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ORIGINAL ARTICLE

Review of the Recent Developments About the Hybrid Propelled Aircraft

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Abstract
In the past decades, the exponential rise in fossil fuel consumption has led to a pressing need for sustainable energy solutions. This surge in fossil fuel use has not only caused severe environmental repercussions but has also raised questions about our global dependence on such non-renewable resources. Addressing these detrimental effects, NASA has urged the aeronautic industry to reduce aircraft fuel burn by a substantial 70% before 2025. As a result of comprehensive government and industry studies, electric aircraft propulsion has emerged as a pivotal focus of research. This encompasses various architectures, such as full-electric, hybrid electric, and turbo-electric systems. The aim is to significantly diminish the environmental impact of aviation and make it more sustainable for the future of passenger flight. This paper provides an overview of the latest state-of-the-art innovations in propulsion systems. It delves into the operational principles, technological requirements, ongoing research, and development efforts pertaining to all components essential for effecting this transformation in aviation technology. Additionally, the document will showcase existing commercial products, prototypes, and demonstrators to offer a comprehensive picture of the current scenario. Overall, this research is a vital step toward achieving energy sustainability and reducing the environmental footprint of the aviation industry. By exploring and advancing electric aircraft propulsion, humanity can move closer to a cleaner, greener future for air travel.

Keywords Hybrid propulsion systems · Fuel cell · Electric aircraft

Abbreviations

ASTM	American Society for Testing and Materials
BED	Battery Electric Displacement
BLI	Boundary Layer Ingestion
CFD	Computational Fluid Dynamics
DC	Direct Current
DP	Distributed Propulsion
EM	Electric Motor
EPS	Electric Propulsion Systems
EVTOL	Electric Vertical Take-Off and Landing
FC	Fuel Cell
GA	General Aviation
GH_2	Gaseous Hydrogen
HEPS	Hybrid Electric Propulsion System
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICE	Internal Combustion Engine
LEAPTech	Leading Edge Asynchronous Propellers Technology
LH_2	Liquid Hydrogen
MTOW	Maximum Take-Off Weight
PEC	Propeller Electronic Controls
PEM	Proton Exchange Membrane
SAF	Sustainable Aviation Fuel
TMS	Thermal Management Systems
UAV	Unmanned Aerial Vehicle
VDC	Volts Direct Current
CFRP	Carbon Fiber Reinforced Polymers

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1 Introduction

Over the past few decades, the economization of transportation has led to a significant increase in fossil fuel consumption, resulting in a substantial rise in pollutant emissions. The escalating CO_2 emissions have driven major industry players and research institutions to develop new aviation propulsion technologies that are more efficient and environmentally friendly. These advancements not only reduce industry operating costs, particularly fuel expenses but also address the environmental concerns associated with the aviation sector. The International Air Transport Association (IATA, 2019) reports that this pursuit of alternative propulsion systems has been motivated by the industry's responsibility for a considerable share of greenhouse gas emissions, accounting for 2% of CO_2 emissions and 3% of all greenhouse gasses. According to Kreimeier et al. [1], alarming projections indicate that without intervention, these emissions are expected to increase by an average of 4–5% annually. The International Civil Aviation Organization (ICAO) warns that by 2050, CO_2 emissions could triple, accounting for a quarter of global carbon emissions. To combat these challenges, NASA has set ambitious goals for aircraft technologies, aiming to reduce noise and carbon emissions by 55 dB and 75%, respectively, within the next two decades when compared to today's transport airliners [2, 3]. Consequently, the urgency to meet emission requirements has spurred academic and industrial researchers to investigate new and sustainable aerospace engine designs.

As a result of these research efforts, Electric Propulsion Systems (EPS) and Hybrid Electric Propulsion Systems (HEPS) have gained significant attention as potential solutions to meet NASA's demands. EPS involves one or more Electric Motors (EM) replacing the conventional Internal Combustion Engine (ICE). This system exhibits the advantage of producing no local emissions since the electric motor is free from pollutants. Moreover, if the electricity required to charge the batteries comes from entirely renewable sources (although accounting for the environmental impact during device manufacturing), aircraft equipped with this technology could genuinely become zero-emission. The prospect of aircraft achieving true zero-emission operation utilizing electricity from entirely renewable sources is indeed promising. Presently, while renewable energy sources like solar, wind, and hydropower are increasingly integrated into the grid, their capacity to support the entire aviation industry's electricity demand remains a challenge. However, there are ongoing efforts to scale up renewable energy infrastructure to meet these demands. For example, solar energy is expected to play a more significant role in future, with advancements in photovoltaic technology and large-scale solar farms becoming more prevalent [4].

Regarding the manufacturing process of the batteries and aircraft components, the environmental impact should not be overlooked. While electric aircraft offers a cleaner operational phase, their production often involves the extraction and processing of raw materials, which can lead to emissions and environmental degradation [5]. Nonetheless, researchers and manufacturers are actively working to develop more sustainable materials and processes. For instance, the implementation of recycling programs for lithium-ion batteries can help reduce the environmental footprint of their production. While promising, current battery technology limitations restrict the range of full-electric aircraft to approximately 500–800 km [6]. Research into solid-state batteries and alternative battery chemistries is ongoing, with potential benefits in terms of safety, energy density, and sustainability [7].

On the other hand, HEPS combines an ICE with an EM, significantly increasing the overall aircraft efficiency while reducing pollutant emissions [8]. This type of propulsion system offers diverse possibilities, involving the integration of electrical components through various technologies, such as fuel cells or batteries [9]. Depending on the level of electrification, the system achieves different degrees of hybridization. These innovative systems provide several advantages, including enhanced aircraft efficiency, reliability, power distribution/quality, emissions and noise reduction, and the ability to access smaller airports [10]. By combining the strengths of conventional propulsion systems and full-electric approaches, hybrid-electric propulsion emerges as the most viable solution for energy-efficient, cleaner, and quieter aviation. However, it does entail increased system weight during the design phase and greater operational complexity. The proper management of electrical components and combustion is crucial to meet environmental requirements and reduce fuel consumption [11], demanding a multidisciplinary approach to address all relevant aspects.

In Sect. 2, an examination of diverse pioneering propulsion systems identified in the existing literature will be conducted. This investigation will encompass a thorough analysis of their respective advantages, disadvantages, as well as potential applications across different aircraft types. Moreover, in Sect. 3, an in-depth presentation of realized demonstrators will be presented, meticulously categorized by size. Ultimately, basing on the collected findings, comprehensive conclusions will be drawn.

2 Innovative Propulsion Systems

This section presents the primary innovative propulsion systems identified in the literature. Notably, classic hybrid systems, commonly employed in the automotive sector, are now gaining momentum in the aeronautical industry due to their potential application on small to medium-sized aircraft. These hybrid systems are considered feasible alternatives, as they are lighter than their battery equivalents and compatible with the current ground services provided at airports. In the aeronautical context, hybrid systems offer a compelling solution to address the challenges of reducing emissions and improving efficiency. By combining the benefits of internal combustion engines with electric motors, these systems achieve a higher overall efficiency while minimizing environmental impact. The hybrid configuration allows for a more gradual transition to full electrification, considering the limitations of current battery technology, particularly when it comes to range and weight constraints.

Moreover, the adaptability of these systems to existing airport infrastructure and ground services is advantageous. Unlike full-electric aircraft, which may require substantial modifications and infrastructure upgrades at airports to support their charging needs, hybrid systems can capitalize on the existing fueling infrastructure and ground handling procedures. This compatibility makes them a practical choice for the current aviation landscape and facilitates their integration into commercial operations. Small- to medium-sized aircraft, which serves regional and short-haul routes, can particularly benefit from these hybrid propulsion systems. The weight reduction and efficiency improvements offered by hybrids play a crucial role in optimizing the performance of such aircraft, enabling more sustainable and cost-effective operations. The growing interest and advancements in hybrid propulsion for the aeronautical sector indicate a promising future for these systems. Researchers, industry players, and regulatory bodies are actively exploring and supporting their development to pave the way for cleaner, greener, and more efficient aviation in the coming years. By capitalizing on the success of hybrid systems in the automotive industry and adapting them to aviation requirements, the aviation sector can make significant strides toward achieving its environmental goals while maintaining operational practicality.

2.1 Sustainable Aviation Fuel SAF

Sustainable Aviation Fuel (SAF) is a viable alternative to conventional fossil-based jet fuel. SAF can be defined as a type of fuel produced from either biological or non-biological sources, as illustrated in Table 1. The crucial aspect of this fuel is its sustainability, as it is derived from non-depletable sources, meaning it can be continuously replenished without causing resource exhaustion. Furthermore, SAF must meet the stringent certification requirements specified by the ASTM jet fuel standards, ensuring its quality and compatibility with existing aviation infrastructure and engines.

This fuel offers significant potential for mitigating the environmental impact of aviation. Utilizing renewable and non-depletable feedstocks, SAF significantly reduce net greenhouse gas emissions compared to conventional fossil fuels. It accomplishes this utilizing carbon sources that are absorbed during the feedstock's growth, essentially creating a closed carbon cycle. As a result, it can help the aviation industry achieve its carbon reduction targets and contribute to global efforts in combatting climate change.

The feedstocks used to produce SAF can be diverse, ranging from agricultural waste and non-edible plant oils to municipal waste and algae. The ability to source these materials sustainably makes SAF a compelling option for the aviation industry as it aligns with environmental stewardship and supports the transition to a more sustainable future. By embracing SAF, the aviation sector can make significant strides toward achieving a greener and more sustainable future, reducing its carbon footprint and promoting environmental responsibility within the industry.

SAF, also known as drop-in fuels [13], belong to a class of biofuels that share the same chemical and physical characteristics as the fuels currently used in aviation. This unique feature is a crucial aspect of its potential success as it enables manufacturers to avoid substantial modifications to aircraft, eliminating the need for a new approval process that could increase production costs. Additionally, fuel suppliers and airports can continue to use their existing fuel supply systems, providing a rapid opportunity to reduce CO_2 emissions. Given the projected demand for SAF by 2050, the criticality of meeting this demand has led to a surge of interest in the topic, underscored by the increasing number of scientific publications [14]. These publications primarily focus on various production technologies, feedstocks, and processing methods for SAF. Regarding the production of SAF, the International Civil Aviation Organization (ICAO) has reported that meeting 100% of the demand by 2050 could result in a remarkable 63% reduction in emissions. However, achieving this level of fuel production would require significant capital investments in SAF production infrastructures and substantial political support.

Researchers have identified three dominant strategies for converting biomass into fuel: chemical routes, biological routes, and thermochemical routes, as reported by Soltanian [15]. ASTM, thus far, has approved seven bio-aviation fuel production technologies [16].

The production of SAF can follow various technology pathways, which are as follows:

1.Chemical Routes: These methods involve chemical processes, such as hydro-processing, esterification, and catalytic conversion, to convert biomass feedstocks into SAF.
2.Biological Routes: These approaches utilize biological processes, such as fermentation and enzymatic conversion, to transform biomass into usable aviation fuel.

Table 1 Biological or non-biological sources for SAF production [12]

Feedstock	SAF production routes	Opportunities	Citation
Municipal Solid Waste MSW	Gasification - FT	(1) Converting waste into higher value products such as jet fuel promotes higher diversion of waste from landfills	Shahabuddin et al., 2020
		(2) Use of waste for biofuel production is preferable to disposal to landfill and incineration without energy recovery	
Used cooking oil	HEFA	(1) Used cooking oil already widely commercialized under HEFA process with Fuel Readiness Level (FRL) and Technology Readiness Level (TRL) of 9	Ben Hassen Trabelsi et al., 2018
	Pyrolysis	(2) Low cost and widely available	
Straw	Gasification - FT	(1) Not in direct competition with food (except barley and oat straw used for animal fodder)	Li et al., 2015
	ATJ	(2) Unlike to be contaminated	
	HFS	(3) Homogeneous characteristics across suppliers	
	Pyrolysis	(4) Consists mainly of cellulose and hemicellulose and thus easier to extract sugars than municipal solid waste or wood	
Energy crops	Gasification - FT	(1) *Jatropha*, algae, and halophytes grown in difficult condition in inhospitable places	SPATS Work Package 1–045 and PPRO 04/75/17, 2017
	ATJ	(2) Algae particularly advantageous growing at rapid speed and can be grown on marginal lands (i.e., not competitive with lands for growing food)	
	HFS	(3) Crops such as *Camelia* are fast-growing and can be cultivated with wheat rotationally	
	Pyrolysis	(4) Large oil and lipid content per mass (e.g., *Jatropha* and *Camelia*)	
Forestry Residues	Gasification - FT	(1) Less competition so widely available for advanced biofuel production	Stephanie Searle, Nikita Pavlenko, Anastasia Kharina, and Jacopo Giuntoli, 2019
	ATJ	(2) Generally, contribute to lower GHG emissions	
	HFS		
	Pyrolysis		
Wood waste	Gasification - FT	(1) Production of wood waste is fairly consistent throughout the year	Cavalett and Cherubini, 2018; De Jong et al., 2015
	ATJ	(2) Current price is negative although depends on the local demand for the feedstock	
	Pyrolysis		

3.Thermochemical Routes: Thermochemical processes, like gasification and pyrolysis, are employed to convert biomass into synthesis gas or bio-oil, which is further processed into SAF.

In this section, the technological production process cited before will be briefly reported:

- Hydro-processed Esters and Fatty Acids

Hydro-processed Esters and Fatty Acids (HEFA) exploit the chemical reaction of hydrogenation. The product of this chemical process, which needs Hydrogen and biomass (animal fats, vegetable oils, etc.) as reactants, is SAF (Sustainable Aviation Fuel). In Fig. 1, a diagram of the technological process is reported.

- Fischer–Tropsch

The Fischer–Tropsch (FT) process is a chemical process, as can be seen in Fig. 2. It consists of removing

- Hydro-processed Esters and Fatty Acids

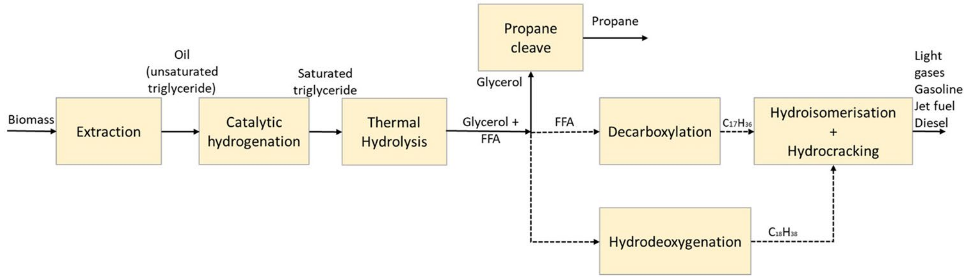

Fig. 1 HEFA Production method [12]

- Fischer-Tropsch

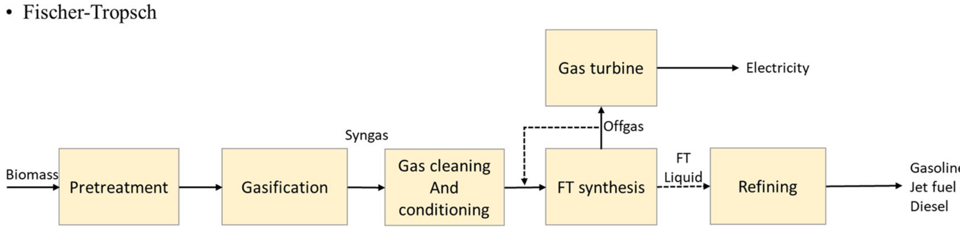

Fig. 2 FT Production method [12]

any carbon contained in the material and breaking it into building blocks used to produce liquid hydrocarbons based on synthesis gas (CO and H_2).

- Alcohol-to-Jet

Alcohol-to-Jet (ATJ) is a biochemical conversion process used in the automotive field to produce biofuels.

- Alcohol-to-Jet

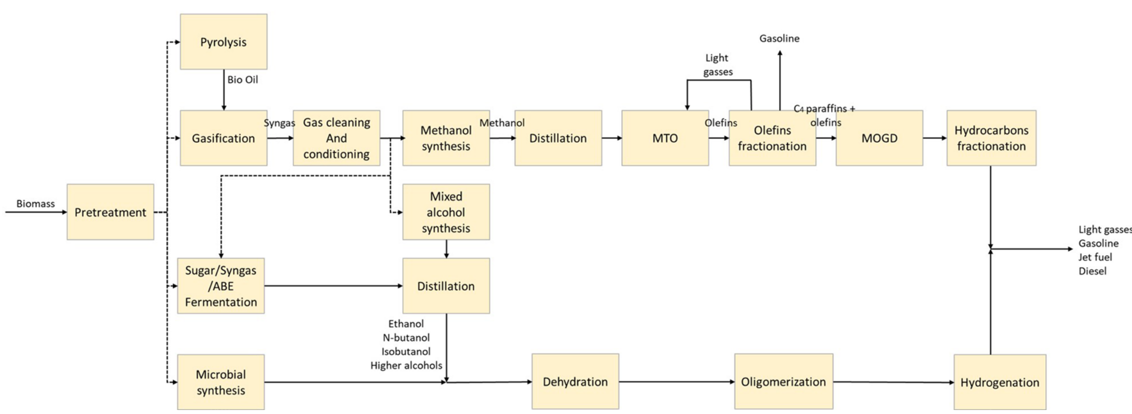

Fig. 3 ATJ Production method [12]

- Synthesized Iso-Paraffins

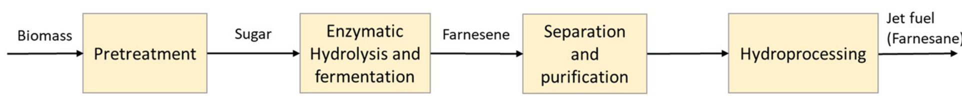

Fig. 4 SIP Production method [12]

Nowadays, it could be applied to the production of aviation fuel. The result of this process, as can be seen in Fig. 3, is a biofuel mixture composed mainly of alcohol and a small portion of conventional aviation fuel. The most common practice for obtaining alcohol derivatives is the fermentation of edible plant sugars.

- Synthesized Iso-Paraffins

  Synthesized Iso-Paraffins (SIP) is a biological platform where microbes convert C6 sugars (like Glucose, Galactose, Mannose, etc.) into Farnesene. These base compounds, after the Hydrogenation process, can be used as SAF (Sustainable Aviation Fuel) (Fig. 4).

Each of these technology pathways has its advantages and challenges, and ongoing research seeks to optimize and advance these methods for large-scale SAF production.

In conclusion, the development and the widespread adoption of SAF hold great promise for mitigating aviation's environmental impact by significantly reducing greenhouse gas emissions. However, overcoming challenges related to production scale, investment, and political support will be critical to achieving the ambitious goals set for SAF production in the coming decades. So it seems that SAF is a simple way to reduce CO_2 emission, but there are also some disadvantages:

- The technology to produce it is not yet economically sustainable.
- SAF currently costs four times as much as conventional jet fuel and it makes up less than one percent of fuel available in the market.
- Experts in the aviation industry say that there is no single solution that can increase the supply of SAF, but a combination of policy incentives, capital investments, and time is necessary for these fuels to be an effective sustainable solution for the industry.

2.2 All Electric Propulsion Systems

The full-electric aircraft configuration, reported in Fig. 5, is the simplest among the electric architectures. It relies solely on a rechargeable battery as the power source, directly connected to an electric motor through a power management system that drives a propeller. Unlike hybrid architectures, this configuration does not support in-flight battery charging, necessitating ground charging before each flight mission. Despite this limitation, the full-electric system boasts higher efficiency compared to conventional propulsion systems due to the exceptional efficiency of its components, namely EMs and Propeller Electronic Controls (PECs). While a conventional ICE propulsion system operates with 20–36% global efficiency, full-electric propulsion system can achieve 75–83% global efficiency, making it about three times more efficient than ICE propulsion [17, 18].

Full-electric aircrafts have several advantages, including zero local emission, reduced noise, and lower operating costs. However, the primary constraint lies in the current limitations of battery technology, which hinders these aircrafts from covering the same distances as jet fuel-driven counterparts. The most limiting disadvantage for this configuration is the current low Battery Electric Displacement (BED), which renders it unsuitable for most aircraft. Additionally, the electrical devices used in the system generate heat during their operation, posing potential challenges when these devices are located within the aircraft fuselage. Effective Thermal Management Systems (TMS) are required to ensure that these devices operate within the temperature range of 20–60 °C. Implementing TMS adds extra weight to the aircraft [19], limiting current designs to light aircraft.

Despite these challenges, the development of electric aircraft is not deterred. The key advantage of electrical

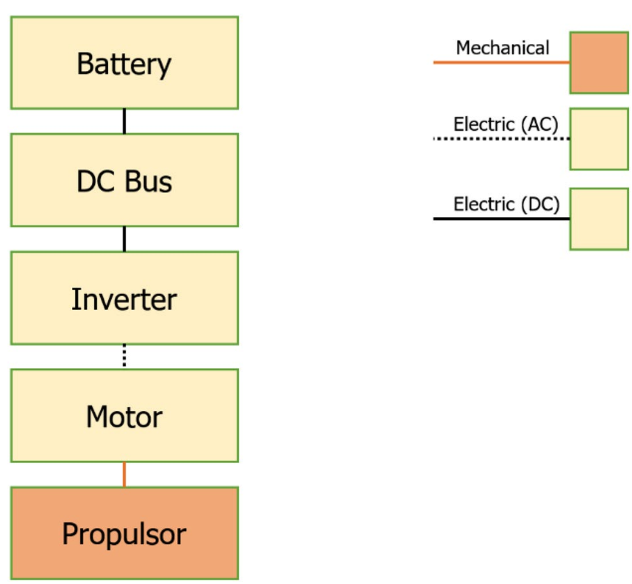

Fig. 5 All Electric propulsion system scheme [15]

technology lies in its scalability, allowing for step-by-step implementation from 1-seat and 2-seat aircraft. Since 2000, numerous manned electric fixed-wing aircrafts have been developed, such as the Antares 20E [20], Electra Flyer C [20], Yuneec 430 [21], Velis Electro from Pipistrel [22], Alia-250 by Beta Technologies [23], and Alice by Eviation [24]. Additionally, commercial applications for electric propulsion systems include aerial vehicles like Vertical Take-Off and Landing (eVTOL) aircraft, such as Lilium Jet [25] and Flyarcher [26]. This feasibility is supported by the observed increase in EM's power density and efficiency, making it a promising architecture [17].

While current limitations exist, the progress in battery technology and the continuous research and development efforts are expected to pave the way for more extensive use of full-electric aircraft in future, revolutionizing aviation with cleaner and more sustainable solutions.

2.2.1 Distributed Propulsion System, DP

The eVTOL class of aircraft utilizes a specific version of electric propulsion called Distributed Propulsion (DP). In this configuration, multiple small electrically driven fans are used for propulsion instead of a classical ICE. This arrangement offers several advantages, including drag reduction, lift augmentation, and swirl cancelation. The use of several small motors allows flexible installation on the wing tip or the tailcone, and this configuration can even benefit from Boundary Layer Ingestion (BLI) [17].

A notable platform developed for the DP configuration is the Leading Edge Asynchronous Propellers Technology (LEAPTech). In this setup, many small propellers are positioned along the wing, blowing on the wing surface to increase dynamic pressure [27]. This increase in dynamic pressure leads to a reduction in wing area, directly impacting the total weight of the structures and reducing drag during cruise conditions. The DP configuration can be further optimized using two types of propellers:

1. Highlift Propellers: These propellers are small in size and located on the upstream leading edge of the wing. They primarily operate during low-speed flight, and during cruise conditions, they can be folded to minimize drag.
2. Cruise Propellers: Bigger in size, these propellers are positioned on the wingtips. They operate only at high speeds and contribute to efficient cruising [28].

CFD (Computational Fluid Dynamics) analyses have demonstrated that distributed propulsion systems significantly enhance wing design and overall aircraft performance [29]. By distributing the propulsion along the wing, the DP configuration improves lift and drag characteristics, making it a compelling choice for eVTOL aircraft.

The distributed propulsion approach opens up new possibilities for aircraft design and performance, making it particularly well-suited for electric vertical take-off and landing vehicles. As electric propulsion technology continues to evolve and improve, the potential for eVTOL aircraft and distributed propulsion systems to revolutionize urban air mobility and address transportation challenges in crowded urban areas becomes increasingly feasible.

2.2.2 Fuel Cell

Hydrogen-powered aircraft can be classified as belonging to the full electric category when hydrogen is utilized as fuel for a fuel cell, rather than being directly burned in an engine. In this configuration, the aircraft operates similarly to full electric systems but with a significantly lower Maximum Take-Off Weight (MTOW) due to the reduced weight of the battery. Refueling times and weights for hydrogen-powered aircraft are more comparable to systems currently present in the market, as opposed to aircraft with battery storage. While these systems still incorporate smaller batteries, their primary function is to serve as a buffer or power boost, rather than storing the energy required for the entire mission cycle. Thus, it is important to highlight the differences between these two energy storage systems mentioned thus far. The thrust component, whether provided by a single electric motor or a DP system, remains the same for both types of systems. Traditional full electric systems are characterized by scaled battery packs capable of storing all the energy required for the complete mission. However, the presence of these battery packs can lead to weight and mass centering challenges.

Conversely, fuel cell systems follow the logic of a traditional ICE. The hydrogen fuel interacts with oxygen in the air within the fuel cell structure, generating current and water through a chemical reaction. Fuel cell systems offer greater versatility as they do not require pre-storage of energy in batteries. Instead, they only need to store the necessary quantity of hydrogen to complete the proposed mission.

Fuel cell systems consist of three main components: the Fuel Cell itself, a hydrogen storage tank (gaseous or liquid), and a buffer battery. The operating principles of fuel cells used in transportation, such as cars, trucks, and aircraft, involve converting the chemical energy in the oxidant (hydrogen) directly into electricity. Fuel cells are highly efficient [30], as there are no mechanical or thermal requirements that would dissipate energy. The process only requires oxygen and hydrogen, and electricity is produced as the reaction takes place. Fuel cells operate with low-voltage DC output, typically around 1/1.1 VDC per cell, which can

Table 2 Fuel Cell typology [36]

Fuel Cell type	Electrolyte conduction	Operating temperature (°C)	Efficiency Advan-tages	Advantages	Citation
Molten Carbonate **MCFC**	Carbonate ions	600–800	50%	1) High efficiency 2) Generate high-grade waste heat 3) Fast reaction kinetics 4) Catalyst not needed	Wilberforce et al., 2017
Solid Oxide **SOFC**	Oxide ions	1000–1200	60%	1) High efficiency 2) Generate high-grade waste heat 3) Fast reaction kinetics 4) Catalyst not needed 5) Wide variety of modular configuration	White et al., 2006
Alkaline **AFC**	Hydroxyl ions	< 100	60%	1) Fast start uptimes 2) Easy to operate 3) Lower component cost 4) Platinum catalyst not needed 5) Minimal Corrosion 6) Low weight and volume	Ma, 2008
Phosphoric Acid **PAFC**	Hydrogen ions	100–200	40%	1) High temperature among the low-temperature fuel cells 2) Generate high-grade waste heat 3) Tolerant to CO2 and minor air impurities 4) Stable electrolyte characteristics	Dell et al., 2014
Proton Exchange Membrane—Polymer Electrolyte Membrane **PEM**	Hydrogen ions	60–100	60%	1) Low temperature, pressure and start-up time 2) Solid, dry, non-corrosive electrolyte 3) High voltage, current and power density 4) Tolerant to CO2 content in air 5) Compact and solid build with simple mechanical design	Dell et al., 2014

be increased through series or parallel connections [31]. Unlike traditional batteries that consume the anode and cathode during operation, fuel cells operate using externally supplied reactants and do not consume any working parts, resulting in a longer lifespan.

Fuel cells can be classified into different types based on the type of electrolyte used (Table 2). This classification divides the family of fuel cells into two groups. The first group, known as high-temperature fuel cells, includes types, such as molten carbonate and solid oxide fuel cells. These cells operate at high temperatures, allowing hydrocarbon fuels like methane to spontaneously reform into hydrogen and efficiently promote electrochemical reactions. The second group, known as low-temperature fuel cells, operates at temperatures below 250 °C. These cells require a catalyst (often made of expensive rare metals) since internal reforming is not possible at lower temperatures. They rely on an external source of hydrogen for operation. Fuel cells in this group include alkaline, phosphoric acid, and Proton Exchange Membrane (PEM) fuel cells showed in Fig. 6, which is the most common one used in automotive and aerospace sector due to it characteristics [32, 33].

By leveraging hydrogen as a fuel source through fuel cell technology, hydrogen-powered aircrafts offer a promising

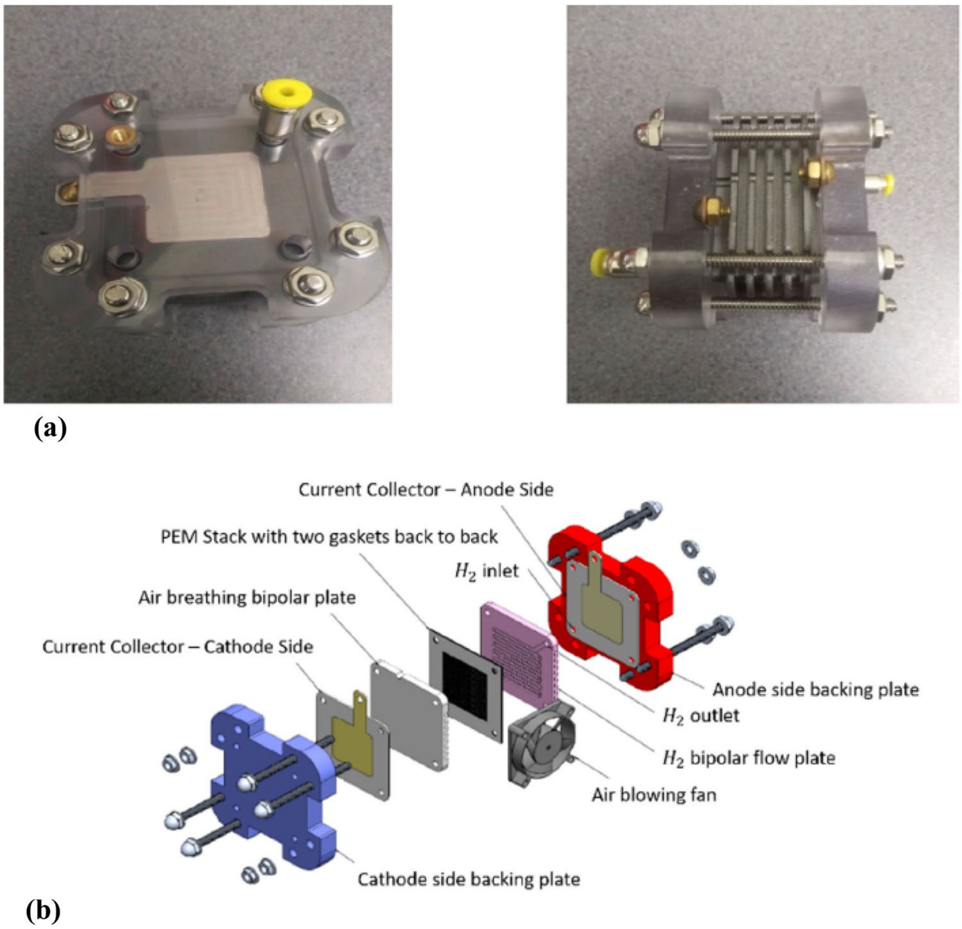

Fig. 6 Fuel Cell prototype (**a**) and sketch scheme (**b**) [34]

solution for achieving electric propulsion while overcoming the limitations of battery-powered systems. Further research and development efforts are ongoing to optimize the performance and efficiency of fuel cells in aviation applications.

The Proton Exchange Membrane (PEM) cell is a type of fuel cell that features a solid electrolyte, typically made of acidified Teflon. It is widely used in the transportation industry due to its compact size, low operating temperature (maximum of 70 °C), and a maximum internal pressure of 2 Bar. These characteristics, along with its simplicity of manufacturing, reliability, and competitive production cost, make PEM cells highly attractive to manufacturers. As a result, the principal manufacturers are continuously working to improve the power output of PEM cells, aiming to expand their applicability across various fields and industries [35].

PEM cells operate on the principle of Proton Exchange, where hydrogen is supplied to the anode and oxygen (from the air) to the cathode. As the hydrogen molecules reach the anode, they undergo a catalytic process that splits them into protons and electrons. The protons pass through the acidified Teflon electrolyte, while the electrons are directed through an external circuit, generating an electric current. Finally, at the cathode, the protons, electrons, and oxygen combine, producing water as a byproduct.

PEM fuel cells offer several advantages that make them suitable for various applications, including:

1. Fast Start-Up: PEM cells can quickly reach full operating capacity, making them ideal for transportation and portable power applications where rapid response is crucial.
2. Compact and Lightweight: The small size and low weight of PEM cells make them well-suited for transportation, particularly in aircraft, where weight and space constraints are significant considerations.
3. High Efficiency: PEM cells boast a high efficiency in converting hydrogen into electricity, reducing energy waste during the electrochemical process.
4. Low Operating Temperature: The relatively low operating temperature of PEM cells allows for rapid start-up and contributes to their overall safety.
5. Minimal Emissions: Hydrogen-powered PEM cells produce only water vapor and heat as byproducts, making them environmentally friendly and zero-emission solutions.

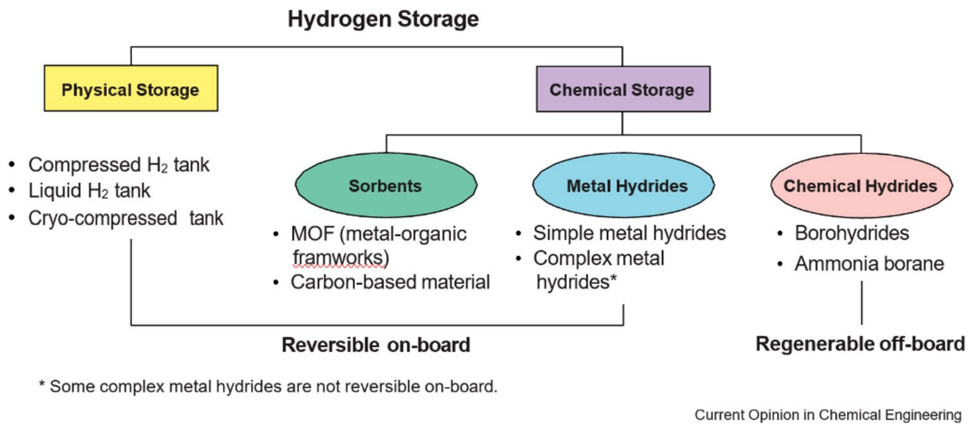

Fig. 7 Hydrogen storage classification [38]

Despite these advantages, PEM cells also face some challenges, including the need for expensive catalysts (usually based on platinum), potential sensitivity to impurities in the hydrogen fuel, and the requirement for efficient water management within the cell. However, ongoing research and development efforts are focused on addressing these challenges and further improving the performance and reliability of PEM cells to broaden their range of applications in transportation and beyond. As hydrogen-based technologies gain momentum as sustainable alternatives to conventional propulsion systems, PEM fuel cells hold significant promise in advancing the electrification of various industries, including aviation and automotive.

After this brief dissertation on the operation of Fuel Cells, the attention is turned toward the second challenge to be faced in the development of such systems: the containment of hydrogen.

The containment of hydrogen, whether in liquid (LH_2) or gaseous (GH_2) form, within tanks on-board aircraft presents a significant challenge in the development of hydrogen-powered systems. There are various techniques to store hydrogen, including compression, liquefaction, and confinement in crystals (Fig. 7). Among these methods, compression is currently the most widely used for hydrogen storage in aircraft [36].

In the compression method, hydrogen gas is stored under high pressure within the tanks. The typical storage pressure ranges from about 20 to 25 MPa. However, future trends aim to increase the storage pressure significantly, reaching levels as high as 70 MPa [37]. The higher storage pressure allows a more compact storage system, enabling aircraft designers to optimize space and weight constraints. Hydrogen compression presents several advantages, such as relatively straightforward technology, efficient refueling processes, and a proven track record in various industries; however, it also comes with some challenges, including the need for robust and lightweight tank materials that can safely handle the high-pressure hydrogen gas.

Liquefaction is another method of hydrogen storage, where hydrogen gas is cooled to extremely low temperatures until it becomes a liquid. In liquid form, hydrogen has a higher energy density than as a gas, making it an attractive option for applications with strict weight limitations. However, the cryogenic temperatures required for liquefaction add complexity to the storage system and can result in some energy losses during the liquefaction process.

The confinement of hydrogen in solid-state materials, often referred to as hydrogen storage in crystal lattices or hydrides, is an emerging research area. Certain materials have the capability to absorb and release hydrogen gas under specific conditions, providing a potential alternative to high-pressure or cryogenic storage. However, this approach is still in the experimental stage, and further research is needed to optimize the materials and storage conditions for practical applications.

In the pursuit of sustainable aviation, hydrogen storage technologies will play a crucial role in determining the feasibility and efficiency of hydrogen-powered aircraft. Advancements in storage methods, including higher storage pressures and innovative materials, will be essential for realizing the full potential of hydrogen as a clean and renewable energy source for aviation and other transportation sectors.

In the aeronautical sector, the storage of hydrogen on-board aircraft requires solutions that are low in weight, cost-effective, and have high density [39]. One method of storage is liquefaction, where hydrogen is converted into a liquid state. In this state, hydrogen is colorless and non-corrosive. Compared to compression storage, current liquid hydrogen (LH_2) tanks can store 0.070 kg/L, while compression tanks store around 0.030 kg/L [40]. However, the critical condition for this configuration is maintaining the tank temperature at −273 °C [41], requiring a cryogenic system. This system would absorb some of the energy produced by the fuel cell system and result in the loss of certain advantages, such as low weight [42].

While the liquefaction method offers advantages in terms of density, there are some difficulties that need to be overcome for it to be feasible. These challenges include addressing evaporation losses in storage tanks, with typical evaporation losses ranging from 0.1 to 1% per day depending on the tank size [43]. Additionally, the high cost of materials used in the construction of the system and the positioning problem of those tanks pose another hurdle [44].

The design of hydrogen storage tanks for aircraft is critical, as they differ from those used in space or automotive operations. Automotive tanks, although designed for a similar lifetime and number of cycles as aircraft tanks, are less influenced by weight limitations. However, automotive LH_2 tanks remain relatively heavy and are not suitable for aeronautical applications. Engineers also need to consider the "dormancy time" problem, which refers to the duration a tank can operate without significant fuel extraction or vapor. Proper tank design is crucial to withstand potential pressure increases that may occur while the aircraft is parked or inactive. The ideal tank design aims for low weight and minimal surface area, as the surface area directly affects boil-off conditions [45].

Another challenge in hydrogen storage systems is the high cost of materials and manufacturing. The materials used to construct tanks must possess high strain, high fracture toughness, high stiffness, low permeation, and low weight to withstand the cryogenic temperatures required by certain storage methods [46]. Aluminum is a primary candidate for hydrogen tanks as it satisfies these requirements [47]. Carbon Fiber Reinforced Polymer (CFRP) is also suitable, providing a weight reduction of 25% compared to traditional materials [48]. The permeability of hydrogen is no longer considered a technical barrier for the development of unlined composite tanks, although the production costs for such tanks will be significantly higher compared to metallic alloy tanks. While this higher cost may be justifiable for space applications, it is more likely that aluminum lithium alloys will be used for aircraft.

Overcoming these challenges in hydrogen storage systems is essential for the widespread adoption of hydrogen-powered aircraft. Ongoing research and technological advancements in materials, design, and manufacturing techniques aim to address these issues and optimize the efficiency, safety, and affordability of hydrogen storage solutions for aviation applications.

2.3 Hybrid-Electric Propulsion Systems HEPs

The implementation of full-electric propulsion systems for aircraft beyond simple demonstrators is challenging due to the current limitations of battery energy storage technology and the development of associated components required for energy distribution on the aircraft. Meeting the ambitious timelines imposed by regulatory bodies like the European Union is difficult with existing technologies. As a more viable approach, the aviation industry is exploring the integration of electric machines to complement traditional turbojet or turboprop systems, leading to the concept of Hybrid Systems. The Hybrid Systems category includes four possible configurations:

- Hybrid Series configuration
- Hybrid Parallel configuration
- Hybrid Series/Parallel configuration
- Turbo-Electric Hybrid

These systems can enhance overall efficiency, reduce emissions, and provide greater flexibility in managing power distribution for various flight conditions. Additionally, hybrid systems enable aircraft designers to leverage the benefits of both traditional propulsion systems and electric technology without fully relying on batteries alone.

Hybrid propulsion systems are seen as a transitional step toward achieving more sustainable aviation until battery technology and energy storage capabilities advance further. These configurations offer a potential pathway to reduce the carbon footprint of aircraft and contribute to the aviation industry's efforts to meet environmental targets while maintaining operational performance and safety standards.

2.3.1 Hybrid Series Configuration

In a Series Hybrid configuration (Fig. 8), the EM is the sole component responsible for driving the propeller, eliminating the need for a gearbox [50]. This setup allows the ICE of the

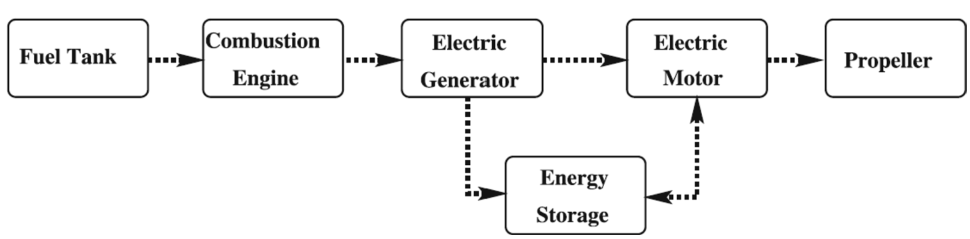

Fig. 8 Hybrid series system [49]

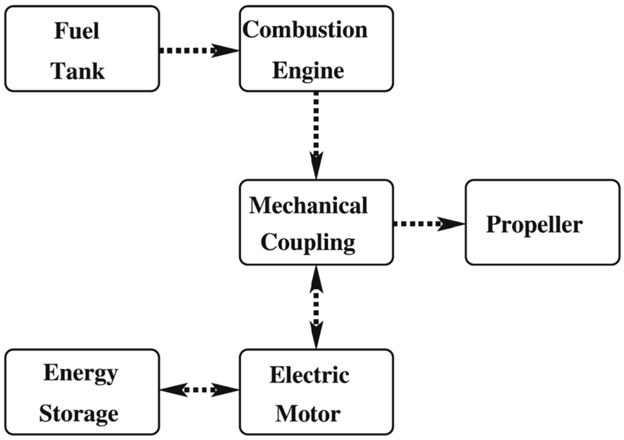

Fig. 9 Hybrid parallel system [49]

system to always operate at its optimal regime, resulting in high fuel efficiency and a longer lifespan. Another advantage is the flexibility in choosing the location of the ICE, as it is mechanically decoupled from the propeller. This characteristic makes the Series Hybrid system particularly attractive for DP applications.

However, the Series Hybrid configuration also suffers from several disadvantages:

- Power Loss: The conversion process involved in the Series Hybrid system leads to a significant power loss. The energy from the ICE is converted into electricity by the generator, and then the electric power is used to drive the propeller through the electric machine. Each step of conversion incurs in losses, reducing overall system efficiency.
- Cost and Bulkiness: The Series Hybrid system can be expensive and bulky due to the need for three main components: the internal combustion engine (ICE), the generator, and the electric machine. All these components must be sized to cope with the maximum power demand, which can result in a heavier and more complex system [51].

The trade-offs between advantages and disadvantages need to be carefully considered when designing a Series Hybrid system for specific aircraft applications. While the system allows better fuel efficiency and flexibility in ICE placement, the power losses and additional components can offset some of these benefits. Engineers must optimize the design to strike a balance between performance, efficiency, and overall system weight, taking into account the specific requirements of the aircraft and the intended operational profile. Additionally, ongoing advancements in technology and materials may help mitigate some of the disadvantages, making Series Hybrid configurations more viable and attractive options for future aircraft propulsion systems.

2.3.2 Hybrid Parallel Configuration

In a Hybrid Parallel configuration, the propeller is driven by both the internal combustion engine (ICE) and the electric machine (EM), which is the main difference compared to the Series Hybrid system (Fig. 9). This mechanical architecture allows the simultaneous or individual assistance of the propeller by the ICE and EM during the working cycle [52]. This configuration offers several advantages:

- Simultaneous Charging: The ICE can drive both the propeller and the motor/generator, allowing for simultaneous propulsion and charging of the battery pack. This means that while the aircraft is in operation, the ICE can generate power to drive the propeller and also supply excess power to charge the batteries, increasing overall system efficiency.
- Reduced Component Count: The Hybrid Parallel system requires only two main components for energy conversion: the internal combustion engine and the motor/generator. This is in contrast to the Series Hybrid configuration, which requires an additional generator between the ICE and the motor. The reduced component count simplifies the system design, potentially reducing costs and maintenance requirements.
- Flexibility in Component Sizing: Since the propeller can be driven by both the ICE and the electric machine individually or simultaneously, the main components of the system, such as the engine and the electric machine, do not need to be sized to cope with maximum power requirements. This flexibility allows for the selection of smaller engines and electric machines, optimizing the system for efficiency and weight considerations [51].

By eliminating the mechanical–electrical energy conversion present in the Series Hybrid configuration, the Hybrid Parallel system can achieve reduced power losses, improving overall system efficiency. However, the main disadvantage of this configuration is the need for an efficient energy management strategy. It becomes crucial to optimize the power contribution of the engine and the electric machine, ensuring they operate under the most efficient conditions at all times. This requires advanced control systems and algorithms to balance power distribution and manage the interplay between the two power sources.

Efficient energy management is critical for maximizing the benefits of the Hybrid Parallel system and optimizing the overall performance and fuel efficiency of the aircraft. With the right control strategies, this configuration can leverage the advantages of both the internal combustion engine and

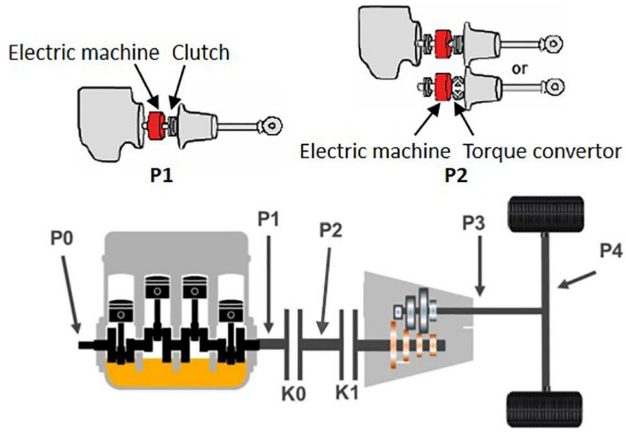

Fig. 10 Hybrid powertrain architectures based on electric machine location [53]

the electric machine, providing a flexible and efficient propulsion solution.

To conclude the discussion of parallel hybrid systems, it is important to understand how they are classified based on the mutual positioning of the thermal (ICE) and electric motor along the aircraft/vehicle driveline. In parallel hybrid systems, this positioning can significantly impact the system's performance. For automotive applications, there are four possible configurations, as shown in Fig. 10: (a) Parallel Pre-Transmission Configuration; (b) Parallel Post-Transmission Configuration; (c) Parallel Through-Transmission Configuration; d)Parallel Split-Transmission Configuration.

For aircraft applications, two primary configurations are commonly used, as shown in Fig. 11:

(a) Single-Shaft Configuration: In the single-shaft architecture, the thermal engine and electric motor are mounted on the same shaft, sharing the load and power distribution to the aircraft's propulsion system. This configuration simplifies the mechanical arrangement but may have some limitations in terms of independent control and efficiency.

(b) Double-Shaft Configuration: In this architecture, the thermal engine (ICE) and electric motor are mounted on separate shafts, each connected to the aircraft's propulsion system. This configuration allows independent control and power distribution between the thermal engine and the electric motor, providing more flexibility in optimizing performance.

The selection of the parallel hybrid system configuration depends on various factors, including the specific aircraft requirements, operational conditions, and desired performance characteristics. Each configuration has its advantages and trade-offs, and careful consideration is necessary to design a parallel hybrid system that best suits the intended application and performance goals.

2.3.3 Hybrid Series–Parallel Configuration

The Hybrid Series–Parallel configuration, also known as the power split configuration, combines elements from both the Series and Parallel hybrid systems, as shown in Fig. 12. The key component in this configuration is the planetary gearbox, which connects the propulsion components, such as the propellers, engine, electric machine (EM), and generator.

One of the main advantages of using a power split configuration is that it allows both the ICE and the EM to

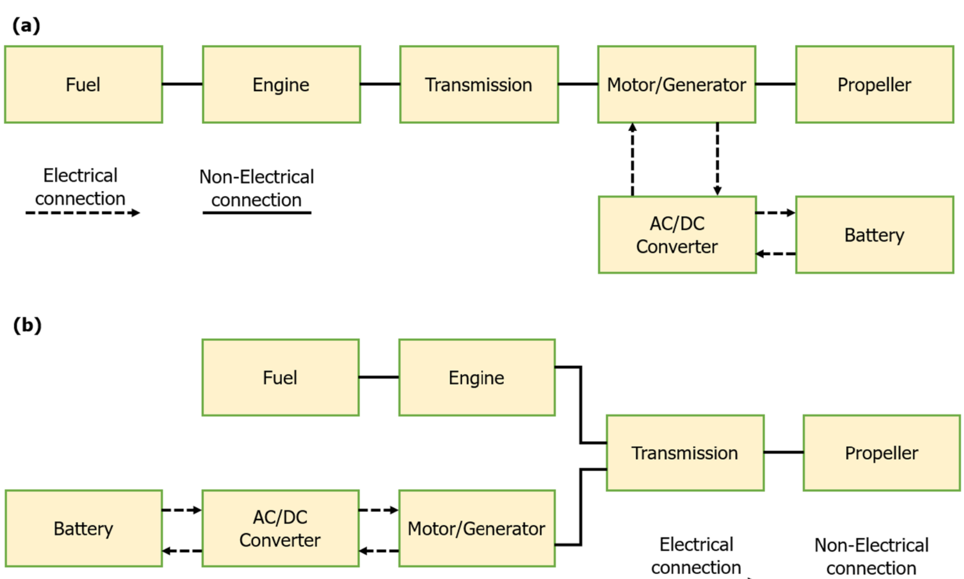

Fig. 11 **a** Single shaft hybrid parallel configuration, **b** Double shaft hybrid parallel configuration for aircraft [54]

operate in their optimal efficiency regions. This improves overall system efficiency compared to the Series Hybrid configuration. However, this configuration also suffers from constant power losses due to the power split mechanism. Since the engines are always connected to each other, they cannot be decoupled, resulting in additional consumption due to the passive drag of the EM when the ICE is driving the propeller. Another minor disadvantage is the cost and lifespan of the mechanical power split component.

2.3.4 Turbo-Electric Hybrid Configuration

This architecture (Fig. 13) is similar to a series hybrid (Fig. 8), but it does not rely on batteries for propulsion energy. In this design, an ICE drives an electric generator and Permanent Magnet Electric Motors power a fan or propeller. All the power comes directly from the fuel, and there are no additional energy storage devices [55].

Like a series hybrid, decoupling the ICE's propulsive function from the EM thrust-producing devices enables higher propulsion performance and provides design flexibility for the aircraft. ICEs can operate close to their peak efficiency power versus speed conditions and be optimally located within the aircraft [56].

This architecture is well suited to be combined with DP concepts, where power is distributed to several EM-driven fans strategically positioned in the airframe for synergistic integration. It also pairs effectively with superconducting electrical systems. The power loss during energy conversion from mechanical to electrical and vice versa is overcome with distributed fans, which increases the effective By-Pass Ratio (BPR) while reducing the fan pressure ratio. When combined with Boundary Layer Ingestion (BLI), overall efficiency is enhanced, reducing vehicle wake dissipation [56].

In the Full Turbo-Electric architecture, all the power from the ICE is used to generate electrical energy. In contrast, the Partial Turbo-Electric variant involves EMs providing part of the propulsive power, while the rest is generated by a turbofan mechanically driven by ICE-driven turbofans. This configuration allows for smaller electrical components and corresponding weight reduction [57]. An example of a Partial Turbo-Electric design is the STARC-ABL concept [58].

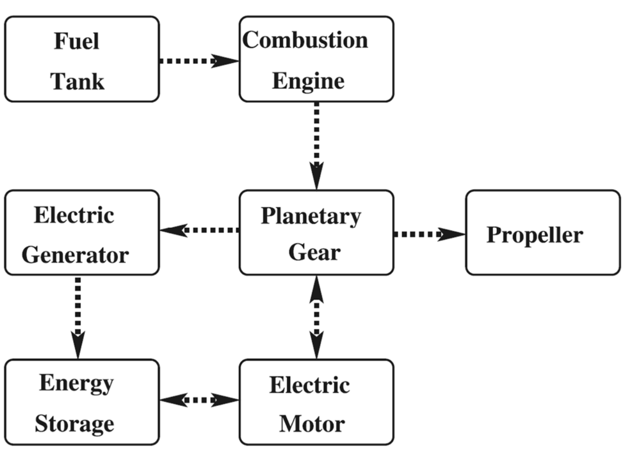

Fig. 12 Hybrid Series–parallel system [49]

An advantage of this architecture is the possibility of using "green fuels" such as Hydrogen. State-of-the-art turboelectric developments combine Solid Oxide Fuel Cells (SOFCs) fueled by hydrogen to supply EMs for driving fans, along with cryogenic superconducting components [49, 59].

These hybrid configurations, including Series, Parallel, Series–Parallel, and Turbo-electric, are commonly used in the aerospace and automotive sectors. The Series configuration allows the engine to operate at its ideal conditions but has relatively low system efficiency due to energy conversion losses. The Series–Parallel configuration is the most functional but also the most complex, making it less popular for aircraft applications. Therefore, the Parallel Hybrid configuration is considered the most versatile option given the current level of technology.

In terms of estimating the range capabilities of these new types of aircraft, classical analytical formulations used in literature do not consider additional sources for propulsive purposes. However, new analytical range equations have been developed to estimate the range of hybrid airliners, taking into account the hybrid propulsion systems [60]. Studies have shown that, with current technology levels, hybrid-electric designs have lower range capabilities compared to their thermal equivalents. For example, a parallel hybrid-electric design could achieve a 28% decrease in fuel mass but with a 14% increase in maximum takeoff weight (MTOW) for a fixed 400-nautical-mile route [61].

The main challenge with these hybrid configurations lies in the current state of the art of the devices required for their operation. With the technologies currently available on the market, it is not feasible to manage the time and distance of routes covered by existing aircraft. Various universities and research organizations have conducted studies on hybrid electric systems and their potential fuel reduction and emission mitigation benefits. These studies have assessed different aspects such as aero-propulsive gains, the mass impact of improved technology, and the sizing and assessment of hybrid electric systems for reference airliners. The following outputs are only some of the results of several studies conducted by various universities and research organizations:

- Zamboni et al. 2019 [61] compared the fuel-saving performance of three hybrid configurations under different assumptions of technology levels. Results illustrated that the parallel architecture is a conservative option considering today's state-of-the-art technology, while the series one can benefit the most from technology improvement.

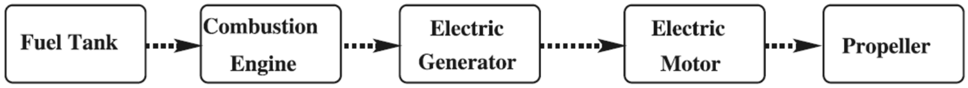

Fig. 13 Turbo-electric hybrid system [49]

- Delft University of Technology has conducted a series of studies on the application of HEPS to regional airliners.
- Bogaert assessed the potential fuel reduction and emission mitigation of hybrid electric regional aircraft [62].
- Vries and Hoogreef et al. [63, 64] discussed the aero-propulsive profits of the hybrid electric system, for example, the leading edge and boundary-layer ingestion. It was concluded that these revenues are easily negated by the increased masses, unless the improved technology could significantly decrease the powertrain mass.
- Pornet et al. (from Bauhaus Luftfahrt) [65, 66] completed the sizing and assessment of the parallel hybrid electric system that comprised motors mounted on the output shafts of conventional gas-turbines, for a 180 PAX reference airliner. Then, results were presented and demonstrated that the advantages of HEPS would be degraded by the significantly increased weight of the electrical system.

3 Flight Demonstrators

After discussing the main hybrid propulsion configurations and their advantages and disadvantages, attention now shifts to the efforts made by universities and research institutions to move from purely theoretical models to functional prototypes capable of flight. The models identified in the literature have been classified according to their geometrical dimensions into the following categories:

- Small scale
- Medium scale
- Large scale

By classifying the prototypes based on their geometrical dimensions, researchers and engineers can better understand the scalability and potential applications of hybrid electric propulsion systems. These prototypes play a crucial role in advancing the development of hybrid electric aviation by providing valuable data, insights, and practical experiences in real-world conditions. They also serve as testbeds for refining the technology and identifying areas for improvement to eventually make hybrid electric aircraft a viable and sustainable option for the aviation industry.

Fig. 14 Carrier H6 hydrone

3.1 Small Scale

The small-scale sector is characterized by Unmanned Aerial Vehicles (UAVs). This scale is convenient for demonstrating the feasibility of hybrid electric technology [67]. The paragraph will list some of the models made to demonstrate the possible advantages of the configurations proposed in the previous chapter:

- In 2005, Harmon et al. from the University of California-Davis proposed a conceptual design method to simultaneously size the aircraft wing and the hybrid propulsion system components. Then, they also carried out a comparison between various configurations and battery-discharging profiles. The main finding of this work is that, for the small, unmanned airplane, the clutch-start parallel configuration with the battery charge-sustaining strategy was the best design and achieved the lowest empty weight, although the flight test has not been completed yet [54].
- In 2012, the Queensland University of Technology (QUT) developed a test rig for the parallel HEPS that combined a 10cc combustion engine and a 600W brushless EM. The experimental result shows that the fuel usage could be decreased by 6%, with only a 5% weight penalty compared to the non-hybrid system [68].
- In 2015, Friedrich and Robertson [69] sized a 20 kg UAV using the hybrid design of a manned airplane. Several EM engine sizes were compared, and the selected one was paired with an ICE through a parallel scheme con-

figuration. Results show up to 47% fuel-saving in comparison to the original ICE-powered aircraft.

- In 2017, Quaternium launched its first hybrid fuel-electric quadrotor drone, HYBRiX. It was equipped with a series-hybrid technology [70].
- In 2023, Harris Aerial is expected to release its newest hybrid quadrotor (Fig. 14[1]), Carrier H6 Hybrid HL [71].

Those cited configurations are only some of the examples that could be found in the literature about this class of vehicle.

3.2 Medium scale

With this class, the applications become more interesting because there is the opportunity to ensure the transportation of people and no longer just objects. It follows that the results reported in the following studies have also received much more attention in the scientific/industrial community than those obtained on the small scale. Additionally, in this paragraph, a list of the prototypes that have been realized will be presented:

- In 2009, German aircraft builder Flight Design presented a hybrid electric system where a 40-hp (30 kW) EM can provide approximately 5 minutes of additional power to a 115-hp (86 kW) ICE [72]. Later, a light airplane, the EcoEagle, was developed by the Embry-Riddle Eagle Flight Research Center to compete in NASA's Green Flight Challenge 2011.
- In 2011, the DA36 E-STAR was the first series-configured hybrid-electric manned airplane. The main partners of the project were Airbus, Diamond Aircraft, and Siemens [73].
- In 2011, Ripple [74] examined the feasibility of HEPS for mid-scale aircraft by retrofitting the General Aviation (GA) and remotely-piloted platforms—DA 20, Cessna 172 Skyhawk, and Predator. The potential fuel savings of the designed mild HEPS could be up to 54 kg, but 27 kg of payload was sacrificed.
- In 2017, Glassock et al. [75] designed a parallel hybrid propulsion system for an 8-passenger skydiving airplane. Results demonstrated that the effective flight duration was severely limited. Nevertheless, this could be compliant with an aircraft whose field of application is short-duration high-power missions, such as skydiving.
- In 2018, Finger et al. [76] compared the series configuration and parallel configuration of HEPS for general light aircraft. The paper claimed that the parallel hybrid architecture is superior to the series one in terms of decreasing the global weight and on-board fuel weight.

Table 3 Scheme of medium-scale demonstrators [54]

Aircraft	Name	Institute or corporation	Hybrid Config.	MTOW [Kg]	ICE/EM installed power [kW]
	SOUL	University of Cambridge	Parallel	210	8/12
	DA36 E-Star	EADS, Diamond Aircraft and Siemens	Series	770	30/70
	EEL	Ampaire	Parallel	2100	156/180

- In 2019, Ampaire flew a hybrid-powered airplane, the Ampaire EEL 337. It was based on the Cessna 337BY, replacing the original rear piston engine with a 180 kW electric motor [77].
- In 2019, Boggero et al. [78] retrofitted the Piper PA-38 Tomahawk using a 22.6 kW EM and a 54.5 kW ICE. If the hybridization of HEPS was set at 30%, the empty mass of the reference Piper airplane was reduced from 512 to 466 kg. The fuel mass could be reduced by around 10 kg since the sized smaller ICE could operate in a higher efficiency working area.

Some of the demonstrator cited above are reported in Table 3.

3.3 Large Scale

The large scale is the most difficult but also the most interesting application because in this class, all regional aircraft configurations that could replace the ATR-sized planes are reunited. Studies conducted by different associations have demonstrated that most of the air traffic is characterized by regional routes. These routes, which are currently operated by turbojet engine vehicles, could be replaced by hybrid turboprop configurations because they are in the nautical-mile range that can be traveled by this type of airplane.

Listed below are some of the models made to demonstrate the possible advantages of the configurations proposed in the previous chapter:

- In 2013, Boeing, paving the way for full-electric regional aviation, funded the startup Zunum to develop the hybrid electric commercial airplane that could be delivered in 2022.
- In 2015, Pornet et al. [79] (from Bauhaus Luftfahrt) proposed a hybrid airliner that achieved 16% fuel reduction for a 900-nautical-mile off-design mission but failed to

[1] (https://www.harrisaerial.com/harris-carrier-h6-hydrone/).

Table 4 Scheme of large-scale demonstrators [54]

Aircraft	Name	Institute	Hybrid Config.	MTOW [t]	Seats	ICE/EM INSTALLED POWER [MW]
	E-FAN X	Airbus, Rolls Royce, Siemens	Series	Unknown	Around 100	3*31[kN]/2
	ZA10	Zunum	Series	5	12	1/-
	ECO-150	ESAreo	TeDP	63	100	-/18
	N3-X	NASA	TeDP	223	300	60/56

reach the original long range (3300 nautical miles) unless being sized with a larger wing area.

- In 2017, Airbus invited Rolls Royce and Siemens as the third partners to support the E-Fan X program, as a first step in the long-term goal of developing a hybrid-electric regional airliner.
- In 2017, Boeing funded the SUGAR team to boost the promotion of subsonic air transport using the hybrid electric concept [80]. The SUGAR Freeze utilized liquefied natural gas instead of jet fuel and generated electricity in flight to power advanced cryogenically cooled motors [81]. Another project was the N3-X, a TeDP-propelled blended-wing-body airplane equipped with a number of boundary-layer ingesting fans [82].
- In 2018, NASA leads the concept of Turboelectric Distributed Propulsion (TeDP) that hybridizes turboshaft engine and distributed electric powertrain in a series architecture. The X-57 "Maxwell" is an 18-motor propelled wing [83].

Table 4 presents design blueprints of several prominent commercial airplanes, as mentioned above. An intriguing parameter for comparing these diverse configurations is their passenger load capacity, clearly indicated by the number of seats specified for each airplane.

In the small-/mid-scale sector, both academic and industrial institutes have presented flying or flying-capable demonstrations. However, the development of large hybrid aircraft is still at the concept design and analysis stage, primarily due to the existing limitations in electrical and other relevant technologies.

The diagram in Fig. 15 highlights the technological limitations present today in the development of hybrid electric aircraft. It shows an area, indicated with a red square, where the majority of the different configurations mentioned above are confined. This area represents the current capabilities and constraints of hybrid electric propulsion systems for aviation. One of the main limitations shown in the diagram is the range that can be covered by hybrid electric aircraft. The maximum distance that these aircraft can currently cover is about 350 nautical miles (648 km). This range is significantly lower compared to conventional commercial airliners, which can cover thousands of miles in a single flight. The limited range of hybrid electric aircraft is a significant

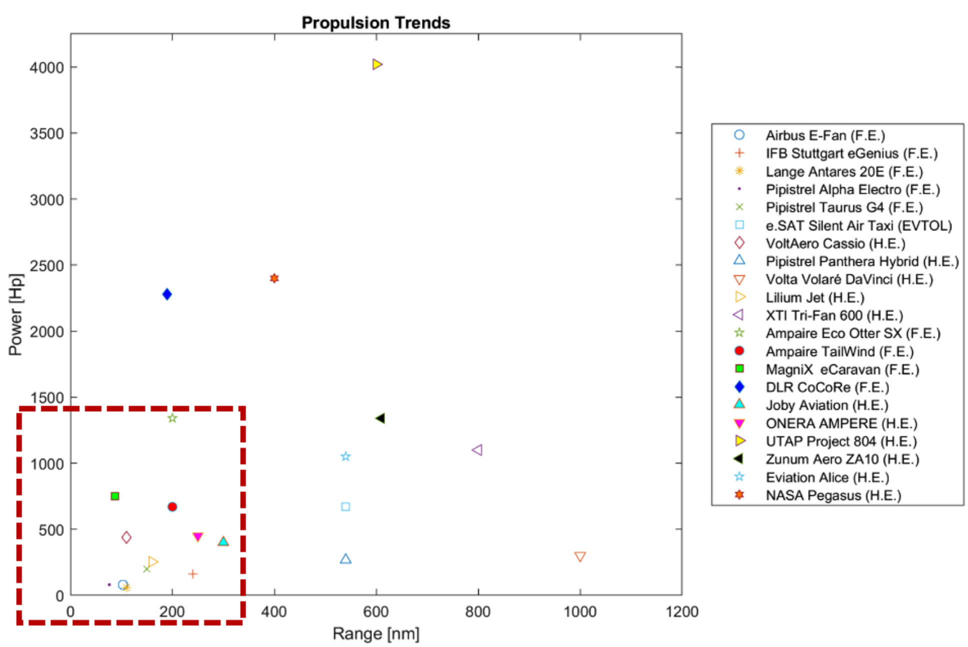

Fig. 15 Comparison of the various proposed demonstrators

challenge that needs to be addressed to make them viable for long-haul flights. Another limitation shown in the diagram is the payload capacity of hybrid electric aircraft. The number of passengers that these aircraft can carry is at most four people. This limitation is also a significant hurdle for hybrid electric aircraft to become a practical option for commercial aviation, where large passenger capacity is essential to meet the demand for air travel. The technological limitations represented in this diagram are primarily due to the current state of electrical and other technologies used in hybrid electric propulsion systems. As mentioned before, the development of large hybrid aircraft is still at the concept design and analysis stage, primarily because of these technological limitations. To make hybrid electric aviation a viable option for commercial use, significant advancements in battery technology, power distribution systems, and other related technologies are needed. Research and development efforts in the aerospace industry, along with advancements in related fields, are focused on overcoming these limitations. As technology continues to evolve and improve, hybrid electric aircraft have the potential to extend their range and payload capacity, making them more competitive with conventional aircraft in future. However, achieving this goal will require continued innovation, investment, and collaboration between academia, industry, and government organizations.

4 Conclusion

The main objective of this work is to explore and assess new propulsion systems that have the potential to reduce CO_2 emissions in aviation and contribute to achieving emission reduction targets set for 2050. Throughout the study, the operating schemes and principles of different propulsion systems, including full-electric aircraft, hybrid systems, and fuel cells, were briefly explained.

It was found that full-electric aircraft, while promising in terms of zero-local-emissions, low noise, and operating cost reduction, currently face significant limitations due to the state of battery technology. As a result, they are mostly implementable in the General Aviation category and may not be suitable for larger commercial aircraft due to range and payload constraints. Hybrid systems, particularly series/parallel configurations, offer greater flexibility and have the potential to be applied to a wider range of aircraft, but they come with some challenges. The mechanical and electrical complexities of these systems can lead to significant power losses and increased weight, impacting their overall efficiency and payload capacity. On the other hand, Sustainable Aviation Fuels (SAF) present a more immediate and viable solution for reducing CO_2 emissions without requiring extensive modifications to existing aircraft or infrastructure. SAF can be used as an alternative to conventional fossil-based jet fuel and can be produced from biological or non-biological sources. This makes SAF a practical option for achieving emission reduction targets in the near term.

In conclusion, the study highlights that further technological advancements in battery technology and energy transport systems are crucial for the widespread implementation of full-electric aircraft. In the meantime, series/parallel hybrid systems and fuel cells can be considered more realistic options for reducing emissions in larger aircraft. However, SAF remains the most feasible and readily applicable solution, providing a significant contribution to reducing CO_2 emissions in the aviation industry without major infrastructure changes. To achieve substantial emission reductions and reach the 2050 targets, a combination of these propulsion technologies and continued research and development efforts will be necessary.

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Author contributions LMC: Data curation, Investigation, Writing, Original draft preparation. GP: Supervision, Reviewing and Editing. SDR: Supervision, Reviewing and Editing: FF: Supervision, Reviewing and Editing. CSG: Supervision, Reviewing and Editing.

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Declarations

Conflict of interest No conflict of interests/competing interests to declare.

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