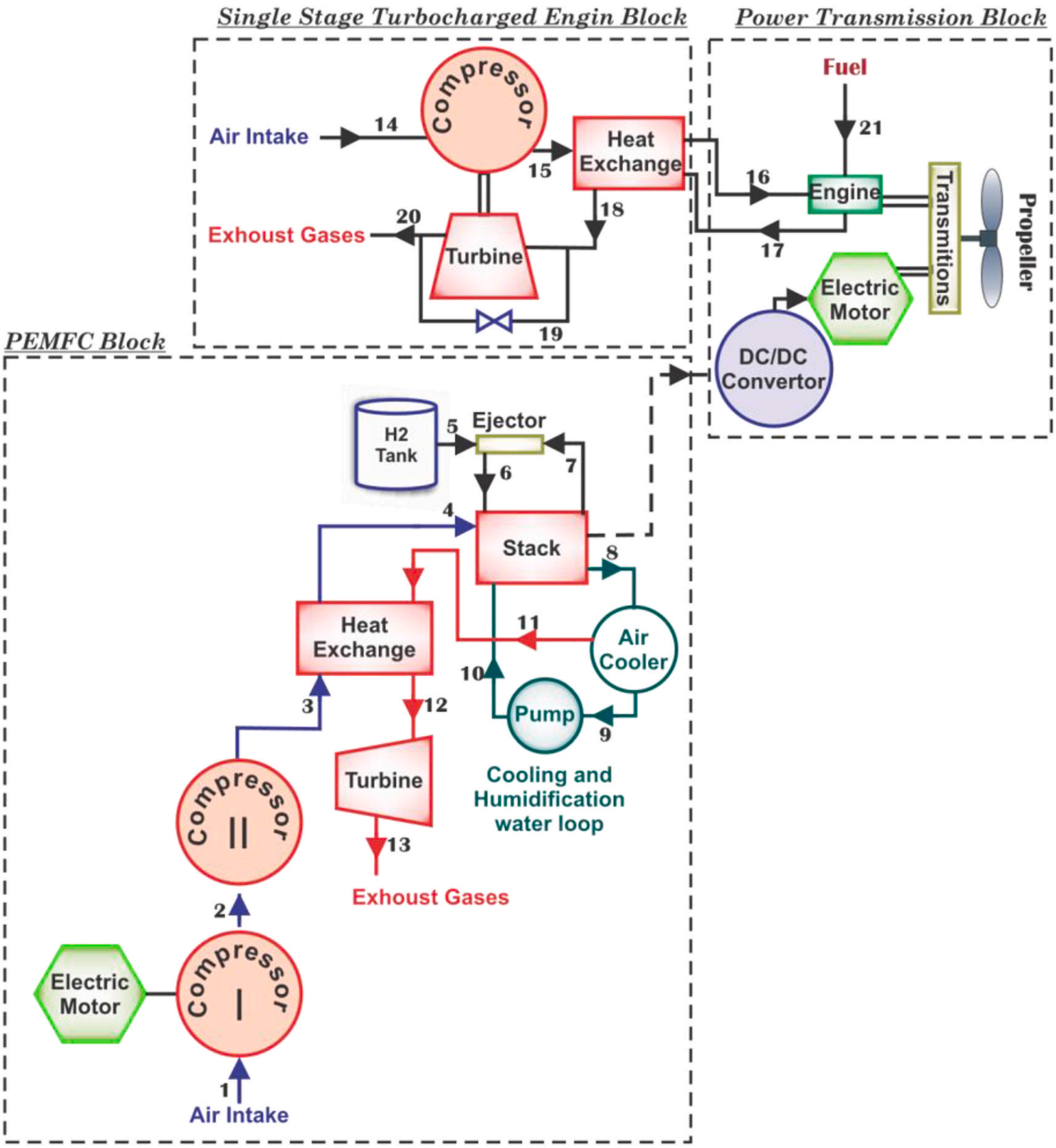

Fig. 18. Schematic diagram of the proposed system [96].

which the power allocation are determined such that the efficiency and lifespan of the power sources are optimized. EMSs for UAVs can be categorized into rule-based, intelligent, or optimization-based methods. Fig. 19 provides a comprehensive overview of the structures of some frequently employed EMS methods for FC-powered UAVs.

Additionally, Table 7 presents a summary of EMS for FC-powered UAVs (FC-UAV), encompassing the utilized methods, objectives, configurations, and verification methods.

Dudek et al. focused on developing a propulsion system for a motor glider that integrated a PEMFC with a Li–Fe battery. The main objective of their design was to optimize the overall performance and efficiency of the aircraft. By combining the advantages of both the PEMFC and the Li–Fe battery, they aimed to enhance the aircraft's capabilities and achieve improved operational characteristics [130].

Few works have been done on the energy management of larger FC aircraft. For instance, A mathematical tool was developed for the preliminary design of a hybrid fuel cell propulsion system for regional aircraft [131]. In this design, both sizing and energy management systems were considered.

3.2.3. PEMFC propulsion systems for regional and large aircraft

The regional aviation sector contributed to 7% of total CO2 emissions in passenger aviation in 2019 [132]. Numerous research efforts have focused on the application of FC technology in both commercial spacecraft and aircraft in recent years. Notably, collaborative initiatives between ZeroAvia and Alaska Air Group, as highlighted in 2021 (ZeroAvia | Alaska Air Group | Hydrogen Powertrain, 2021), hold the potential to introduce FC-powered aircraft to the regional market. This involves retrofitting a 76-seat aircraft to harness hydrogen power [133].

Airbus made a ground-breaking announcement with its ZEROe initiative, signalling a pioneering effort in the development of a fully electrical concept aircraft. The unveiling of this concept in December 2020 showcased a propulsion system entirely powered by FCs, marking a significant leap forward in the pursuit of sustainable and environmentally friendly aviation solutions. The fully electrical concept represents a notable stride towards redefining the conventional aircraft propulsion paradigm and aligns with the aviation industry's broader commitment to reducing its environmental footprint.

Marciello and colleagues [16] out an extensive study on the sustainable design of regional hybrid-electric aircraft. Their research

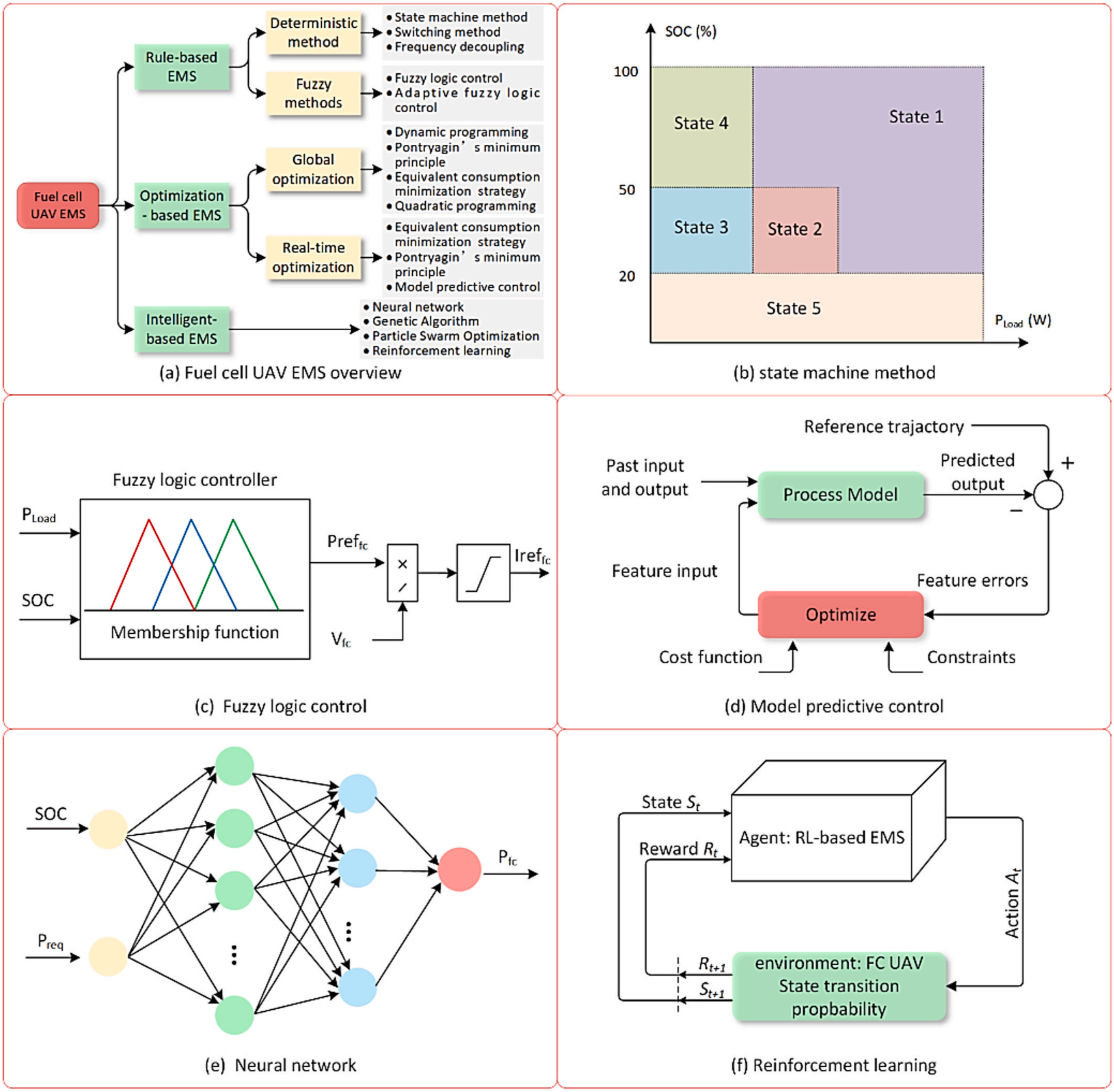

Fig. 19. EMS employed in FC UAVs. (a) FC UAV EMS overview. (b) State machine approach. (c) Fuzzy logic control. (d) MPC. (e) NN. (f) RL. [50].

suggests that FC hybrid electric propulsion has the potential to be a feasible solution for regional aircraft, with the most likely realization in the mid-term timeframe, particularly between 2035 and 2045. Sparano et al. also created a mathematical tool for the conceptual design of hybrid FC powertrain systems for aircraft, aiming to support the preliminary design phase of regional aircraft.

Affonso Jr. and colleagues analyzed various designs for regulating temperature in FC aircraft configurations, both in series and in parallel [16]. Seyam and his team explored the financial and ecological consequences of aircraft engines that use a combination of hydrogen and other fuels [134]. In their research, they focused on a hybrid aircraft engine that combined a molten carbonate FC system with a traditional turbofan system.

Scott and colleagues [135] examined the electrification/hydrogen hybridization of military vehicles in the US army. They determined that armoured tanks, freight trains, boats, oceangoing vessels, helicopters, prop planes, and jumbo jets could potentially transition using identified technological advancements and solutions outlined in the literature without compromising performance requirements. Additionally, they estimated that transitioning the energy source for United States Army vehicles could result in an environmental improvement equivalent to removing nearly 700,000 passenger cars from the road today.

A model-based preliminary design method was proposed to optimize weight and efficiency in the propulsion system of a four-seater hybrid electric fuel cell aircraft [136]. In this approach, the limits of the heat management system were also considered.

Limited research has also been carried out on the utilization of H_2 fuel for propulsion in large aircraft. Stockford [78] examined the advantages and efficiency of implementing a hydrogen FC-powered e-taxi system on an A320 class airliner and determined that the proposed

Table 7
Specifications of the EMSs employed for FC UAVs [50].

Approach	Aim	Powertrain	Verification	Comments	Ref
State machine	Enhancement efficiency of the system	FC/Battery	Rapid control prototype	The proposed method achieves an overall efficiency exceeding 90% across various initial SOC states.	[103]
Rule-based	Achieving equilibrium between fuel usage and SOC	FC/Battery	Ground test platform	The power system's reliability is enhanced by ensuring that no power sources are depleted prematurely	[104]
State machine	Manage the power system for FC utilize an online EMS for UAV operations.	FC/Battery	Simulation	The EMS system is integrated with the FC compressor's optimal power control, resulting in a 2.6% energy savings when compared to using constant compressor power	[105]
Fuzzy logic	Manage the power system for FC utilize an online EMS for UAV operations.	FC/Battery	Test bench	The fuzzy approach yields optimal results in terms of fuel efficiency when contrasted with passive EMS and state machine implementations.	[106]
Fuzzy logic	Hydrogen conservation and superior effectiveness.	FC/Battery	Simulation/HIL	The SOC will have a significant impact on the fuel operating parameters, with a low SOC resulting in decreased efficiency.	[107]
Fuzzy logic	Safeguarding the FC and guaranteeing optimal performance.	FC/Battery	Simulation	The efficiency of the proposed method surpasses that of the deterministic method.	[108]
Fuzzy logic	… … ….	FC/Battery	Simulation/ Experiment	The controller has successfully decreased hydrogen consumption by 22%.	[109]
Fuzzy state machine	To guarantee prolonged durability	FC/PV/Battery	Simulation	A 6.7% reduction in hydrogen fuel consumption was reported, compared to using a constrained thermostat control system.	[110]
Switching logic	To guarantee prolonged durability	FC/PV/Battery	Test	The system's stability can be assured.	[111]
Frequency decoupling	… … ….	FC/Ultracapacitor	Simulation	The wiener filter outperforms the wavelet transform in terms of the average high-frequency component, effectiveness, and average SOC value.	[112]
Frequency decoupling and ECMS	To extend the lifespan of the power source.	FC/Battery	Simulation	The SOC of the battery remains within an acceptable range when compared to the rule-based strategy, which allows the FC to output a constant power, resulting in a 3% saving of hydrogen.	[113]
Dynamic programming	To guarantee prolonged durability	FC/Battery	Simulation	Hybridization has the potential to separate the aircraft constraint from the aircraft energy requirements, leading to enhanced performance via a well-integrated design process.	[114]
PMP	Online optimization	FC/Battery	Simulation	A 4% reduction in hydrogen consumption is achieved when compared to the rule-based method, resulting in a relatively low average power change rate for the fuel cell, ultimately enhancing its durability.	[115]
PMP	Enhancing service longevity and increasing fuel efficiency	FC/Battery	Simulations/ Experiment	Achieving a 20% reduction in hydrogen consumption when compared to the rule-based approach.	[116]
PMP satisfactory optimization	Enhancing service longevity and increasing fuel efficiency.	FC/Battery	Simulation	The fluctuation in FC output power has been significantly decreased, while the hydrogen consumption remains comparable to the standard PMP method.	[117]
Improved PMP	To ensure long-endurance	FC/Battery	Simulation	A reduced rate of power consumption and a 5.4% increase in hydrogen efficiency are attained when compared to fuzzy logic.	[118]
Fuzzy ECMS	To ensure the SOC is in a suitable range	ICE/Battery	Simulation	F-ECMS has the capability to optimize fuel consumption while managing the SOC.	[119]
ECMS	Enhancing service longevity and increasing fuel efficiency.	FC/Battery/ Ultracapacitor	Simulation	Attains a consistent FC flow and reduces hydrogen consumption by 2.16% in comparison to the rule-based approach.	[120]
Multi-mode MPC	Enhancing service longevity and increasing fuel efficiency.	FC/Battery	Simulation	A reduction of 87% in FC power transients and a saving of 2% in hydrogen are achieved when compared to the single-mode benchmark strategy.	[121]
MPC	To test the influence of the velocity forecasting method	ICE/Battery	Simulation	The MPC can achieve a 7% higher hydrogen saving compared to the ECMS, thanks to the prediction results of the neural network.	[122]
NN and fuzzy	Enhancing service longevity and increasing fuel efficiency	FC/Ultracapacitor	Simulation	The suggested framework will guarantee that the SOC remains within the specified limit.	[123]
GA optimized NN	Preventing the frequent start-stop and sudden load fluctuations of the FC.	FC/Battery	Simulation	The FC's start-stop has decreased in comparison to NN and ECMS. Additionally, the fuel consumption is similar to the DP outcome.	[124]
Reinforcement learning	Achieving real-time functionality in applications and achieving near-optimal global optimization	FC/Battery	Simulation	Fuel savings of 6.14% can be achieved, along with a 21.7% reduction in start-stop times for FCs when compared to the rule-based method.	[125]
Reinforcement learning	Attaining cost-effective computation, maximum efficiency, and fuel savings	FC/Ultracapacitor/ Battery	Simulation	The RL-based method demonstrates lower fuel consumption compared to ECMS, while also exhibiting higher computational efficiency than the DP method.	[126]
Improved Q-learning	To enhance the overall efficiency	FC/Battery	HIL/Test	The proposed strategy leads to an overall efficiency of 52%, marking an 8% increase compared to that of the state machine.	[127]
Double Q-learning	To guarantee prolonged durability	ICE/Battery	Simulation	The RL approach has the potential to decrease the processing time while maintaining a similar level of performance in terms of fuel efficiency and cost savings when compared to the DP method.	[87]

(*continued on next page*)

Table 7 (*continued*)

Approach	Aim	Powertrain	Verification	Comments	Ref
RB-EMS FSRB-EMS ECMS	To minimize H_2 consumption	FC/Battery	Test	Power management strategies allow power sources to operate within their optimal range, prolonging their lifespan, and resulting in a 3% reduction in hydrogen consumption.	[113]
Non-causal and causal control approaches	To minimize fuel consumption to prolong flight duration	FC/Battery	–		
Adaptive neuro-fuzzy inference system (ANFIS)	To control the power output of the FC	FC/Battery	Simulation	The controller efficiently regulates the power distribution between the FC system and the battery, leading to enhanced power management capabilities.	[128]
Rule-based	To prolong the flight duration	FC/Battery	Test	Over the course of 12 flights, an extra combined flight duration of around 2 min was achieved. The total hydrogen usage during the 12 flights was recorded as 0.0736 g. The average energy consumption of the fuel cell alone during the 12 flights amounted to 0.235 W-hours.	[92]
Decentralized EMS	To increase lifespan and reliability of the system	FCs/Supercapacitors	Simulation	The power load can be automatically separated into low and high-frequency ranges and distributed to FC. This has resulted in a great deal of flexibility and scalability.	[129]
EMS-PPA	To minimize the fuel consumption	FC/Photovoltaic/ Battery/ Supercapacitor	Simulation	The results obtained have validated the effectiveness of the suggested approach, with an efficiency of 95.34% and a minimal hydrogen consumption of 15.7559 gm.	[30]

system could result in a fuel reduction of up to 1% and an expected decrease in total maintenance cost of up to 7.3%. Furthermore, an estimated improvement of up to 5.97% in net profit is projected when compared to the annual after-tax profit of the reference operator in 2016.

Schroder et al. [137] devised a stack model aimed at investigating the optimal operating conditions for commercial single-aisle aircraft powered by PEMFCs. The model incorporates a comprehensive analysis of water management within the FC system. The findings underscore that conditions conducive to maximizing the overall system efficiency during a specific flight phase markedly deviate from those focused solely on optimizing stack efficiency.

The Hy4 project [3] is the first four-seat passenger aircraft in the world to be powered by FC technology. While demonstration projects are increasingly focusing on larger applications, there have been very limited demonstrations of hydrogen for propulsion (FC and turbine) [1].

AeroVironment achieved success in its initial test flight utilizing a high-altitude, long-endurance (HALE) aircraft powered by PEM FCs with a liquid hydrogen tank in 2003 [138]. The flight duration was extended to 9 h through the utilization of chemical hydride fueling technology developed by Millennium Cell Inc [95]. In 2006, the Naval Research Lab (NRL) conducted its first 3.3-h flight test using PEM FC and hydrogen gas [95].

Boeing conducted a trial of a two-seater aircraft with a wingspan of 16.3 m in Spain, achieving a 20-min flight at a speed of 60 miles per hour using only power generated by PEM FCs in 2008 [139,140]. The Antares DLR-H_2, one of the earliest manned aircraft powered entirely by FCs, showcased its capabilities in 2009 [141,142].

The Skyleader Rapid 200, developed in 2010 under the ENFICA-FC program, has the capability of a 40-min flight [143,144]. In 2016, a collaborative effort between a small plane manufacturer (Pipistrel), a fuel cell producer (Hydrogenic), the University of Ulm, and the German Aerospace Center led to the testing of the HY4. This fuel-cell powered 2-seat aeroplane was equipped with a 9-kg hydrogen tank and underwent a successful flight test at the Stuttgart airport in Germany [143].

The National Aeronautics and Space Administration (NASA) in the USA provided funding for a project led by the Center for Cryogenic High-Efficiency Electrical Technologies for Aircraft (CHEETA) to create an aircraft that utilizes an LH_2 PEMFC system to operate fully electric fans. One of the objectives of this initiative was to showcase the potential of cryogenic hydrogen for larger aircraft [95]. A research group, spearheaded by The German Aerospace Center (DLR), designed the HY4, a four-seater hydrogen FC aircraft [30], which successfully conducted its maiden flight in 2016 [31]. The powertrain of the HY4 comprises a PEMFC connected to an 80 kW electric motor, supplemented by a battery. Approximately 10 kg of hydrogen is stored in gaseous form within a tank at 437 bar. The HY4 has a maximum weight of 1.5 tonnes and is capable of flying at speeds of 145 km h–1 for a distance of around 1000 km [37].

The HyFlyer initiative, spearheaded by ZeroAvia in the United States, sought to reduce carbon emissions from medium-range, six-seater aircraft by substituting the traditional propeller powertrain with a compressed hydrogen PEMFC system [93]. ZeroAvia successfully conducted flight tests on its prototype powertrain, utilizing a Piper PA-46 Light Sport Aircraft from Piper Aircraft in the USA [94,129].

Suangqi et al. compared performance of a two-seater light aircraft with hybrid FC/battery and FC-only propulsion systems. Their findings suggest integrating both technologies enhances overall efficiency and operational characteristics [54]. The numerical analysis revealed that the battery's presence expanded the FC system's operating range, resulting in a substantial improvement in propulsion efficiency. Moreover, the aircraft's quantified hydrogen consumption showed a noteworthy 7.63% decrease compared to the FC-only propulsion system, thanks to the battery integration.

G. Renouard-Vallet et al. [145] conducted an investigation and evaluation of the performance of various FCs for aircraft applications under different conditions (at reduced pressure, lower vibrations, etc.) on a laboratory scale. The test results demonstrated that aircraft powered solely by H_2/O_2 FC were capable of producing up to 20-kW power output with 10 L of clean water as the byproduct. The world's first new test bed "Anates-DLR-H_2" was developed by DLR and successfully completed an altitude by covering a distance of about 2550.56 m at an operating pressure of 72.5 kPa (which was 29.0 kPa below the normal atmospheric pressure) on July 9, 2009 [145].

Recently, the same DLR team effectively tested another H_2-fueled air vehicle, the "HY-4" (capable of carrying four passengers) with a 9-kg fuel storage tank, which successfully covered a range of 1500 km. The electric motor (80 kW) attached to it could achieve a maximum speed of 200 km per hour along with a cruising speed of 145 km per hour [143]. "Air Bus" has been actively involved in the aviation sector for 15 years to integrate new aircraft for the upcoming generations, providing a safe and smarter journey. Leading R&D groups such as Boeing Research & Technology and NASA are committed to developing a new aircraft system, mainly hybrid electric jets for short/regional travel purposes by 2020, with higher fuel efficiency and more eco-friendly [146].

Various developed air vehicles and recent modifications in their configuration are summarized in Table. A comprehensive inspection is also underway for FC-attached unmanned air vehicles (UAV) which are not yet fully established. Complete technical information about UAVs has been described by Dong et al. [147]. However, the first UAV flight

(Hornet UAV) introduced by Aero Vironment in 2003 had a durability of 15 min, whereas after one decade, in 2013 the LH_2 Ion Tiger UAV came into light with an endurance of 48 h [147]. According to aeronautics research experts, the development of FC-attached UAVs is a promising area for future advancements in aviation technology.

The integration of PEMFC and turbine systems for aircraft propulsion was explored by Seiz et al. [148]. A basic schematic diagram illustrating this application can be found in Fig. 20, where a novel FC-gas turbine hybrid propulsion concept is introduced. This concept utilizes the water mass flow generated by a hydrogen FC to enhance the efficiency and power output of the gas turbine engine through burner steam injection. The innovative idea involves using the product water from the FC to improve the performance and emission characteristics of the Gas Turbine (GT) engine. The process includes condensing and separating the FC product water from the residual air mass flow, pressurizing it, and then re-evaporating it before injecting it into the GT engine.

3.3. SOFC systems for aircraft propulsion

The solid oxide electrolyte material in SOFC enables it to operate within a wide temperature range of 600 to 1000 °C [97,98], resulting in high energy conversion efficiency without the need for an expensive catalyst like in PEMFC. Apart from hydrogen, SOFC can also utilize hydrocarbons such as methane, propane, biofuels, natural gas, and gasoline [32,100]. Researchers propose that SOFCs could potentially serve as viable alternatives for the next generation of FC-powered aircraft, and further advancements in research and development in this field could lead to more sustainable and efficient aviation technologies [16].

The elevated operational temperature facilitates the combined utilization of the SOFC with the turbine-less jet engine [25,71,97]. In turbine-less jet engines based on SOFC, the discharge from the SOFC can be employed to pre-warm the compressed air and the premixed hydrocarbon fuels. Additionally, the discharge from the SOFC can also be combusted in jet engines, leading to a significant enhancement in fuel efficiency [71].The particular energy density can achieve up to 800 Wh/kg for the hybrid propulsion systems of SOFC-jet engine [71,141].

SOFC systems eliminate the need for a water management system unlike low-temperature FCs (such as PEMFCs) because the water produced in the form of steam exits the system. Additionally, SOFCs have a longer lifespan than PEMFCs, which can prolong the propulsion system and the aircraft's mission duration. However, the energy density of SOFCs is inferior to that of PEMFCs, which can result in increased weight of the propulsion system. A significant downside of the SOFC is the extended warm-up and start-up time required [32].

Present solid oxide fuel cell (SOFC) technologies typically restrict the operational temperature range to 600–1000 °C in order to lower material expenses and ensure system reliability [97,98].

Combining SOFC and jet engines for the propulsion purpose of larger aircraft is an ongoing research subject which has attracted much interest. Fig. 21 shows the schematic diagram for this configuration.

Fig. 22 also shows the components of the hybrid get engine/SOFC powertrain system.

There has been some research conducted on the use of SOFC in aircraft powertrain systems. For example, Ji et al. [149] examined the performance characteristics of a SOFC hybrid jet engine propulsion system under four different operating modes, with the aim of achieving 50%–100% thrust variation. Mode 1 involves regulating the fuel flow in the reformer under constant air flow for the SOFC system, while Mode 2 involves regulating the fuel flow in the afterburner with zero fresh air for afterburners.

Mode 3 involves regulating the fuel and air flow for the SOFC, while Mode 4 involves regulating the fuel flow in the afterburner with constant air flow. It has been determined that the performance of the engine can be varied in a wide range under operating mode 4 by increasing the afterburner temperature from 832 K to 2261 K. Operating mode 4 is considered the most effective.

Alizadeh and colleagues [74] examined the thermodynamic implications of utilizing integrated SOFC systems for medium-sized aircraft (see Fig. 23). They computed the exergy and energy efficiencies of the primary components and found that the SOFCs achieved maximum values of 84.54% and 80.31%, respectively. The integrated system as a whole demonstrated energy and exergy efficiencies of 57.53% and 47.18%, respectively. Additionally, the SOFC exhibited optimal performance at 800C, with a maximum power density of 1.23 W/cm^2.

Liu et al. [150] conducted a study on the integrated SOFC and gas turbine propulsion systems, analyzing the impact of exhaust recirculation in the anode, cathode, and both. The research findings indicated that the hybrid systems outperformed traditional gas turbine propulsion by nearly double. Additionally, the inclusion of exhaust recirculation was found to enhance the overall efficiency of the system. Fig. 24 illustrates schematic diagrams of the various configurations discussed in the study.

Chang and his team [150] conducted a theoretical study on the operational abilities of a compact UAV that has a propulsion system made up of a battery and an FC, leading to a fully electric setup. They

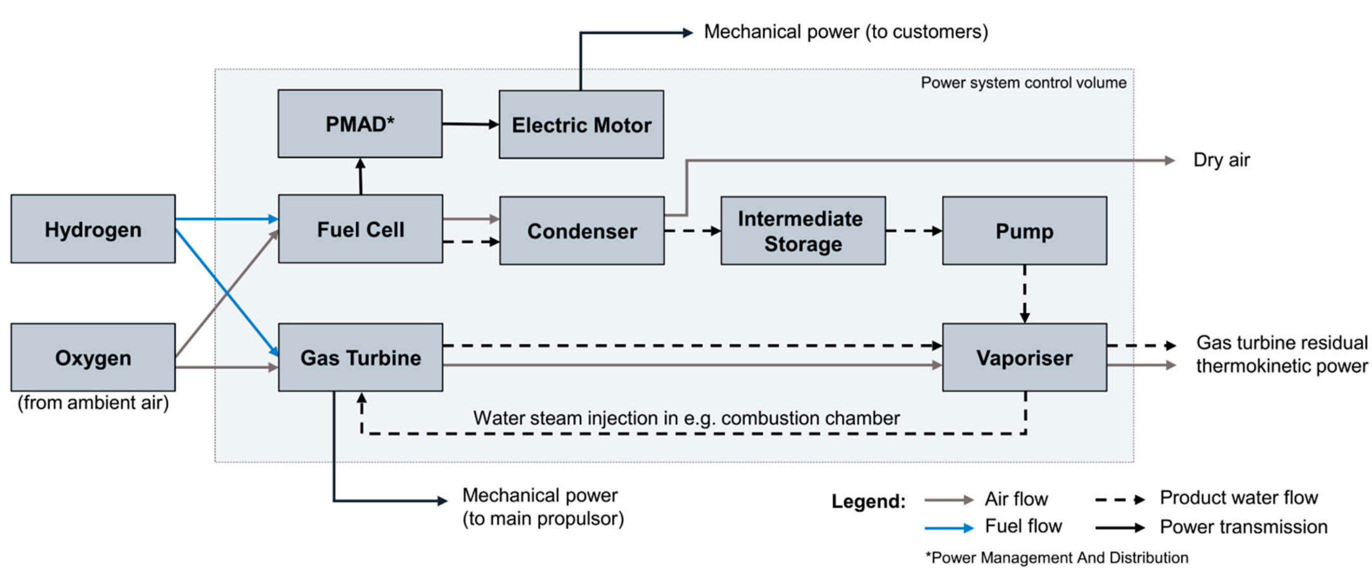

Fig. 20. Schematic diagram for a FC–GT hybrid propulsion system [148].

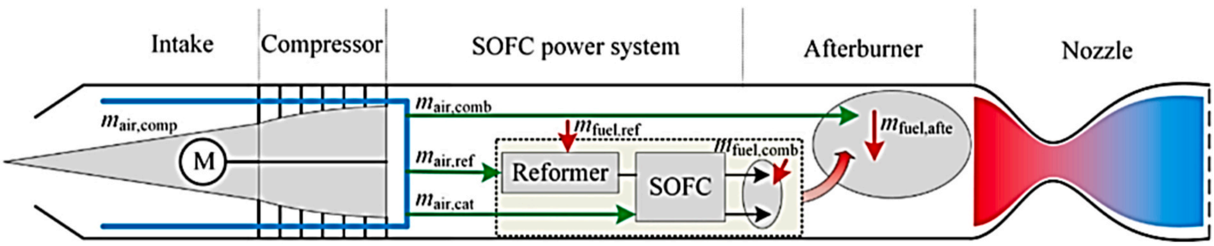

Fig. 21. Schematic diagram for a SOFC hybrid electric propulsion system [149].

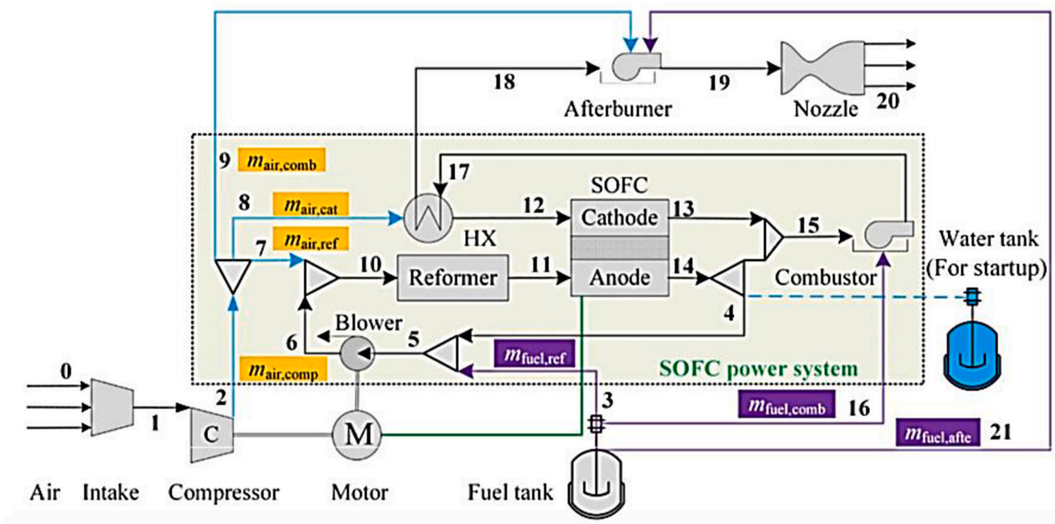

Fig. 22. Schematic diagram for the SOFC power system in the hybrid jet engine [149].

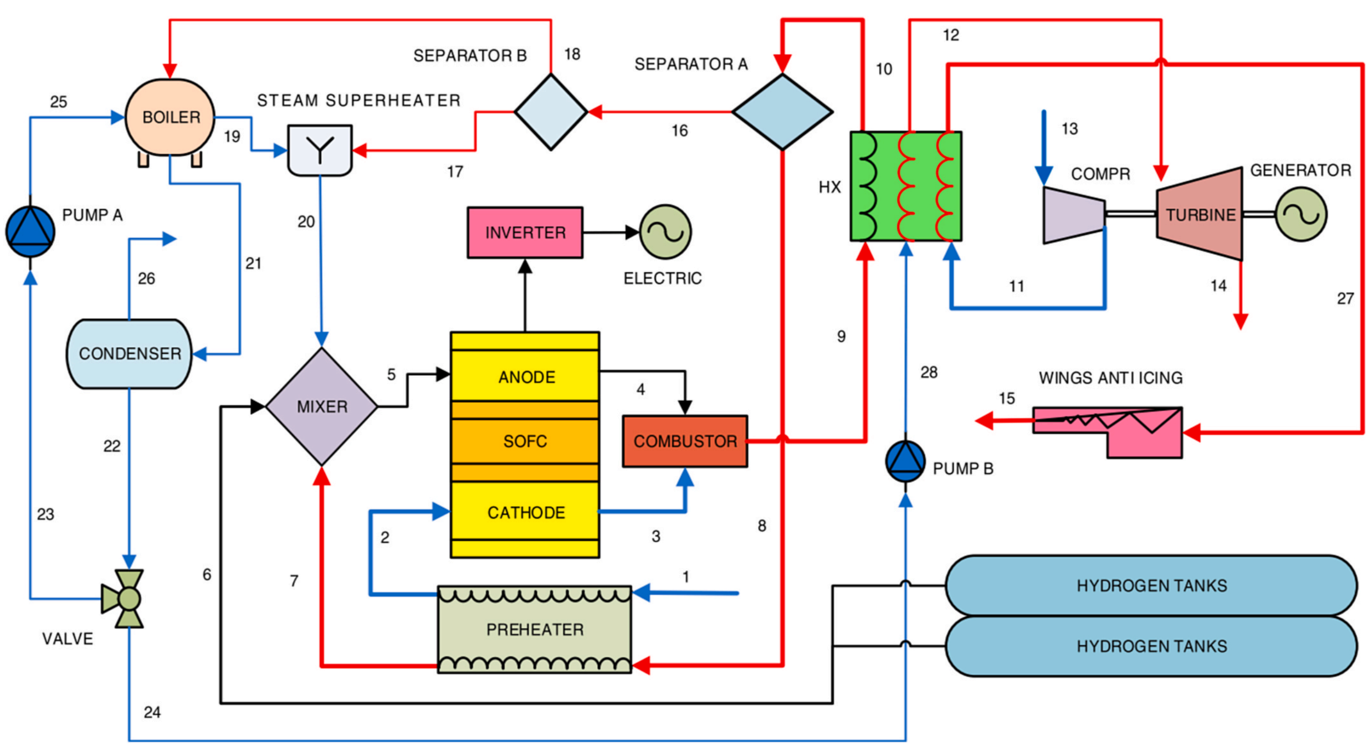

Fig. 23. Flow diagram for the integrated SOFC system [74].

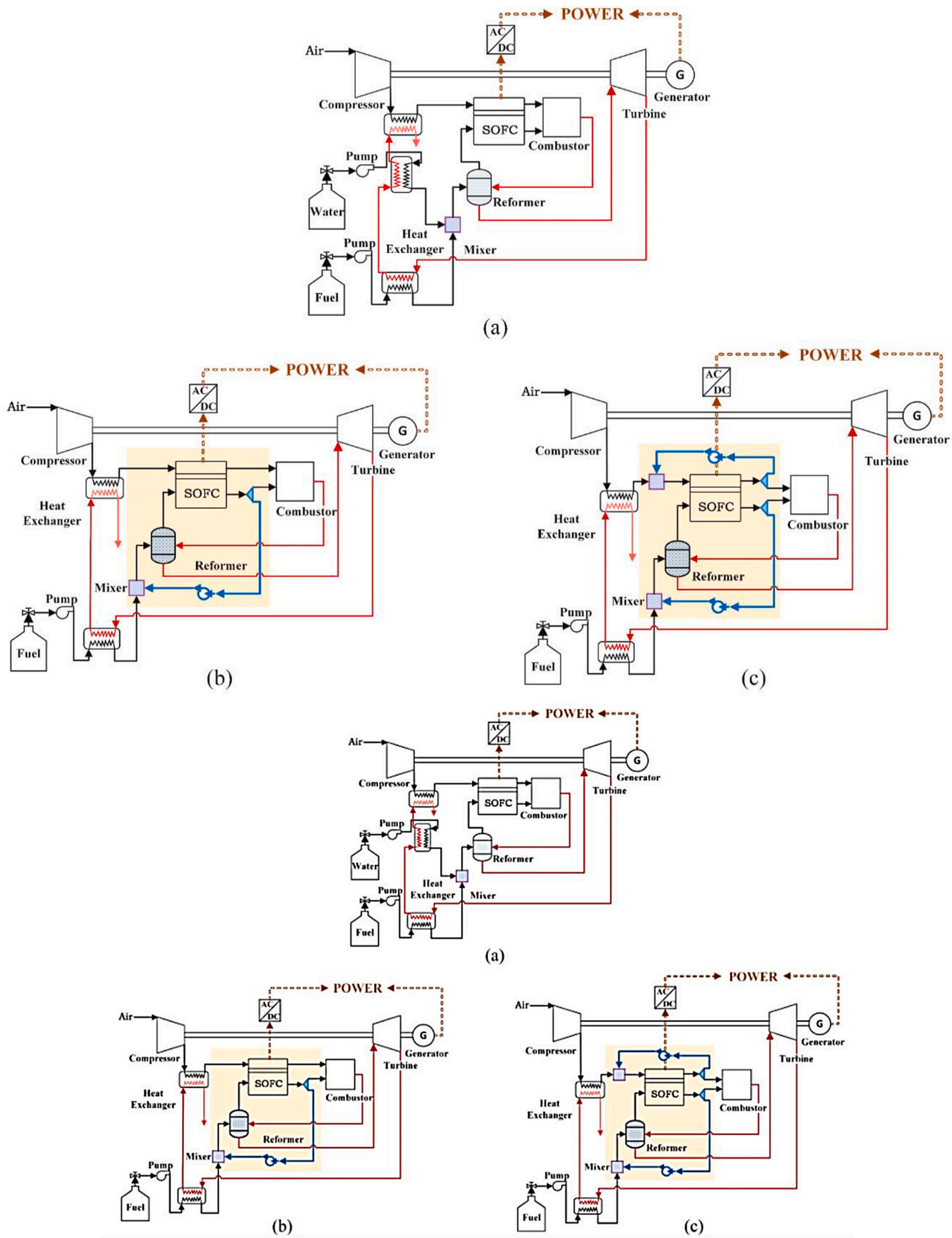

Fig. 24. Configuration of a hybrid system, including: (a) The basic gas turbine hybrid power generation system (BHS); (b) The anode exhaust recirculation hybrid power generation system (ARHS); (c) Anode and cathode exhaust recirculation hybrid power generation system (ACRHS) [141].

evaluated the efficiencies of both the SOFC and PEMFC in this scenario [151]. The PEMFC's performance is significantly more sensitive to changes in current when compared to the SOFC. Additionally, the PEMFC requires a size that is approximately twice as large as the SOFC. It was noted that changes in altitude have a greater effect on the SOFC's performance as opposed to the PEMFC.

Wilson and colleagues created a thermodynamic framework for a hybrid SOFC-GT propulsion system. A 1-MW SOFC-GT hybrid power system was assembled for an aircraft propulsion idea. The hybrid system demonstrated overall efficiencies of over 75% FTE during typical 36,000 feet cruise flight conditions [97].

The impact of six fuel types on the performance of a hybrid SOFC and gas turbine propulsion system was studied by Rupiper et al. [98]. The most efficient performance of the hybrid system is achieved when using H_2 as the fuel source. The highest electrical efficiency of the hybrid configuration is 64.7% when using H_2 fuel, 60.3% with CH4 fuel, 60.9% with C3H8 fuel, 61.7% with JP-4 fuel, 61.0% with JP-5 fuel, and 61.2% with JP-10 fuel. These results show a significant improvement over the standard gas turbine cycle. When utilizing H_2 fuel, the overall integrated system is expected to be 24.5% more efficient than the standard gas turbine system.

Wang et al. evaluated the performance of a tiny drone with an FC + BATTERY powertrain [100]. They studied both PEM and SOFC in their work. By comparing the performance of the two FCs, it is shown that SOFC suppresses PEMFC in terms of producing electrical power.

Nam et al. [139] examined the possibility of employing giant multi-mega Watt superconducting electric motors for FC/battery propulsion systems in aircraft (Fig. 25). They used hydrogen for both the cooling purpose of the electric motor and fueling the FC system and concluded although the specific power for the designed superconducting is very high, the specific power of the current energy storage systems is enough to provide the electric motor power demand.

Integrating SOFC into turbofan propulsion systems has been considered in some works. Fig. 26 depicts the schematic diagram for this configuration as well as the layout for this combined SOFC-turbofan system [119].

In a separate study, Seyam et al. [143] introduced two high bypass three-shaft turbofan engines that incorporated a molten carbonate FC (MCFC-turbofan) and a SOFC-Turbofan (Fig. 27). An analysis of energy and exergy was carried out to assess the aircraft's performance during cruising operation. The fuels utilized were kerosene and a blend of 75% methane and 25% hydrogen. The findings revealed that the base turbofan generated a maximum thrust force of 153 kN, while the SOFC- and MCFC-turbofans produced 116 kN and 107 kN, respectively. The thermal and exergy efficiencies were 43.4% and 52% for the base-turbofan, 52.8% and 66.2% for the SOFC-turbofan, and 71% and 87.6% for the MCFC-turbofan. By using alternative fuel blends, carbon emissions decreased from 18 kg/s to approximately 3.7 kg/s. The weight of the turbofan engine increased by 18% with the SOFC and 40% with the MCFC, resulting in a reduction of the thrust-to-weight-ratio from 2.7 for the base-turbofan to 1.5 for the SOFC-turbofan and 1.06 for the MCFC-turbofan. Although the addition of an FC led to an increase in engine weight, it also enhanced system performance and lowered emissions.

Seyam et al. [152] introduced a hybrid turbofan and molten carbonate FC (MCFC) system that includes a steam reformer, a water gas shift reactor, and a catalytic burner (see Fig. 28). They also examined five potential fuels for propulsion and determined that a traditional turbofan can generate 42 MW with 59% energetic efficiency and 71% energetic efficiency, while the hybrid MCFC turbofan can produce 40 MW by combining all five alternative fuels, but with higher performance of 65% and 80% energetic and energetic efficiencies, respectively. Additionally, CO2 emissions are significantly reduced by 75%. The fuel blends offer improved performance and much lower CO2 emissions.

Rostami et al. introduced a new hybrid propulsion system which incorporated SOFCs and downstream cycles; used in a small drone [145]. An illustration of the system is seen in Fig. 29.

Seyam and colleagues [146] conducted a study on how different types of fuels affect the efficiency of a combined SOFC-gas turbine FC system for aircraft. Their findings suggest that utilizing a hybrid turbofan aircraft engine can enhance turbofan performance. Moreover, they discovered that a fuel blend consisting of 60% ethanol and 40% hydrogen can lead to a 5% increase in performance and a 73% reduction in carbon emissions.

Zhixing and colleagues [153] introduced a sizing optimization method for a turbine-less engine integrated with an SOFC on unmanned aerial vehicles. Their findings indicated that the maximal thrust and thrust variation range of the engine increased by approximately 46% and 38–40%, respectively, compared to those of the turbojet engine. The schematic diagram for this design can be observed in Fig. 30. Ji et al. [147] performed an exergy analysis on their proposed SOFC turbine-less propulsion system proposed for aircraft propulsion.

In another attempt to develop hydrogen propulsion systems [155], the idea of integrating ducted fan engines with high-temperature fuel cell systems for aircraft propulsion was explored, showing that this integration could reduce the weight and volume of fuel cell systems. Moreover, the performance of the turbo engine is substantially enhanced, and the efficiency of the fuel cell can increase considerably [147].

3.3.1. SOFC systems for auxiliary power units (APUs)

FC air vehicles are equipped with an APU, which is essential for

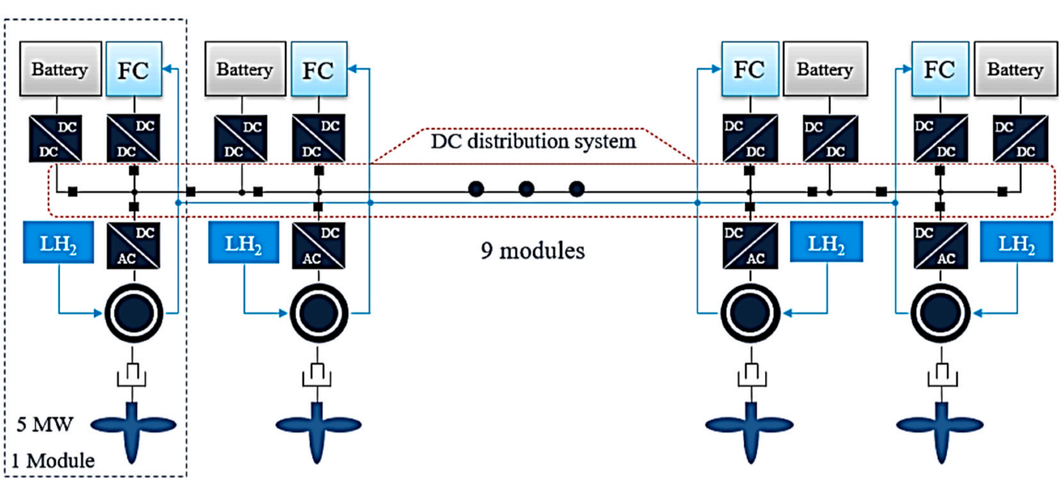

Fig. 25. Configuration of the power units in the proposed APS. [139].

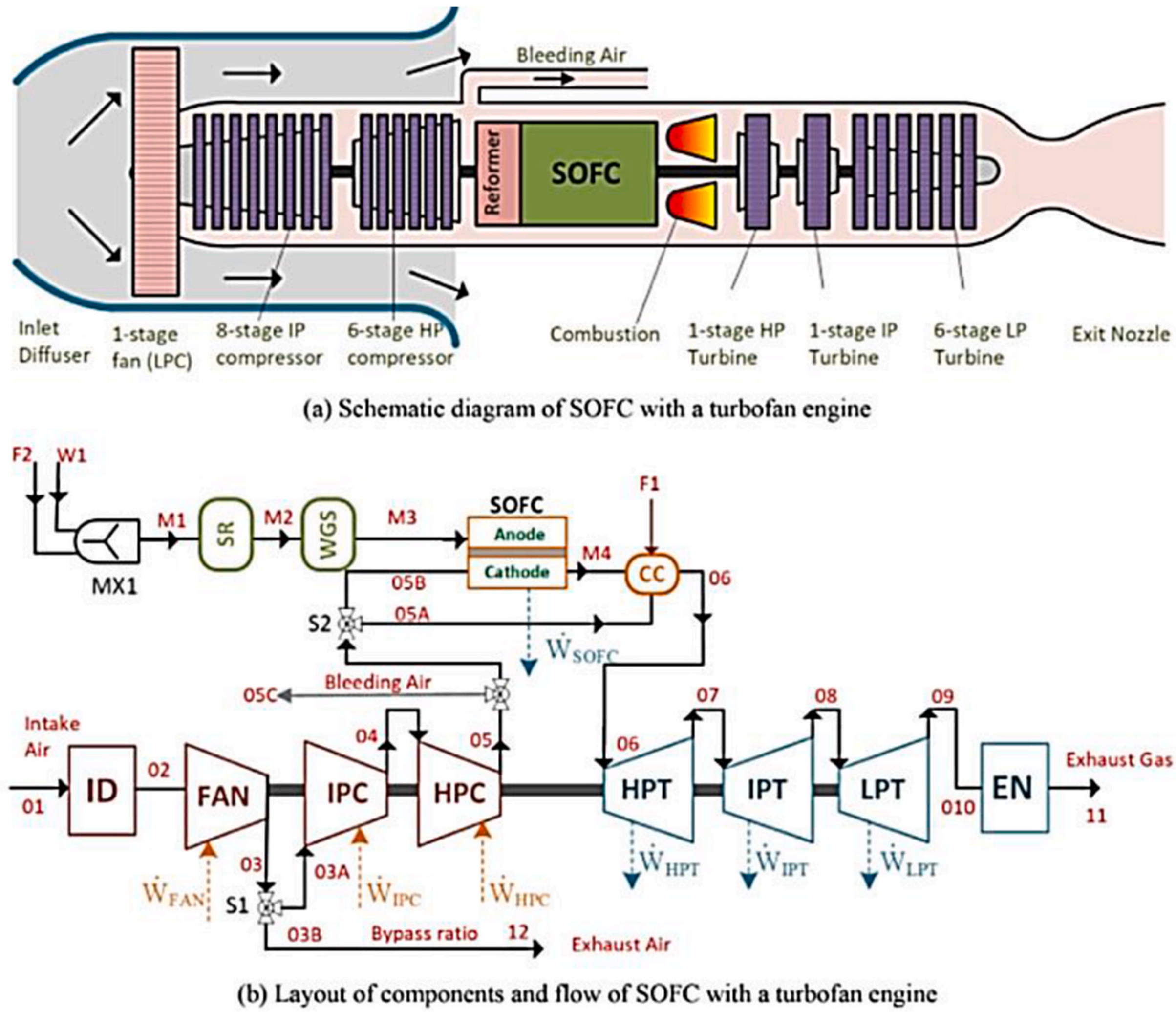

Fig. 26. Schematic diagram for a SOFC-turbofan propulsion system [141].

starting the engines. Unlike traditional APUs that operate at high temperatures, produce loud noise, and emit foul odors, the H_2-fueled APU is a more environmentally friendly option. It eliminates pollution, operates quietly, and is cost-effective. Additionally, the FC-based APU can be used at airports without any restrictions, unlike traditional APUs, making it a more versatile and independent power source [139].

FCs have the potential to be utilized on aircrafts alongside or instead of Auxiliary Power Units (APUs). While traditional APUs are typically comprised of a small gas turbine that provides power for electrical and pneumatic systems when the aircraft is on the ground, as well as serving as a backup power source during flight, FCs could gradually become integrated into aircraft APUs by powering systems that are currently reliant on batteries, such as emergency door systems [72]. According to a report from Boeing, implementing SOFC-powered APUs for all non-propulsion loads on an aircraft could result in a 40% reduction in fuel consumption for onboard energy during cruising compared to traditional APUs [72]. It is worth noting, however, that auxiliary units contribute only a small fraction to the overall energy consumption of an aircraft [37].

PEMFCs are currently under development for use as auxiliary power units (APUs) in large commercial aircraft [152,156]. For example, Boeing has successfully integrated a fuel cell system into the 787-8 aircraft, providing 1.5 MW of power for various onboard systems such as galleys, entertainment units, and as a backup power source during critical phases of flight [145,157]. Similarly, Airbus has collaborated with DLR to evaluate a 20 kW fuel cell emergency power system for the ATRA research aircraft (A320) [146,158].

3.4. Other FC systems for aircraft propulsion

There have been very few studies on the use of FC systems other than PEMFC and SOFC systems for aircraft propulsion. For example, Gonzalez et al. [159] conducted a comparison of Direct methanol FC (DMFC) and H_2 proton exchange membrane fuel (PEMFC/H_2) cell performance under atmospheric flight conditions of Unmanned Aerial Vehicles. They found that atmospheric flight conditions have a greater impact on PEMFC/H_2 performance compared to DMFCs. Additionally, low pressure has a more significant effect on PEMFC/H_2 performance than on DMFC performance. Furthermore, atmospheric relative humidity has a greater impact on PEMFC/H_2 performance, especially at high cell temperatures, while DMFC performance is minimally affected.

In a separate investigation, Shaimaa and colleagues introduce a hybrid aircraft engine that combines a molten carbonate fuel cell system with a conventional turbofan system [134]. The proposed layout is depicted in Fig. 31. As shown in the diagram, the MCFC units are linked to a steam reforming and a water gas shift system.

3.5. Implementation of FC systems in commercial aircraft

Numerous research endeavours have been conducted over the last two decades on hybrid electric FC aircraft, resulting in the development of a few prototypes. Fig. 32 provides a summary of the commercial

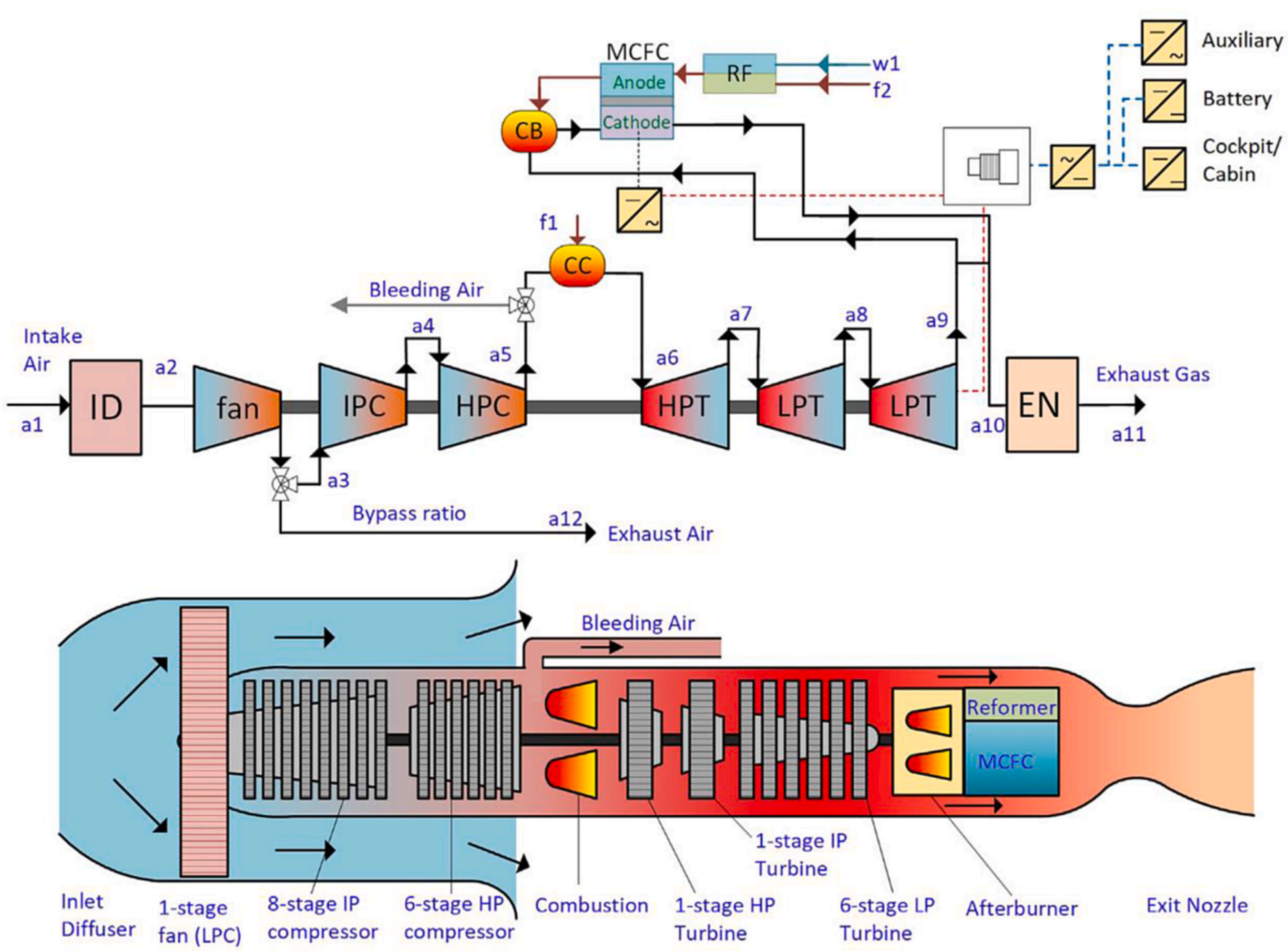

Fig. 27. Hybrid MCFC-turbofan engine [143].

implementation of FC systems in aircraft from 2005 to the present.

4. Challenges and future perspective

The challenges associated with the application of hydrogen for aircraft propulsion are being actively addressed through research, innovation, and industry collaboration [6]. The main challenges associated with this application were studied in a comprehensive survey done on the Cryoplane project [10]. H_2 storage, water management and contrail formation, and degradation of FC are the main ongoing challenges for aircraft H_2 propulsion which will be discussed in the following.

4.1. On-board H_2 storage

One of the challenges for the application of the H2 propulsion systems in aircraft is the on-board storage of H2. Hydrogen may be stored on-board either in the form of gas or liquid in reservoirs or it can be stored in some material; each method has its challenges [62].

Hydrogen contains 2.8 times more energy per unit mass than Jet A. Nevertheless, its volumetric energy density is notably lower compared to Jet A. At standard temperature and pressure (STP), which is defined as 0 °C at 100 kPa, hydrogen exists as a gas with a density of 0.899 kg/m3. On the other hand, Jet A has a density of 808 kg/m3, making it approximately 900 times denser. In order to carry sufficient hydrogen in an aircraft, its density must be increased. This can be achieved by storing gaseous hydrogen (GH2) at high pressure or by liquefying it and storing the liquid hydrogen (LH2) at extremely low temperatures.

The current industrial standard involves storing GH2 at 700 MPa (700 bar or approximately 700 times atmospheric pressure) and at ambient temperature. While higher pressure storage is feasible, the increase in energy density becomes less significant. Hydrogen has a boiling point of −253 °C (20 K) at atmospheric pressure. Presently, LH_2 is stored slightly above atmospheric pressure (1.01–1.5 bar or 101–150 kPa) at cryogenic temperatures ranging from −253 to −248 °C [16,78].

H_2 storage may be performed either through physical-based or material-based approaches (Fig. 33).

The H_2 storage methods can be divided into physical-based storage, which includes compressed H_2, Liquefied H_2, and Cryo-compressed H_2, and material-based storage, which encompasses metal-organic framework (MOF), carbon nanostructures, metal-hybrids, liquid organic hydrogen carriers (LOHCs), and chemicals.

Liquid and cryo-compressed hydrogen have emerged as the most favourable options for on-board storage due to their higher gravimetric density and more efficient hydrogen release. Nevertheless, as indicated in Table 8, the mass fraction of the liquid hydrogen tank remains significantly greater than that in automobiles, presenting a significant obstacle for the application of liquid H_2 in aircraft.

Material-centric H_2 storage technologies are currently undergoing development. Nevertheless, borohydride metals, LOHC, and ammonia present intriguing storage solutions with significant potential for advancement in the future, given their current low TRL. Table 9 provides a comparison of the physical-centric H_2 storage methods.

There are several logistical hurdles that must be overcome before

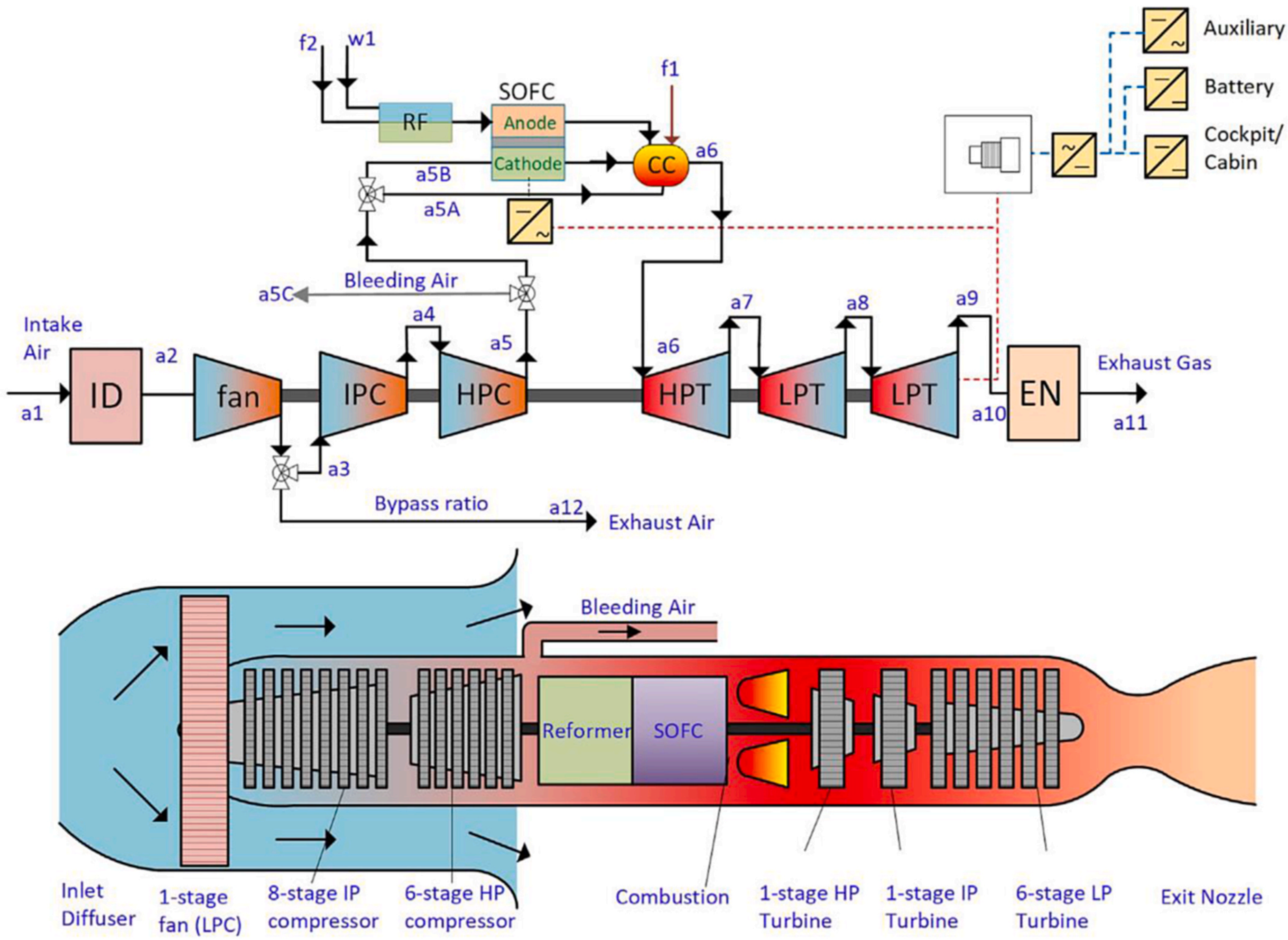

Fig. 28. Hybrid SOFC-turbofan engine [143].

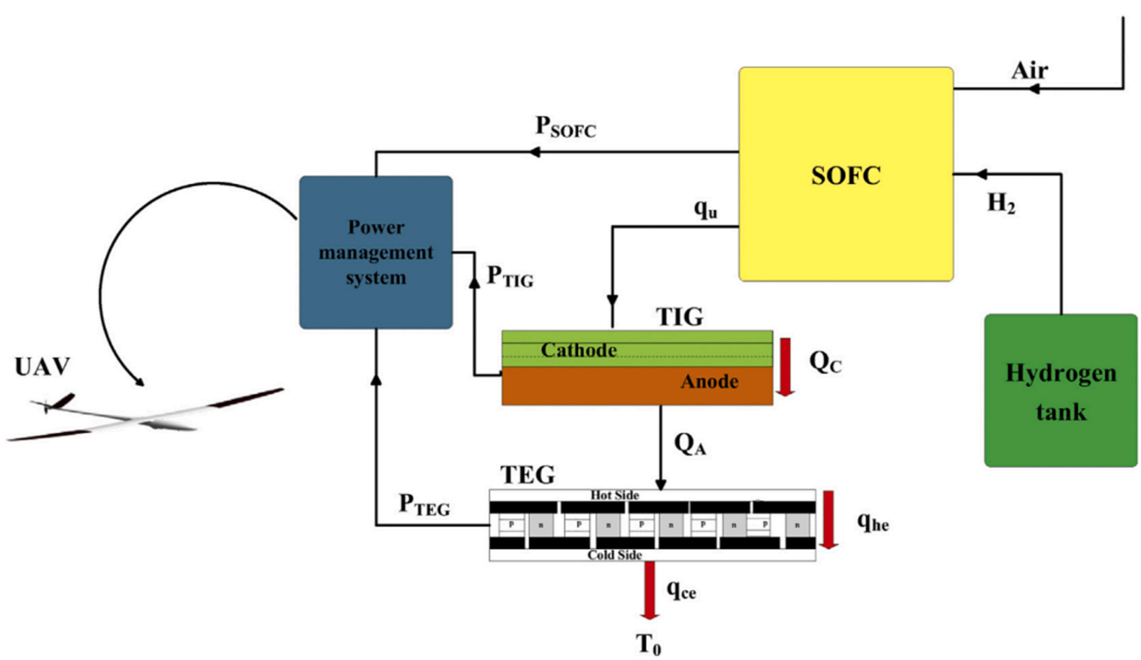

Fig. 29. Layout of the UAV propulsion system [145].

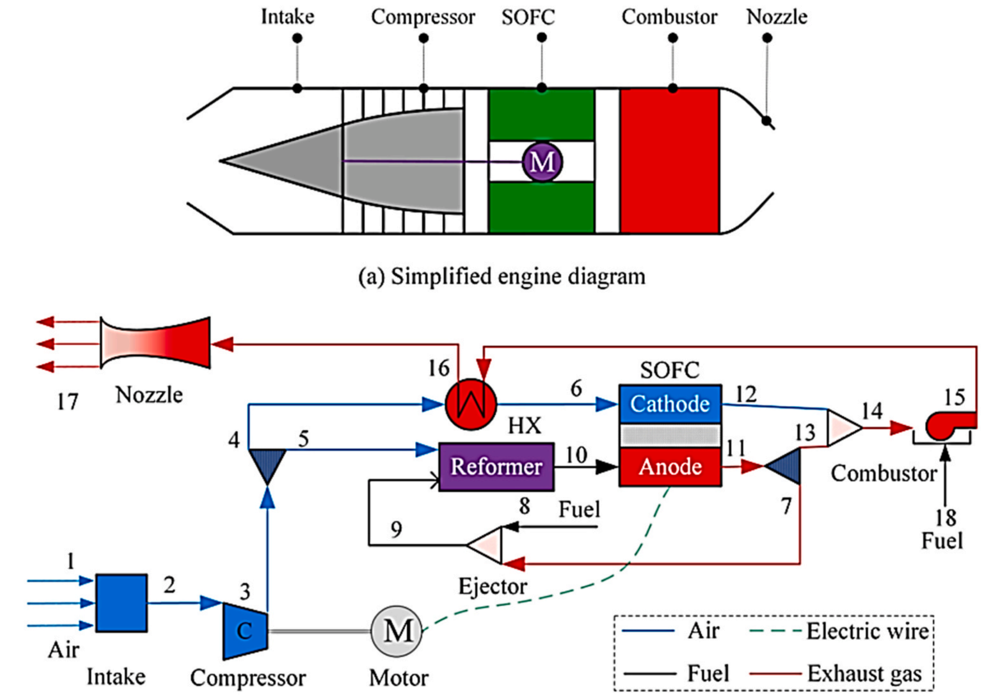

Fig. 30. Schematic diagram for the turbine-less SOFC propulsion system [153,154].

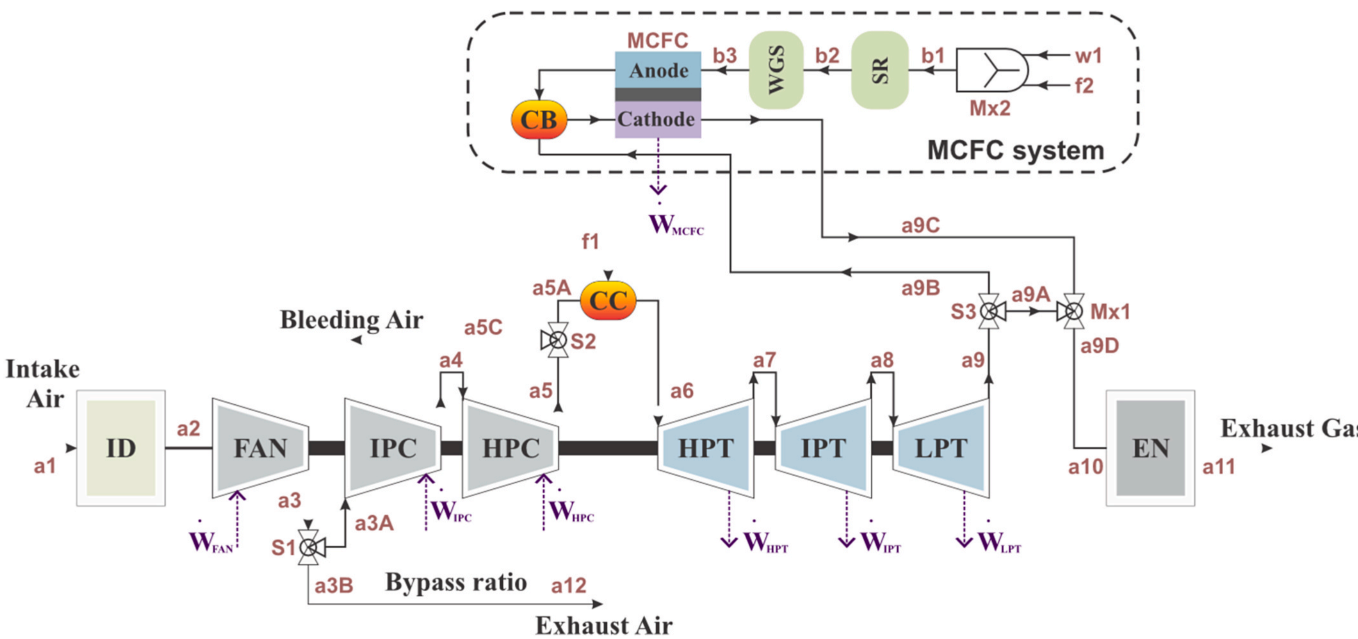

Fig. 31. Proposed hybridized aircraft engine [134].

cryogenic fuels can be utilized in practical applications. Airports must be able to support the large storage or liquefaction facilities for LNG or LH_2 in order to refuel aircraft. It is crucial to ensure the purity of the cryogen storage tanks and the aircraft system components in order to prevent contamination, maintain dielectric properties, and prevent any reaction between LNG and water [4].

The environmental advantages of low CO_2 emissions are negated if LNG, which is primarily made up of methane (a more harmful greenhouse gas than CO_2), leaks directly into the atmosphere. Nevertheless, there are additional emission benefits as the sulfur content of the fuel is reduced by over 15% [4]. The use of material-based H_2 storage systems in aircraft is currently in the research stage, and there have been no reported implementations for this application. Fig. 34 also provides an overview of the material-based technologies for H_2 storage.

Integration of H_2 fuel tank into the aircraft is the other challenge which needs to be addressed. Fig. 35 depicts the tank and passenger cabin layout for an LH_2-powered narrow-body aircraft.

The primary reason behind the decreased performance of liquid hydrogen aircraft when compared to aircraft using conventional jet fuel is the weight of the fuel tank. This weight is significantly higher in liquid hydrogen tanks due to the large volume of the liquid hydrogen. Onarato et al. [10] conducted a study on the impact of integrating fuel tanks in regional, medium, and large aircraft, and they concluded that employing an integral tank structure is more advantageous for larger aircraft.

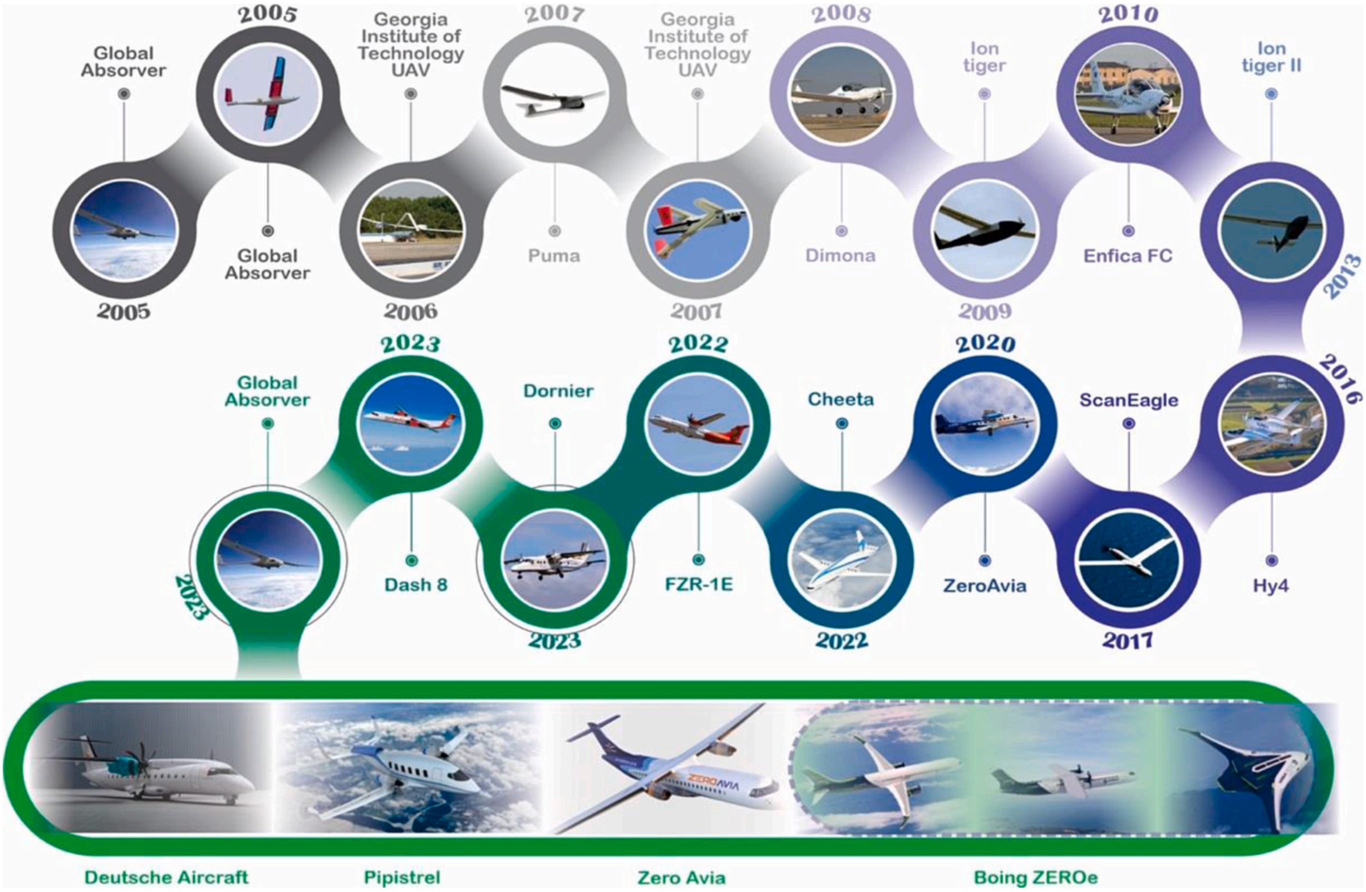

Fig. 32. History of commercial implementation of FC systems in aircraft.

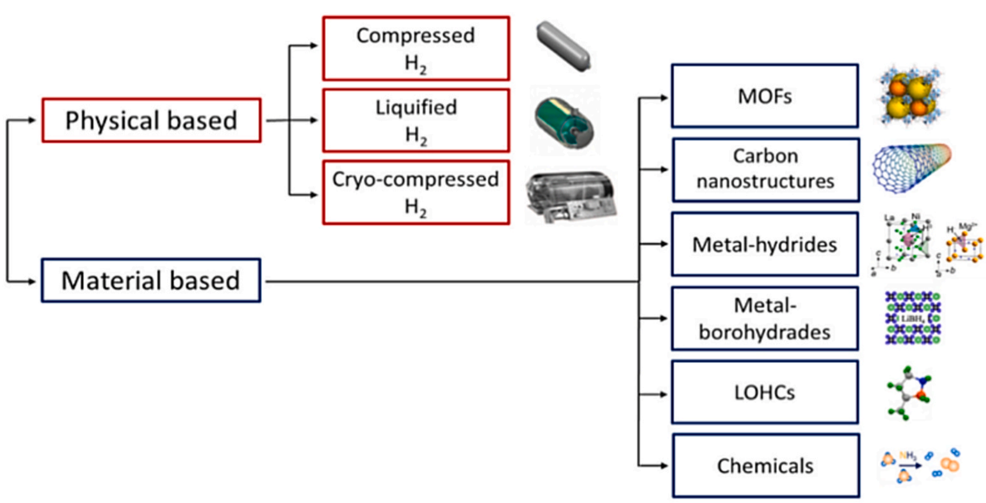

Fig. 33. Hydrogen storage approaches in aircraft [62].

Additionally, the inclusion of both front and rear tanks would lead to a reduction in fuel consumption. In cases where the external pressure is notably low or the ambient temperature is high, the storage capacity of hydrogen may be compromised. The design of the inner and outer vessel should be reassessed for these specific scenarios with extremely low pressure and high temperature [38], depending on the altitude.4.2 Water management and contrail.

The idea of using cryogenic hydrogen for cooling electric components in aircraft hydrogen propulsion systems was explored in a study [160].

4.2. Water management and contrail

Water management in FC systems refers to controlling the production, removal, and distribution of water to achieve optimal performance and efficiency.

For air-cooled FC systems used in aircraft propulsion, there are unique challenges related to water management arising from the specific

Table 8
A comparison between the stored H_2 and fuel tank mass fraction in vehicles and aircraft [10].

	Stored hydrogen mass (kg)	Fuel tank mass fraction
Toyota Mirai GH_2 storage	5	0.06
Shuttle on-board LH_2 storage	100	0.25
Ariane fuel tank (LH_2)	28,000	0.84
Shuttle external tank (LH_2)	230,000	0.83

operating conditions of aviation. These include low pressure at high altitudes affecting water vapor pressure and boiling point, pressure changes during ascent/descent causing condensation or evaporation, temperature extremes from ground to cruising risking membrane dehydration or ice formation, dry air at high altitudes leading to electrolyte dehydration, weight and space constraints for compact water management solutions, dynamic operating conditions across flight phases requiring responsive water control, high reliability and safety standards making any water management failure unacceptable, as well as condensation management during descent and ice prevention strategies at high altitudes. Furthermore, rapid changes in altitude during

Table 9
Comparison of hydrogen technology [62].

Technology	n_g (wt%)	n_v (MJ/L)	T[°C]; P[bar]	ΔT[°C]; ΔP[bar]	Kinetics	Safety	Maturity level
$C-\ H_2$	5.7	5.6	20; 700	35; −699	Fast	Low	High
$L-\ H_2$	7.5	6.4	−253; 1.5	313; 0	Fast	Medium	High
$C_c-\ H_2$	7 to 10	6.1 to 5.9	−207 to −195; 350 to 700	267 to 255; −349 to −699	Fast	Low	High

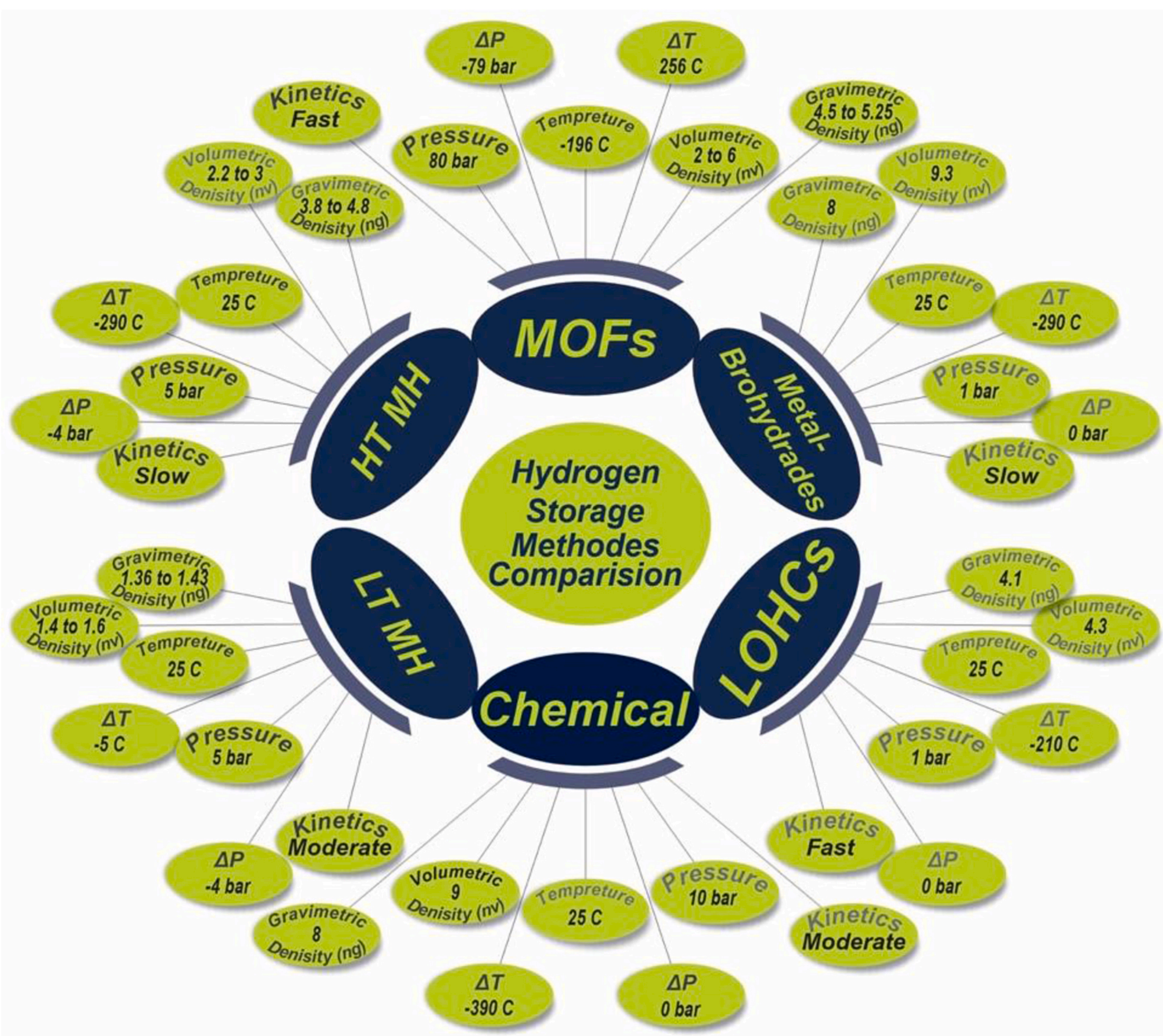

Fig. 34. Summary of the material-based H_2 storage approaches.

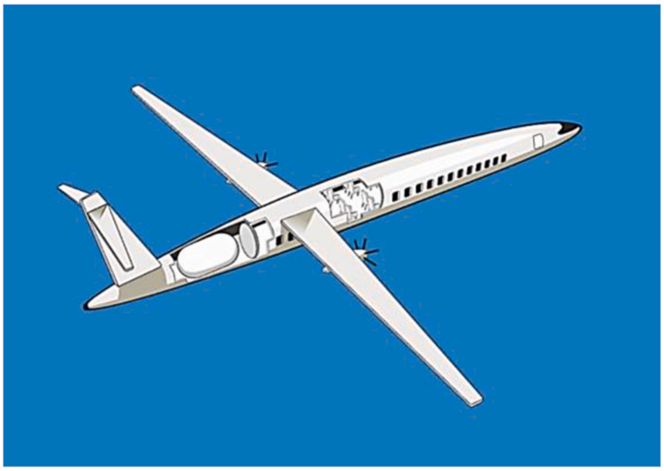

Fig. 35. Schematic diagram for the fuel tank location in a narrow-body LH_2-powered aircraft [10].

ascent and descent lead to pressure variations, which can cause condensation or evaporation of water in the system, complicating effective water management [161].

At high cruising altitudes, extremely low ambient temperatures can cause water produced in the fuel cell to freeze, potentially blocking gas flow channels and damaging components. Additionally, the frequent temperature fluctuations between ground operations and high-altitude cruising altitudes impact water condensation/evaporation dynamics within the system. Effective thermal management is crucial to mitigate freezing risks and maintain optimal water balance for peak fuel cell performance in aviation applications [162].

The extremely dry air at high cruising altitudes can lead to severe dehydration of the fuel cell membrane in air-cooled systems. Air-cooled fuel cell systems exhibit low performance due to electrolyte dehydration caused by ambient dry air. Maintaining adequate humidity within the stack is essential and can be achieved via using pressurized inlet air to mitigate the level of electrolyte dehydration caused by dry airflow at high altitudes, thereby improving water management and overall fuel cell performance [161].

From weight and space points of views, aircraft applications mandate lightweight components, including efficient yet compact water management systems for fuel cells and due to the limited installation space in aircraft, highly integrated and compact system designs are required. However, proper water management aims at achieving optimal humidity conditions which is critical for performance. Therefore, the water management solution must carefully balance efficiency and compactness to meet the stringent weight and space constraints of onboard aircraft systems [137].

Aircraft engines experience fluctuating power demands across flight phases like takeoff, cruise, and landing. Therefore, air stoichiometry and operating pressure influence the water balance and system efficiency. The fuel cell's water management must rapidly adapt to these changing conditions to maintain this balance. Additionally, during rapid ascent/descent transitions with substantial ambient fluctuations, the compact, integrated water management system must exhibit high responsiveness to prevent performance degradation from imbalances. Promptly adapting water removal/distribution based on the varying demands across all flight regimes is crucial [163].

Aviation mandate's stringent reliability standards for critical systems like fuel cells. Every component must achieve a low failure rate with redundancies mandatory if not possible. Any failure, including water management issues, could have severe consequences. However, aircraft systems must also be lightweight and efficient. Therefore, the fuel cell design must incorporate redundant components and fail-safes for continuous safe operation, while carefully balancing reliability needs against weight and efficiency constraints [164].

Condensation and freezing are risks that require proper management. Properly managing condensation, especially during descent when the temperature increases, is critical to avoid water pooling and potential flooding in the fuel cell system. Moreover, advanced thermal management strategies are needed to prevent water from freezing at high altitudes [165].

Finally, from the system complexity and maintenance point of view, the water management system must be seamlessly integrated with the overall fuel cell system and other aircraft systems, which can be complex. Furthermore, the system should be designed for easy inspection and maintenance to ensure long-term reliability and performance.

Contrails, or condensation trails, are line-shaped clouds formed when aircraft exhaust meets cold, high-altitude air, causing water vapor to condense into ice crystals. Although hydrogen propulsion systems significantly reduce CO_2 emissions, they can still produce contrails, as the water vapor from the hydrogen combustion may contribute to their formation. These contrails can affect climate change by trapping heat, similar to traditional aircraft emissions, as shown in Fig. 36 Thus, while hydrogen propulsion is a step toward cleaner aviation, managing contrail formation remains a key challenge in mitigating its environmental impact.

Aircraft FC propulsion systems have been blamed for aiding in the creation of contrails. Nevertheless, Gierens put forward the hypothesis on contrail formation by FCs and determined that despite the frequent occurrence of contrail formation by FCs, their environmental effect is less significant compared to contrails produced by jet engines. The majority of FC contrails are expected to be brief, and the persistent ones will generally be less dense and have a shorter lifespan on average than conventional persistent contrails [166].

Although H_2 turbines generate increased water vapor and lead to more frequent contrail formation, they release fewer aerosol particles than kerosene turbines. Consequently, contrails from H2 aircraft contain fewer and larger ice crystals, resulting in a reduced optical depth and decreased radiative forcing [6,69].

In general, the use of H_2 aircraft could result in a decrease in contrail-related climate impact of 16%–29% in terms of radiative forcing, based on the 2015–2050 transition scenarios [40]. Burkhardt et al. have also conducted a recent study on the potential reduction in radiative forcing based on the initial ice crystal number.

4.3. FC and battery degradation

One of the principal challenges for FC systems is their limited lifetime. Degradation for FC systems refer to all phenomena that adversely affect their lifetime. FC systems may be degraded as time goes by (calendar degradation) or because of usage. Currently, the minimum operation hours for automotive PEMFCs targeted by SAE is 5000 h.

Several mechanisms contribute to aging in FC systems. Fig. 37 summarizes these aging mechanisms and illustrates the changes in one of the characteristic diagrams (output voltage vs. current density) resulting from ageing.

Furthermore, aside from the stress factors previously discussed, ambient temperature, relative humidity, and atmospheric pressure may also impact FC degradation. A decrease in atmospheric pressure has been linked to activation polarization loss on the FC cathode [147]. Research conducted earlier indicated that the degradation of the polarization curve was a result of the low atmospheric pressure [159]. Moreover, both low pressure and ambient temperature can have an impact on hydrogen storage.

The impact of operating conditions on fuel cell (FC) degradation in aircraft has been studied in research [177], which concluded that the cruising mode is the safest for FC health, while variable load modes can be very damaging.

Recent works have examined the effect of energy management systems on extending FC lifespan. For example, incorporating an integrated

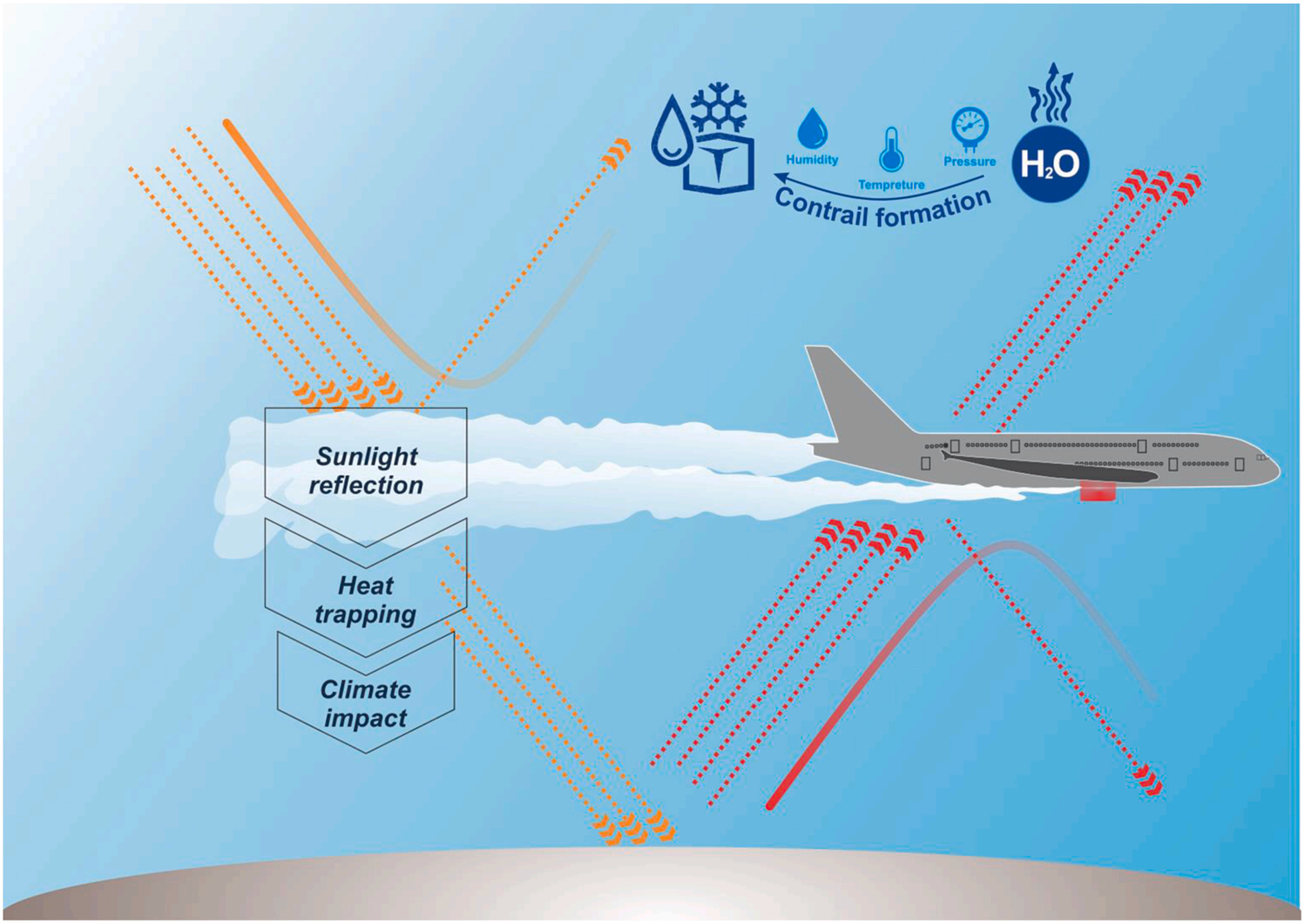

Fig. 36. Contrail formation and its impact on climate.

sizing and energy management system in the design of a hybrid FC and battery propulsion system has been shown to significantly extend FC life [178]. Additionally, using a model-predictive controller [179] for managing a hybrid FC and battery powertrain in UAVs can increase FC lifespan by reducing internal losses and power stress. Furthermore, including FC aging costs in the performance index of an optimal energy management system has been demonstrated to reduce FC degradation [180].

A recent study [181] examined the suitability of prognostics and health management for aviation PEM fuel cells. It showed that health management can help extend the lifespan of fuel cells in aircraft by partially avoiding high power and rapid load variation regimes.

The impact of FC degradation on propulsion system efficiency and reliability was analyzed in two configurations. It was found that the fuel cell stack ambiance has less impact on system efficiency and reliability in a Series-Parallel configuration compared to a Parallel-Series configuration [182].

5. Conclusion

This paper provides a comprehensive exploration of hydrogen application in aircraft propulsion systems. First, the advantages of H_2 as a fuel and in FCHE systems are highlighted, reinforcing its feasibility and environmental benefits. The study presents an in-depth analysis of various hybrid electric fuel cell configurations, focusing on PEMFC systems as the most developed and promising technology for aviation applications. In addition to PEMFC, SOFC systems, considered the future of fuel cell technology, are thoroughly examined for both propulsion and APU roles.

Advanced energy management strategies for fuel cell systems in UAV and an exploration of the multi-stack and balance-of-plant designs for optimizing performance are presented. Furthermore, by evaluating both PEMFC and SOFC systems across a range of aircraft types, from UAVs to large commercial airliners, this study offers a broader and more integrated view than previous research.

Existing and ongoing challenges for H_2 propulsion systems including H_2 storage, water management and contrail, and fuel cell degradation are discussed, and the efforts undertaken to address these issues are highlighted.

Current research sets the stage for future work to focus on addressing remaining challenges and enhancing system reliability, safety, and efficiency. Looking forward, this research envisions review of the works on the special electric components including electric motors, batteries, power electronics components, etc. that are to be employed for hydrogen propulsion systems in aircraft. Overcoming the technical barriers in fuel cell and electric devices technologies, and hydrogen storage and production cost will be pivotal in making H_2-powered aviation viable for large-scale commercial use.

CRediT authorship contribution statement

Mehdi Soleymani: Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Data curation, Conceptualization. **Vahid Mostafavi:** Writing – original draft, Data curation. **Marie Hebert:** Writing – review & editing. **Sousso Kelouwani:** Validation, Conceptualization. **Loïc Boulon:** Writing – review & editing,

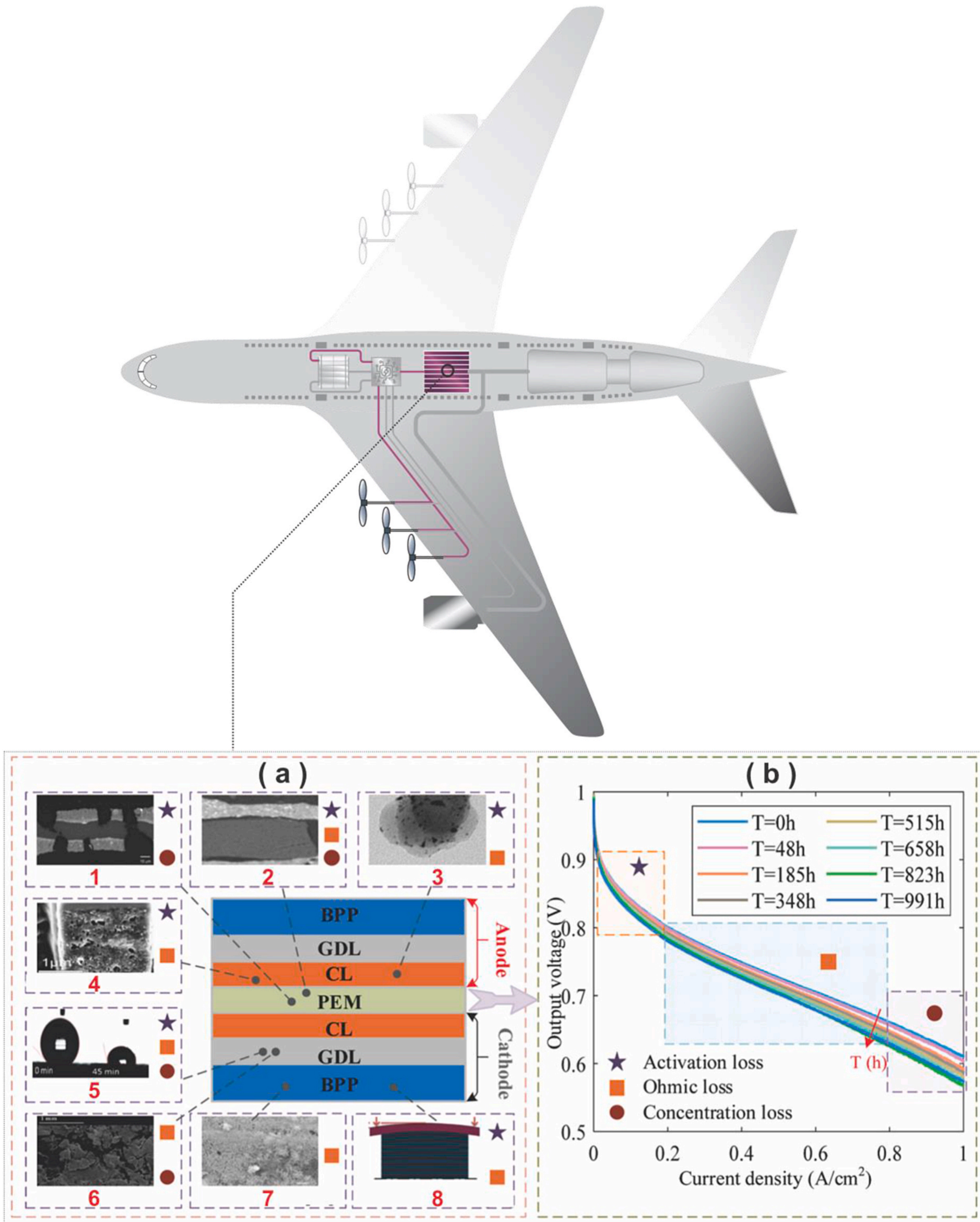

Fig. 37. Fuel cell stack: a) Aging mechanism (1- Cracking [167], 2- Delamination [168], 3- Coarsening [169], 4- Carbon corrosion [170], 5- Hydrophobicity [171], 6- Erosion by gas [172], 7- BPP corrosion [173], 8- BPP deformation [174]) and b) Polarization curves in operating mode without ripple current [175,176].

Conceptualization.

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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