Aerospace Power Electronics, Energy Management and Power Distribution Architectures for Fuel Cell-Powered Hybrid-Electric Aircraft and eVTOLs: A Review

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Abstract: - Fuel cell-powered hybrid-electric aircraft and electric Vertical Take-Off and Landing (eVTOL) systems are emerging as promising solutions for sustainable aviation due to their potential for low-emission and high-efficiency propulsion. However, integrating multiple onboard energy sources, including hydrogen fuel cells, batteries, and distributed electric propulsion systems, introduces significant challenges for energy management, onboard power distribution, and the integration of aerospace power electronics. This paper reviews energy management strategies and power distribution architectures for fuel cell-powered hybrid-electric aircraft and eVTOL systems. Various propulsion configurations, including series, parallel, turboelectric, and fuel-cell hybrid-electric architectures for regional aircraft, unmanned aerial vehicles (UAVs), and urban air mobility platforms, are examined. Energy management approaches, including rule-based, optimization-based, predictive, and intelligent control methods, are evaluated with emphasis on hydrogen consumption, system reliability, component degradation, and mission adaptability. Particular attention is given to aerospace power electronics, including high-voltage DC power distribution, bidirectional DC/DC converters, electric propulsion drives, and wide-bandgap semiconductor technologies such as silicon carbide (SiC) and gallium nitride (GaN) for lightweight, high-power-density operation. Challenges related to hydrogen storage, thermal management, fault tolerance, safety, and certification are also discussed. Finally, critical research gaps and future directions toward intelligent, reliable, and certification-oriented onboard electrical power systems for next-generation hybrid-electric aviation are identified.

Key-Words: - Hybrid-electric aircraft, eVTOL, Aerospace power electronics, Fuel Cell, Energy management, Onboard power distribution

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1 Introduction

Driven by mounting environmental concerns, carbon regulations, and the surging demand for air transportation, there is a proactive movement towards sustainable and low-emission energy sources for powering the aviation sector. Conventional aircraft, which rely on fossil fuel-based power sources, are among the primary contributors to greenhouse gas emissions, global pollution, and noise, thereby necessitating a switch to cleaner power sources [1], [2]. Besides conventional aircraft, there is an emergence of Urban Air Mobility (UAM), Advanced Air Mobility (AAM), and electric Vertical Take-Off and Landing (eVTOL) aircraft that require light-weight, efficient, and sustainable power sources onboard [1], [2]. Hybrid-electric aircraft are envisioned to play a substantial role in reducing emissions, improving efficiency, and providing quieter and more flexible operations.

Hydrogen fuel-cell propulsion can extend endurance relative to battery-only propulsion for some missions [3] and produces no direct CO_2 during fuel-cell operation [4]. These benefits depend on aircraft and mission design. High-pressure or cryogenic tanks add mass and occupy airframe volume [5], while cooling hardware adds mass and can increase drag [2]. These penalties can reduce payload or range [2], [5]. Certification must address hydrogen leakage, fire hazards, and electrical faults [6]. Lifecycle greenhouse-gas emissions depend on hydrogen production and supply, including compression or liquefaction and delivery, as well as on the energy consumed during flight [4].

But, due to the highly dynamic power requirements of aircraft during take-off, hovering, climbing, and maneuvering, the power demands are not readily satisfied by a single fuel cell. Thus, a fuel cell combined with an energy storage device, such as

a battery and/or supercapacitor, has been considered in a hybrid-electric propulsion system, where the fuel cell provides the cruise power, and the battery/supercapacitor provides transient power and regenerative energy during dynamic power demand [7], [8], [9]. Such an operation enhances propulsion performance, improves overall efficiency, and reduces the load on the fuel cell stack. Though, coordinating the multiple energy sources complicates the power flow coordination, onboard power management, thermal management, use of the energy storage devices, and reliability and optimization of the system.

Merely hybridizing fuel cell and battery aircraft does not inherently improve endurance, energy efficiency, or cost-effectiveness. The overall performance of hybrid fuel cell–battery aircraft depends heavily on the hybrid configurations, electrical topologies, and power management strategies, where the strengths of fuel cells and batteries are synergized, and degradation is minimized [7], [8], [9], [10], [11], [12]. Improper power management strategies could lead to excessive hydrogen consumption, accelerated battery degradation, thermal stress, voltage instability, and loss of reliability. In the case of eVTOL and UAM, the challenging operating profiles of frequent power surges, repetitive takeoff and landing flight cycles, and stringent weight requirements demand high-performing onboard power systems [13], [14], [15].

An Energy Management System (EMS) is essential for managing energy flow between fuel cells, batteries, propulsion, and other loads and subsystems in different flight phases. Various EMS strategies for hybrid-electric aircraft systems have also been reported in the literature, namely, rule-based, fuzzy logic, optimization, predictive, distributed, and artificial intelligence-based control methods [8], [11], [12], [16]. Rule-based control strategies are the most commonly used due to their simplicity and lower computational demand, while optimization-based techniques such as Model Predictive Control (MPC), dynamic programming, and metaheuristic algorithms provide better efficiency and power management. More recently, intelligent and learning-based EMS strategies are being considered for managing uncertain mission profiles and dynamic conditions. But, using these advanced strategies in aircraft systems is difficult due to the reliability and certification standards in the aerospace industry.

Besides, the on-board electrical power distribution systems play another role in hybrid-electric aviation. The emergence of MEA and AEA concepts requires more-electric, or all-electric, and intelligent power networks with high power density and high fault tolerance [17], [18]. More and more DC power distribution systems are being utilized in modern aircraft systems due to fewer conversion losses, ease of control, and better matching with fuel cells and batteries. Also, advanced power electronics, such as high-frequency DC/DC converters, bidirectional converters, and multilevel inverters, are emerging in aerospace power electronics, including new semiconductor devices like silicon carbide (SiC) and gallium nitride (GaN) technologies [10], [19].

While there has been significant research effort focusing on hybrid-electric aircraft configuration, on-board electric system, and fuel cell propulsion system for aircraft [2], [8], [10], [17], [18], [1], [11], [17], multistack fuel cell systems, emergency power system (EPS), and control architecture [9], [15], unmanned aerial vehicle (UAV)/urban air mobility (UAM) energy management [14]. The aforementioned review papers only provide a general overview of hybrid-electric propulsion technologies or are dedicated to platforms such as UAVs or the propulsion scheme like hybrid-electric systems, and do not explore and compare the onboard power architectures and energy management strategies for fuel cell-powered aircraft and eVTOL in the aviation sector. Also, the effect of the interplay among the electrical architecture, hybrid topologies, mission-based operational constraints, thermal constraints, fault tolerance, and certification-oriented energy management system (EMS) design in a fuel cell-powered aircraft has not been explored thoroughly in the literature review so far [1], [8], [11], [12], [13], [17], [18].

In light of the rapid progress in hydrogen-electric aircraft and eVTOL technology, this paper provides a detailed overview of energy management and onboard power distribution for fuel cell-powered hybrid-electric aircraft and eVTOL. First, it presents an overview of hybrid-electric propulsion systems, fuel cells, DC/DC interfaces, electrical buses in aircraft, and power distribution methods. Then, an overview and comparison of energy management strategies for hybrid systems, including rule-based, optimization-based, predictive, distributed, and intelligent control methods, are provided with an emphasis on aerospace operational requirements. Finally, it reviews aerospace-specific requirements, including safety, thermal management, reliability, degradation, and mission-specific flight profiles, and identifies the gaps and future research directions toward lightweight, reliable, efficient, and certification-oriented hybrid-electric power systems for the next generation of sustainable aircraft.

2 Review Methodology

ScienceDirect, IEEE Xplore, MDPI, Springer Nature Link, and IOPscience searches covering publications from 2014 to 2026 were conducted between 12 June 2026 and 7 November 2026. The terms "fuel-cell aircraft," "hybrid-electric aircraft," and "eVTOL" were searched for energy management, power electronics, onboard power distribution, hydrogen storage, thermal management, and safety.

Journal articles, conference papers, and technical reports on fuel-cell propulsion or onboard electrical systems in aircraft and eVTOLs were eligible sources. Unrelated records with insufficient technical detail for the review were also excluded. Non-aviation sources were retained as background if relevant to an aviation technology. In total, 1036 records were reviewed by title and abstract, 102 full texts were assessed for eligibility, and 56 sources were included in the synthesis. Of the 109 publications cited in this review, 56 met the eligibility criteria for inclusion in the evidence synthesis, while the remaining 53 provided background and technical context.

Check for clarity of system boundary and operating conditions, transparency of assumptions and comparers if applicable, completeness of reporting on performance, and validation of the studies presented. All studies were categorized as conceptual, simulation-based, bench-based, or flight-based. All quantitative comparisons were allowed only in studies with comparable conditions and system boundaries. Conceptual studies were used to explain design trade-offs and research gaps.

This review distinguishes four levels of evidence. Experimental findings are reported at the scale tested, such as the laboratory converter measurements in [20]. Simulation findings are interpreted within the model and mission assumptions. Conceptual proposals, such as the integrated power-management architecture presented in this review, describe candidate designs that require validation. Anticipated developments are presented as research directions whose aircraft-level benefits remain to be demonstrated.

3 Fuel-Cell-Based Hybrid-Electric Aircraft Configurations

3.1 Hybrid-Electric Aircraft Configuration

A hybrid-electric aircraft utilizes a combination of thermal (gas turbine) and electrochemical (fuel cell) power sources, electric machines, and energy storage (batteries) to provide propulsion and energy. System configurations include series, parallel, series/parallel, turboelectric, and all-electric, each with different efficiency, weight, and integration complexity for different aircraft classes and missions [21], [22], [23]. Fuel cells are considered for small, regional, and commuter aircraft, with the addition of distributed electric propulsion to compensate for the efficiency penalty due to added mass [21], [24], [25].

3.2 EVTOL Electric Propulsion Systems

3.2.1 Series Architecture

With power supplied only to propulsors by a power source (fuel cell or engine–generator) in a series hybrid, there is no mechanical coupling between the latter and the propeller/fan, which significantly facilitates the propulsors' arrangement and encourages distributed propulsion, but larger electric machines and converters are needed, adding weight penalties and cooling challenges [21], [22], [26]. A series configuration is preferred for small aircraft and fuel-cell systems, where flexible electrical architecture is cited as the main advantage [21], [25].

3.2.2 Parallel architecture

In parallel hybrids, the thermal or fuel-cell-driven shaft is connected to the propulsor through the usual mechanical path, along with an electric machine used for assist or regeneration along the same shaft. Compared to series configurations, the maximum take-off mass and total mission energy can be reduced, albeit with a lower block-fuel and emissions reduction [26], [27], [28]. Parallel fuel-cell/battery hybrids are good candidates for retrofits and test rigs, having been explored on lab propulsion benches and small aircraft [7], [27], [29], [30].

3.2.3 Turboelectric concept

For turboelectric configurations, the gas turbine acts as the main engine for electricity generation, with all thrust being electric, enabling revolutionary concepts such as turboelectric distributed propulsion and boundary-layer ingestion that could provide substantial drag and fuel savings for regional and narrow-body aircraft, provided high drag savings (7.5–10%) and high power density are realized [21], [23], [26], [31]. The turboelectric configurations are often referenced as the long-range aircraft option with the advent of high-performance electric technology [21], [23], [31].

3.3 Aircraft Fuel-Cell Integration

Fuel cells are integrated as either main propulsion systems (fuel-cell electric or fuel-cell hybrid aircraft) or as auxiliary power units (APU) or backup:

Primary fuel-cell electric / hybrid: Fuel cells provide cruise or continuous power, with batteries or supercapacitors supplying peaks (take-off/climb) and transients. Configurations are fuel-cell series systems and fuel-cell-electric parallel hybrids, often combined with distributed electric propulsion [21], [25], [30], [32], [33].

Auxiliary/APU roles: Fuel cells can energize the on‑board systems of more‑electric aircraft or hybrid turboelectric concepts, enhancing the overall efficiency and allowing for hydrogen to become the main energy vector [21], [23], [25], [34].

There are design trade-offs that impact hydrogen volume and weight storage, power density of the fuel cell stack, flight conditions of altitude and temperature, and integration with the existing airframe and certification [21], [25], [30], [32], [34]. Properly sized fuel cell and battery hybrid systems show potential for increased endurance and reduced emissions without increasing maximum take-off weight for light and regional aircraft [24], [25], [30], [32]. Table I compares the various types of aircraft by propulsion power path, energy source, fuel-cell role, mission demands, and integration trade-offs. For a fuel-cell-electric configuration, the fuel cell provides electricity to the propulsion motors via a fuel cell. A battery can also be used in a fuel-cell-electric configuration. In a turboelectric configuration, the turbine drives a generator for the propulsion motors. A parallel hybrid has mechanical and electric torque at the propulsor shaft. An eVTOL refers to an aircraft or mission that can accommodate different propulsion configurations. The trade-offs detailed in Table 1 (Appendix) depend on the power path and mission.

4 Proposed Systems-Oriented Taxonomy of Hydrogen-Electric Aircraft Technologies

Most of the review papers classify hydrogen-electric propulsion technologies based on the propulsion system architecture (series, parallel, turboelectric), energy management approach, or power electronics configuration [35], [36], [37]. These approaches provide a technical description of different types of technologies but do not indicate how the individual technologies alleviate engineering challenges to implement them in an actual aircraft environment [24], [36]. Hence, this review proposes a system-level categorization of the technologies based on the aircraft constraints.

Energy generation technologies, such as proton exchange membrane fuel cells, solid oxide fuel cells, and hybrid fuel-cell/battery systems, belong to the first category [38], [39], [40]. Their goals are to increase the energy conversion efficiency and fulfill the power demand of the aircraft [38], [39], [41]. Energy storage technologies, such as compressed hydrogen, liquid hydrogen, cryo-compressed, structural tanks, and multifunctional energy storage, form the second category [36], [41], [42]. Their impacts are on aircraft mass, volume, and mission duration [39], [40], [43]. The third category consists of power conversion and distribution technologies, such as high-voltage DC architectures, silicon carbide (SiC) and gallium nitride (GaN) converters, and electrical protection systems [40], [41], [44]. These technologies improve power density, electrical efficiency, and system reliability [41], [44]. Intelligent energy management technologies, such as rule-based control, model predictive control, equivalent consumption minimization strategies, reinforcement learning, and digital twin-enabled optimization, constitute the fourth category [24], [40], [41],[45]. Their primary objective is to allocate power among multiple energy sources on board the aircraft [36], [40], [43]. Finally, aircraft integration technologies, such as distributed electric propulsion, superconducting electrical machines, thermal management systems, lightweight structures, and integrated aero-propulsion-energy co-design, are the fifth category [36], [44], [46]. They directly affect the payload, range, and certification of aircraft [24], [25], [35].

This systems-based taxonomy points out that hydrogen-electric flight is a multidisciplinary systems engineering challenge [24], [25], [46]. It brings attention to how improvements in one area affect overall aircraft performance, weight, efficiency, and reliability.

The proposed systems-based taxonomy of enabling technologies for hydrogen-electric aircraft is presented in Figure 1 (Appendix). Contrary to conventional classification based on propulsion systems or components, the proposed taxonomy classifies the technologies based on their functional role in contributing to aircraft performance. The five key functional domains, energy generation, energy storage, power conversion and distribution, intelligent energy management, and aircraft integration, collectively affect payload capacity, mission range, efficiency, reliability, power density, and certification readiness. This taxonomy highlights the interdisciplinary aspect of hydrogen-electric aviation and provides an organizational structure for the subsequent sections of this review.

5 Energy Management Strategies

This section describes the power sharing between the fuel cell, battery, and other power sources, as well as the development of control strategies from rule-based to advanced optimization-based approaches, focusing on the trade-off between fuel/hydrogen consumption, component lifespan, and safety constraints for aggressive flight profiles. Figure 2 (Appendix) illustrates the control hierarchy of a fuel-cell/battery aircraft with an optional supercapacitor. The flight mission profile determines the time-varying propulsion demand. The supervisory energy management system (EMS) takes this demand and information on the status of the power sources to set power references. The power-flow controller converts these references into converter commands and enforces limits on battery state of charge, fuel-cell power and ramp rate, and component temperature. In this example, the fuel cell would supply continuous power, the battery would cover the peak power, and the optional supercapacitor would buffer the short periods. The sources are separated from the common direct-current (DC) bus through their converter interfaces, and the propulsion inverter and motor convert bus power into shaft power. Power at the mission level differs from fast converter control, and it also emphasizes that meeting propulsion demand depends on the available power and operating limits of each source.

5.1 Power Flow Control in Hybrid-Electric Aircraft

Power flow control dictates the sharing of load between the fuel cell, battery, and potentially an engine, on the DC bus or shaft, depending on architecture: converters, direct hybrid, or semi-direct hybrid. A middle ground is the PMCD module (Power Management Control and Delivery), where fuel cell mode, hybrid mode, battery mode, active/passive charging, and recuperation can be integrated, as well as system redundancy and safety for airplanes, such as HY4 [10]. The power system topology and power system control are designed in a co-design manner to reduce hydrogen consumption and reduce fuel cell degradation and battery degradation for different flight phases for a hydrogen aircraft [9], [17].

5.2 Rule-Based Energy Management

Rule-based approaches involve state machines or maps that incorporate thresholds on DC-bus voltage, SoC, power demand, or fuel cell parameters. For eVTOL and turboprop hybrids, state machine-based control logic designates the fuel cell as the main power source and the battery for peak shaving or as a backup, chosen for its simplicity, reliability, and low computational demand [13], [18], [47], [48]. Degradation-aware rule-based algorithms add various fuel cell idling power levels, ramp-rate limiters, or a fuzzy layer to reduce start/stop stress and maintain the battery within a specified SoC window [8], [47], [49], [50]. Rule-based approaches are commonly adopted as benchmark algorithms for performance comparison with more advanced optimization strategies [8], [18], [47], [51].

5.3 Optimization-Based Energy Management

Optimization-based EMS explicitly minimize fuel/ hydrogen consumption, aging cost, or multi-objective criteria constrained by system and mission constraints. Strategies include dynamic programming, model-predictive control, and search/heuristic and intelligent methods [17], [49], [51], [52], [53], [54], [55], [56].

5.3.1 Model Predictive Control (MPC)

MPC solves an optimal control problem over a finite horizon in a receding fashion based on a prediction model of the aircraft and hybrid powertrain. In fuel-cell UAVs and aircraft, MPC-based EMS tracks SoC or DC-bus targets without exceeding internal losses, power stress, or fuel-cell degradation [49]. For larger-scale hybrid aircraft, nonlinear MPC based on coupled aerodynamic–propulsion models or full aerodynamics and propulsion models minimizes block fuel burn while considering flight dynamics and other constraints [51], [54], [55]. Hybrid fuel-cell systems can be modeled by mixed-integer formulations (e.g., MILP) that allow online-capable MPC; compared to more sophisticated MIQCP, MILP may provide the best trade-off among model fidelity, solution optimality, and computational time [57].

5.3.2 Dynamic Programming

Dynamic programming (DP) determines the optimal power split along a specific mission profile offline. For a fuel-cell/gasoline hybrid aircraft, DP finds the optimal power sharing between the engines and the fuel cell that minimizes the fuel consumption while meeting the power requirements [52]. DP has been used as a "gold standard" to validate simpler real-time power controllers, including control rules and MPC-based controllers, for hybrid helicopters and fixed-wing aircraft [47], [51], [54]. Due to its computational complexity and non-causality, DP is mainly used to design and evaluate the performance

of real-time hybrid power controllers, rather than being used in-flight [17], [47], [52], [54].

5.3.3 Other Search Technique Optimization Approaches

Meta-heuristics or convex optimization are also utilized by other optimization EMSs. Particle swarm optimization (PSO) can be used to tune the membership thresholds of the fuzzy-logic controller in a fuel-cell/battery EMS to minimize the equivalent hydrogen consumption, which results in better fuel economy and dynamic response than a pure fuzzy-logic controller and a rule-based EMS [58]. Convex programming has been used in a hybrid aircraft EMS to formulate the fuel minimization objective with aircraft dynamics and powertrain loss models as a convex problem, which can be efficiently used to implement predictive control with a guaranteed global optimum [55]. Sequential convex optimization can provide the optimal state-of-charge (SoC) reference trajectory for a UAV battery incorporating mission and system requirements [49]. Search or evolutionary optimization methods are referenced in the more general reviews of the hybrid aircraft as promising methods for conceptual design and offline EMS optimization [17], [19], [56].

5.3.4 Intelligent Control Approaches

Intelligent EMS uses fuzzy logic, neural networks, or learning types. The fuzzy rule-based controller for fuel-cell hybrid aircraft and UAV is more robust for load variations compared to the crisp rule-based approach and can be extended to include frequency decoupling or ECMS ideas [8], [17], [18], [50]. Fuzzy EMS tuned by PSO to improve the membership functions further improves hydrogen usage [58]. Adaptive or hierarchical structures use fuzzy-logic neural networks to tune the prediction horizon of an MPC layer to achieve a balance between optimality and computational complexity while considering battery health [49]. Reviews of hybrid aircraft and heavy-duty fuel-cell vehicles indicate the trend towards layered, health-aware, and learning-based EMS, especially MPC-based structures considering both performance and degradation objectives [17], [56].

5.4 Comparative Assessment of Energy Management Strategies

Many different energy management strategies have been suggested for hydrogen-electric aircraft. Depending on the mission profile, onboard computational capabilities, and certification requirements, different energy management strategies are applicable [59], [60], [61]. Dynamic Programming (DP) is widely applied as an energy management strategy to obtain the global optimum, which makes it a suitable benchmark to compare other strategies against [52], [54], [62], [63], [64]. Because DP requires significant computation, it is not viable for real-time implementation on an actual aircraft [54], [62], [65].

Comparisons should be conducted using a common mission and report payload, take-off mass, and energy use. For a conceptual tiltrotor mission with 75 miles of cruise and 5 minutes of hover, Ng et al. [3] predicted 500 lb for the fuel-cell–battery architecture versus less than 250 lb for the battery-only architecture in the study's sizing assumptions. For control strategies, Luo et al. [66] found that in a simulated hybrid eVTOL mission, their average fuel cell power was 5.31% lower with adaptive model predictive control than with a rule-based strategy in a hybrid eVTOL simulation. Comparisons between the baseline and validation methods, and battery state of charge, are needed to include the baseline and the final battery state of charge, as lower fuel-cell power could reflect more battery charge.

The trade-off between optimality and computational burden can be best addressed using the Equivalent Consumption Minimization Strategies and Model Predictive Control, which provide near-optimal performance in hydrogen consumption while maintaining sufficient computational efficiency for onboard implementation, thus holding the most promise for a flight-certified energy management system in the future [54], [67], [68], [69].

AI-based techniques such as reinforcement learning and deep neural networks hold promise for adaptive and predictive energy management under uncertain operating conditions [58], [64], [70]. But, due to a lack of explainability, extensive training, and verification and certification challenges, these techniques are currently difficult to apply to safety-critical aerospace applications.

In contrast, the simplicity, robustness, deterministic nature, and verification process of rule-based and fuzzy logic controllers may make them desirable for immediate implementation [59], [71], [72], [73]. Though they may have lower fuel usage efficiency compared to the optimization-based approaches, they are mature and certification-ready control strategies that can be implemented immediately for hydrogen-electric aircraft [54], [58], [60], [72].

5.5 Energy Management Challenges in Aviation Applications

There are other EMS issues unique to aviation vehicles as well:

1. Safety and certification: EMS needs to guarantee safe landing in case of failures (such as

turbine failure) by adequately reserving SoC and complying with strict redundancy and fail-safe requirements [10], [17], [48]. Safety-driven constraints and considerations (e.g., flight envelope, fuel cell temperature, thrust-to-drag ratio) restrict the applied strategies [9], [17], [19], [48].

2. Degradation and lifetime: Fuel-cell and battery aging depend strongly on power transients, SoC swings, and operating points. Lifetime-conscious EMSs introduce idling, ramp-rate constraints, and objectives that combine hydrogen use with aging cost [8], [19], [49], [50], [56].

3. Prediction and computation: Although aircraft have more predictable paths, the high-fidelity models and constraints (mass change, propulsion network, thermal limits) pose challenges for real-time optimization. Techniques such as convexification, hierarchical model predictive control (MPC), and adaptive prediction horizons are being explored to satisfy onboard computational requirements [17], [49], [51], [54], [55], [57].

3. Topology and scalability: Power-flow methodologies have a significant dependence on the selected architecture (e.g., converter-based, direct, PMCD-type). Scaling to regional jets and narrow-body aircraft introduces considerations regarding system weight, redundancy, and integration with existing avionics and thermal systems [1], [9], [10], [51], [54].

The EMS for fuel cell-based hybrid-electric aircraft and eVTOLs can be a simple, rule-based power-sharing strategy or more advanced methodologies closely tied to power-flow and system architecture and are based on optimization and intelligent control. Power-flow and system architecture strategies, such as PMCD and well-designed topologies, provide flexible operating modes and optimization strategies, such as MPC, DP, convex optimization, or heuristic optimization, to achieve fuel/hydrogen savings and lifetime advantages, while considering a large number of constraints in a specific mission profile. Intelligent and hierarchical EMS, while accounting for numerous constraints, provide robustness and health-aware control but pose challenges for real-time implementation, certification, and integration with overall aircraft safety and aerodynamic considerations.

6 Onboard Power Distribution and Aerospace Power Electronics

6.1 Aircraft Electrical Power Distribution Architectures

More- and all-electric aircraft are advancing from conventional 28 V DC and 115/200 V, 400 Hz AC to high-voltage DC and hybrid AC/DC systems to enhance efficiency and reduce wiring weight [74], [75]. Hybrid-electric and fuel-cell aircraft are considered microgrids inside the aircraft with multiple voltage buses and converters [74].

6.1.1 AC system

The standard systems employ three-phase 115/200 V,400 Hz AC systems derived from engine-driven generators via constant-speed or variable-speed constant-frequency (VSCF) converters [74], [75], [76]. While AC is preferred for some legacy loads and large rotating machinery, it entails heavier wiring and more intricate frequency regulation when used for high-power applications [74], [76].

6.1.2 DC system

MEA architectures proposed after 2000 use 270 V DC or medium-voltage DC (e.g., ±5 kV) to achieve higher power density and easy integration of power electronics and storage [74], [75], [77]. The DC bus is used to couple batteries, fuel cells, and inverters used for electric propulsion systems, allowing the use of distributed propulsion and easy power-flow management [10], [61], [74], [78].

6.1.3 Hybrid AC/DC architecture

Hybrid architectures combine AC generation with rectifiers and DC links, supplying multiple DC levels and residual AC loads [74], [75], [79]. Multiport converters and onboard microgrid concepts support flexible coupling of AC machines, DC sources, and propulsion in fuel-cell and hybrid aircraft [61], [74], [79].

6.2 Aerospace Power Electronic Converters

Power electronic converters are central to voltage adaptation, isolation, and power sharing in MEA and electric aircraft [74], [80].

6.2.1 DC/DC converters

DC/DC converters connect fuel cells, batteries, and DC buses with regulation and, often, galvanic isolation. Buck–boost stages are key in eVTOL hybrid FC–battery systems, where wide input/output ranges and high gravimetric power density are required [20]. Multiport and reconfigurable isolated

converters can simultaneously interface multiple sources and loads and support bidirectional power and recuperation [10], [79]. Dual- and triple-active bridge and LLC-type topologies are widely studied for aircraft HVDC links [79], [81].

6.2.2 Inverters

High-frequency, high-efficiency inverters using WBG devices are demonstrated for aerospace, showing stable performance and reduced losses compared with Si-based solutions [78], [80], [82].

6.2.3 Bidirectional Converters

Bidirectional isolated DC/DC converters enable energy flow between storage, fuel cells, and propulsion buses, supporting charge, discharge, and regenerative modes [3], [10], [81]. Comparative studies of dual-active-bridge (DAB), ISOP, NPC, and ANPC configurations indicate trade-offs among efficiency, EMI, thermal performance, and power density, with ANPC and DAB particularly attractive for MEA applications [81].

6.3 Wide Bandgap Devices for Aerospace Applications

WBG devices are pivotal for achieving the power density and efficiency targets of electric and hybrid aircraft.

SiC and GaN Technologies: SiC MOSFETs and GaN HEMTs support higher blocking voltages, switching frequencies, and junction temperatures than Si MOSFETs, thereby reducing converter size and improving efficiency [20], [76], [78], [80], [82]. Experimental DC/DC boost and DC/AC inverters using GaN and SiC show robust high-frequency operation suitable for aerospace environments [82]. Menzi et al. [20] reported specific powers of approximately 86 kW/kg and 44 kW/kg for their 15 kW all-GaN and all-SiC buck–boost converter prototypes, respectively. The GaN value was calculated using the measured prototype mass of 175 g and met the 80 kW/kg converter research target cited for 2040. These values describe laboratory converter modules. An aircraft-installed comparison would also require accounting for the complete cooling and installation hardware. Reliability and protection of WBG devices, including tailored lifetime models and condition monitoring, remain active research topics [83], [84], [85].

6.4 Protection, Reliability, and Thermal Management

The aircraft EPS must accommodate high fault currents, DC arc issues, and stringent safety requirements. The conventional circuit breaker technology is not able to work with large faults that can arise in all-electric propulsion systems, which has prompted researchers to develop solid-state and WBG-based circuit breakers, along with protection techniques [74], [76], [77].

Reliability of power electronic converters (PECs) is critical, as the failure rate of flight-critical loads is directly proportional to the PECs associated with them [84], [85]. Some studies identify wear-out mechanisms in capacitors, cosmic-ray impacts at high voltages, and propose new models based on the physics of failure for wide-bandgap (WBG) devices [83], [84], [85]. Thermal management is also crucial, involving liquid-cooled heat sinks, 3D printing, and other thermal considerations, and is required for high-power-density, WBG-based DC/DC and inverter stages for eVTOL and MEA platforms [20], [78], [80], [82].

6.5 Proposed Integrated Aerospace Power Management Framework for Fuel-Cell eVTOL Systems

Figure 3 (Appendix) shows how hydrogen storage, electrical conversion, propulsion, and supervisory control are integrated in a representative electric vertical take-off and landing (eVTOL) aircraft. The hydrogen storage system supplies the proton-exchange membrane fuel-cell stack, which feeds the DC distribution bus through an isolated DC/DC converter in the illustrated configuration. A battery and an optional supercapacitor exchange power with the bus through bidirectional interfaces. The bus supplies the propulsion inverters and motors, as well as auxiliary loads through a separate branch. The propulsion motors drive the lift or cruise propulsors, depending on the aircraft layout. The power-electronics layer includes conversion, filtering, and protection functions. The EMS monitors source availability, state of charge, temperatures, and fault status, then coordinates power sharing within mission and safety limits. The architecture assumes that the fuel cell supplies sustained demand and that storage supports short-duration peaks. Its central design implication is that source sizing, bus protection, thermal management, and fault response must be evaluated together to determine whether the aircraft can meet its power demands during normal and degraded operation.

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7 Challenges and Future Directions

7.1 Hydrogen Storage and Safety

The use of hydrogen fuel presents significant challenges due to its extremely low density, which necessitates the use of high-pressure or cryogenic containment tanks that add bulk and weight, posing significant challenges for integration within aircraft structures [5], [32], [86]. Safety concerns include leakage, fire risks, cryogenic hazards, effects of embrittlement on materials, and the crashworthiness of hydrogen fuel storage tanks [6], [87], [88], [89]. Recent studies highlight the need for improved insulation, leak detection, boil‑off management, and hazard analysis to mitigate safety risks for commercial operations [87], [88], [89].

7.2 Weight and Power Density Limitations

Fuel cell systems and hydrogen tanks remain far behind the power density of turbofans, while hybrid FC–battery concepts increase MTO mass compared to kerosene reference aircraft [5], [32], [90], [91], [92]. Even aircraft optimized around FC–battery for regional aircraft showed higher weights than their conventional counterparts, and the performance gap is primarily dominated by the specific energy of the battery and the mass-to-power ratio of the fuel cell [5], [32], [91], [92]. Improvements in stack materials, thermal management, and gravimetric capacity of the tanks are explored as future research directions [5], [32], [40], [92], [93].

7.3 System-Level Weight Bottlenecks and Design Trade-Offs in Hydrogen-Electric Aircraft

It is well known that hydrogen fuel cells present a highly appealing solution for zero-emission aircraft, given that fuel cell electrochemical reaction efficiency is high relative to other reaction forms, and hydrogen has an exceptional energy density specific to mass [94], [95], [96]. From an aircraft perspective, but, hydrogen-electric propulsion technology fundamentally suffers from fuel cell system weight and volume penalties rather than those associated with the fuel itself [45], [94]. An aircraft propulsion system contributes not only to aircraft energy and exergy efficiency but also to aircraft empty weight fraction, useful load, aircraft range, and operational cost [97]. The commercialization of hydrogen-powered aircraft is arguably the most consequential bottleneck that is entirely attributable to current propulsion technologies failing to compete on specific power and energy density terms, among other certification qualifications such as safety, reliability, and others.

To make the hydrogen-electric plane concept viable, it is essential to incorporate various components into the propulsion system, including hydrogen pressure vessels, fuel-cell stacks, battery modules, thermal control systems, electric motors, electronic power controllers, and the necessary structural support [2], [45], [61]. Each of these components contributes to improved efficiency and flexibility; however, the cumulative effect is a significant increase in the propulsion system's empty weight [45], [98]. Since the maximum takeoff weight is largely dictated by structural, aerodynamic, and certification constraints, any increase in propulsion system weight will correspondingly reduce the payload or usable fuel weight [97]. Consequently, this escalation in propulsion system weight leads to a higher empty-weight fraction, a decreased payload fraction, a shortened operational range, and an overall compromise of the business case [97], [99]. This relationship highlights why weight remains a critical constraint on hydrogen-electric airplane designs, despite advancements in fuel-cell and electric motor efficiencies.

The challenge extends beyond the sheer weight of propulsion systems. A heavier propulsion system impacts the aircraft's center of gravity, structural design, wing loading, and power loading, all of which in turn influence the aircraft's aerodynamic efficiency and overall performance, including take-off distance, rate of climb, and loiter time [86], [97]. Future aircraft design must embrace advanced aero-propulsion-energy co-design techniques, ensuring that propulsion system design, structural design, electrical system design, and mission profiles are not considered independently but are instead closely integrated for optimal outcomes [45], [86], [96], [99]. These advanced multidisciplinary design optimization techniques will be crucial in achieving the right balance between payload, energy storage, structural integrity, and aircraft performance.

The most challenging engineering hurdle is hydrogen storage. Hydrogen has an exceptional gravimetric energy density of about three times that of conventional fuel, but its volumetric energy density is very low under normal conditions [2], [86], [95]. To be used in aircraft, hydrogen fuel must be stored as high-pressure gas, cryogenic liquid, or other forms such as metal hydrides or new chemical carriers [2], [86], [100]. Each form has different requirements for pressure, insulation, boil-off losses, volume, complexity, safety, and maturity [86], [99], [100]. The hydrogen storage system weighs more and occupies more space than the hydrogen fuel itself

[101]. The large storage space needed for cryogenic tanks influences the shape and structure of the fuselage, aerodynamic drag, and center of gravity of the aircraft.

Understanding how the propulsion system mass is distributed is critical to identifying the largest contributors to overall aircraft mass. Instead of viewing components in isolation, the propulsion system is considered as a mass budget that consists of hydrogen storage tanks, fuel cell stacks, air compressors, humidifiers, thermal systems, batteries, supercapacitors, DC/DC converters, propulsion inverters, electric machines, protection gear, wiring harnesses, cooling systems, and structural component mass breakdowns [2], [14], [45]. This mass breakdown provides the designer with insight into the dominant contributors to weight and where to focus technology improvements to enhance aircraft performance.

Thermal management is another source of propulsion system weight that is often overlooked. Proton exchange membrane fuel cells (PEMFCs) reject a significant fraction of their energy as heat [98], [99]. Liquid cooling for the fuel cells requires pumps, plumbing, radiators, heat exchangers, and thermal management hardware [2], [45]. These systems add to the weight of the propulsion system and cause a significant drag hit due to the increased cooling surface [2], [45], [98]. At very high altitudes, the decreased air density reduces radiator effectiveness, requiring even larger heat exchangers to maintain an acceptable temperature range [2], [98]. Thus, thermal management becomes intricately linked to aerodynamic performance, propulsion performance, and structural weight [96], [98]. Improvements in thermal management technology are likely to contribute to future aircraft performance as significantly as improvements in fuel cells or battery technology.

Assessing the existing propulsion technologies through specific power (kW per kg) and specific energy (Wh per kg) clearly highlights their shortcomings. Fuel cell stacks have a relatively high specific energy but a relatively low specific power; therefore, they are optimized for cruise conditions [38], [45]. Fuel cells cannot easily provide the high power needed for take-off, climb, hovering, and maneuvering [38], [100]. Batteries have an excellent transient power response (specific power), but their specific energy is comparatively low, which negatively impacts mission endurance for longer-duration operations [2], [14], [102]. Electric propulsion motors continue to set records in improving the power-to-weight ratio, but the challenge is to maintain thermal control and ensure reliable operation when operating continuously at high power [14], [103]. Power electronics converters must carefully balance the switching rate, conversion efficiency, cooling, and mitigation of harmonics, alongside weight [14], [61]. The hydrogen storage system highlights the duality of the engineering compromise by offering excellent fuel characteristics but imposing a relatively heavy penalty due to the containment system [86], [99], [101]. The mission-specific requirements clearly indicate that none of the existing propulsion technologies alone can fulfill all aerospace requirements; hence, the need to carefully design hybrid systems.

Energy management strategies should likewise consider the entire mission of the aircraft, as opposed to a specific control problem. This is because the power demand levels differ significantly during different phases of the aircraft mission, such as take-off, climbing, cruising, descending, landing, and hovering for electric vertical take-off and landing (eVTOL) aircraft [14], [45], [61]. During take-off and hovering, the battery or supercapacitor will likely be required alongside the fuel cell to meet the high instantaneous power demand [14], [38], [100]. During cruising, the fuel cell usually becomes the main source of energy due to its better energy and hydrogen usage, in which case hybridization ratios, battery dimensions, and strategies should be optimized considering the entire mission envelope instead of a specific mode [45], [61], [98]. The future intelligent energy management system should consider the entire mission, the health of the components, prediction and optimization, and adaptive control to optimally allocate power based on the requirements, as well as minimize hydrogen and battery usage, temperature, and degradation.

The design of hydrogen-electric aircraft can be seen as a collection of trade-offs where one cannot independently improve individual aspects. For example, a bigger battery improves transient power but adds to the aircraft's structural weight, decreasing payload [14], [98]. A larger fuel cell stack increases continuous power but also adds more weight, along with the need for bigger cooling systems [45]. Larger hydrogen tanks improve range and reduce cabin space, possibly affecting fuselage shape [2], [86], [101]. Electric propulsion distributed across the airframe enhances aerodynamic efficiency and propulsive system fault tolerance but requires additional electrical power wiring, converters, and complexity [45], [86]. Redundancy also improves safety and certification but increases aircraft weight [86], [99]. Future aircraft designs will increasingly rely on multidisciplinary design optimization frameworks that simultaneously consider and make

better trade-offs between payload, range, energy efficiency, structural weight, thermal performance, reliability, safety, and certification constraints.

Looking beyond current technological limitations, several emerging technologies have the potential to improve the viability of hydrogen-electric aircraft substantially. Ultra-lightweight composite cryogenic tanks, conformal hydrogen storage integrated into aircraft structures, structural hydrogen tanks, higher-specific-power fuel-cell stacks, solid oxide fuel cells for cruise propulsion, superconducting electrical machines, superconducting high-voltage DC power distribution, multifunctional structural batteries, advanced silicon carbide (SiC) and gallium nitride (GaN) power electronics, digital twin-enabled aircraft energy management, health-aware artificial intelligence control, and integrated aero-propulsion-energy co-design methodologies collectively represent promising research directions. However, these technologies differ considerably in terms of technology readiness, implementation complexity, certification requirements, and expected impact on aircraft performance. Future review studies would therefore benefit from evaluating these emerging technologies according to both their maturity and their anticipated contributions toward reducing propulsion system weight, improving power density, enhancing aircraft efficiency, and enabling practical hydrogen-electric aviation.

7.4 Reliability and Certification Issues

Fuel cells powered by hydrogen provide propulsion with different failure modes (e.g., cryogenic hydrogen leaks, electric shorts, thermal runaway, etc.), which are considered in the current safety analysis [6], [87]. Gap analysis of current regulatory standards indicates new or incomplete regulatory requirements for hydrogen-related hazards, hydrogen/chip storage systems, and fire/explosion hazard and occupant survivability for novel and not yet fully developed configurations, such as eVTOL [6], [104], [105], [106], [107]. Reliable prediction methods for redundancy in electric motors (e.g., multiplex electric motors) are needed to achieve the more demanding airworthiness targets [87], [105], [107].

7.5 Intelligent and Autonomous Power Management

Deep reinforcement learning, hybrid learning, and intelligent BMS for EMS have been proposed to improve power split, minimize fuel consumption, and maximize the lifetime of hybrid components for hybrid-electric aircraft [92], [93], [108], [109]. Machine-learning-based state estimation and control methodologies can further improve the safety and performance of these aircraft [93], [108], [109]. But data and model availability, computational complexity, and explainability, and the certification of AI algorithms remain challenging for critical control and safety functions. Currently, the scalability of hydrogen fuel cell–electric aviation is limited by storage safety and performance (mass and power density), fuel cell system reliability, and intelligent and certifiable control; advancements in materials, system co-design, safety assessment, and AI-driven system management jointly offer a pathway forward towards scalable fuel cell–powered aircraft and eVTOLs.

Figure 4 (Appendix) describes the design parameters affecting aircraft performance. Hydrogen storage is what gives an aircraft usable fuel capacity, which is also determined by the tank mass and volume. Fuel cells provide sustained electrical power, while the battery or supercapacitor provides peak power. Power electronics control conversion losses, the installed mass, and fault protection. Thermal management provides a range of low to high-temperature operating conditions, as well as weight and drag associated with powering these systems. The aircraft structure and aerodynamics determine how these systems are packaged and how much power is needed. Phase-specific requirements determine the flight and expected mission, while certification requirements define the integration and response to failures. With a fixed mission and maximum take-off mass, a larger battery may increase hover but decrease the mass available for payload or fuel. A larger cooling system can deliver more power from a continuous fuel cell but at the cost of mass and drag. As a result, improving just one component metric might improve the aircraft in the long run, but not help the whole installation

7.6 Technology Maturity Assessment and Research Roadmap

Several means to improve the performance of hydrogen-electric aircraft have been proposed. They vary greatly in terms of technology readiness, complexity, certification, and performance impact. A survey of these technologies provides insight into the maturity of ongoing work and the priorities for future aircraft systems research. Table 2 (Appendix) shows the maturity ratings of qualitative components that have had the broadest range of validations for their particular aviation application, starting from conceptual design or simulation to laboratory testing, ground-based testing, and flight demonstration. The expected aircraft-level impacts on specific outcomes

were examined, such as installed mass, mission hydrogen consumption, payload, or reliability. For example, Menzi et al. [20] show high converter-specific power in laboratory tests, and the installed mass benefit depends on the aircraft's cooling and protection requirements. Ng et al. [3] demonstrated hybrid power sharing on a test bench, while the payload benefit is measured based on conceptual aircraft size. These limitations limit the range of component and subsystem performance to the level. As summarized in Table 2 (Appendix), SiC and GaN-based wide-bandgap power electronics, as well as high-voltage DC electrical distribution, appear to be the most mature enabling technologies that will form the core of the next generation of hybrid electric aircraft. Proton exchange membrane fuel cells and advanced, optimization-based energy management strategies are similarly well-matured for the near-term demonstrator and regional aircraft applications. In contrast, superconducting electrical machines, structural hydrogen storage, and structural batteries have the potential to revolutionize the aircraft environment by enabling transformational decreases in the weight of the propulsion system and increased power density/higher energy content; but these technologies are still at very low technology readiness levels and require significant materials, cryogenics, aircraft certification, and manufacturing breakthroughs. Future research efforts should focus on the system synergy of lightweight structures, advanced propulsion, and smart energy management and aircraft systems integration.

7.7 Future Outlook and Research Directions

Transitioning from research and development for improved components to integrated systems engineering at the aircraft level will be key for the future development of hydrogen-electric aircraft. Near-term research development and demonstration should focus on fuel cell-specific power and durability, hydrogen storage mass and volume reduction, thermal management, and power electronics and electrical distribution systems that are lightweight, highly efficient, and highly reliable. Advanced MPC, ECMS, and other computationally efficient energy management strategies for mission-aware and real-time power allocation must be developed.

In the medium term, investigation into lightweight and conformal hydrogen storage, degradation- and health-aware energy management, AI-assisted predictive control, and multidisciplinary optimization of the propulsion, electrical, thermal, structural, and aerodynamic systems are warranted. Focus should be placed on profoundly minimizing propulsion-system contribution to the aircraft empty-weight fraction while still enabling adequate payload, range, endurance, safety, and reliability. Certification-oriented design and fault-tolerant architectures should be embraced earlier in the process rather than later in the process after the technology has been developed.

In the longer term, emerging technologies such as superconducting electric machines and systems, multifunctional energy storage structures, next-generation hydrogen-based airframes, and integrated aero-propulsion-energy systems could provide breakthrough enhancements in the power density and weight reduction of aircraft systems. The future path of the research should consider a larger scope of maximizing the holistic energy system of the airplane, particularly for weight, payload, range, power density, efficiency, heat rejection, reliability, safety, and certification.

8 Conclusion

Fuel cell-powered hybrid electric aircraft and eVTOL aircraft have the potential to contribute to greener aviation. This paper conducted a comprehensive review of the predominant hybrid electric propulsion topologies, power architectures, power electronic devices used in aerospace applications, and energy management strategies for fuel cell-powered aircraft. The significance of the intelligent Energy Management System (EMS), high-voltage DC power architecture, bidirectional power electronic converters, and wide-bandgap devices to enhance the performance metrics in terms of efficiency, power density, operational flexibility, and system reliability was discussed. Various challenges related to hydrogen storage, thermal management, safety, aging, certification, and real-time control were also reviewed and addressed. Although there has been significant progress in hybrid-electric aircraft, research gaps remain in energy/thermal management, coordination of multiple fuel cell stacks, fault-tolerant onboard power architecture, and intelligent control systems that address certification requirements. Future research directions should focus on high-power-density, efficient aerospace power electronics; innovative, intelligent energy management system techniques; hydrogen storage technologies; and aircraft electrical architectures suitable for next-generation green aviation. These research areas will be pursued through a coordinated, accelerated research agenda that will contribute to the rapid development and commercialization of fuel cell-based hybrid-electric aircraft and eVTOLs.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

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APPENDIX

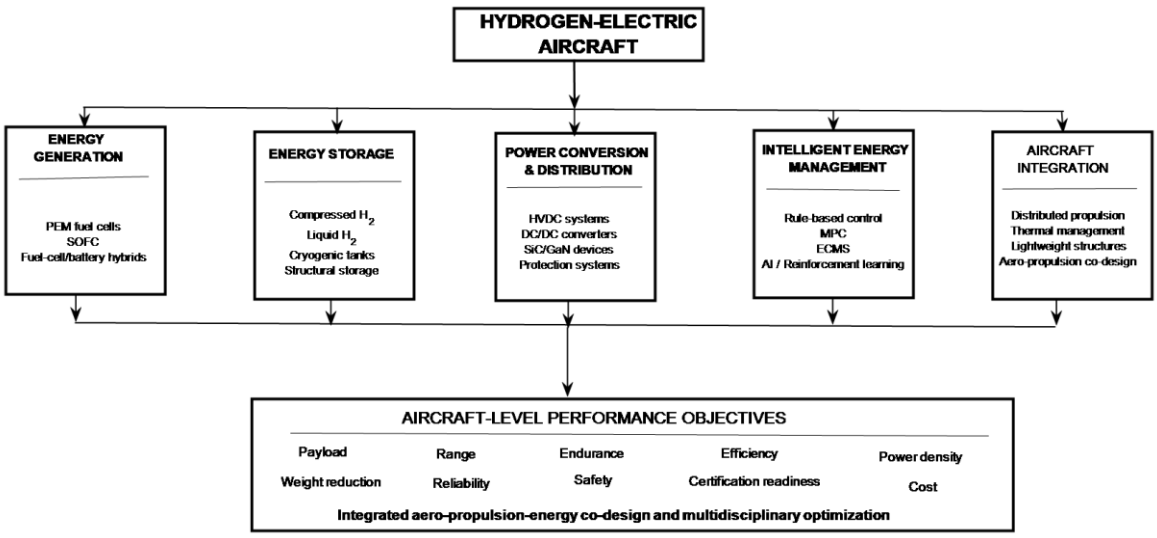

Fig. 1: Systems-Oriented Taxonomy of Hydrogen-Electric Aircraft Technologies
Source: created by the authors.

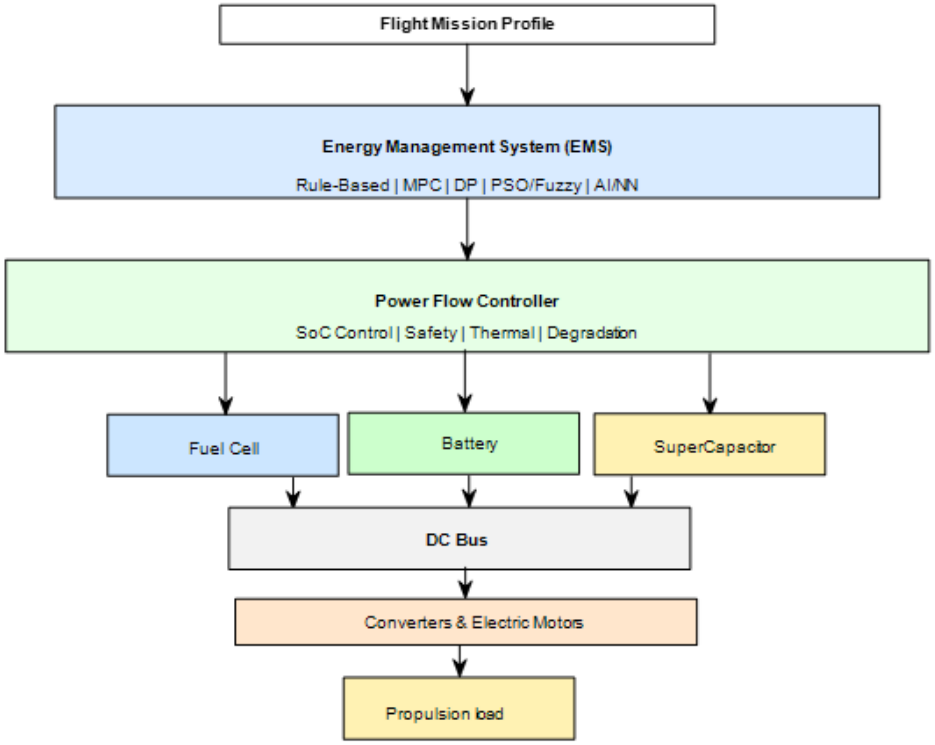

Fig. 2: Conceptual control hierarchy for fuel-cell–battery electric propulsion with optional supercapacitor buffering. The arrows in the upper part trace the progression from the flight mission profile through supervisory power allocation to source control. The arrows in the lower part trace electrical power from the sources through the DC bus and propulsion drive to the propulsion load
Source: created by the authors

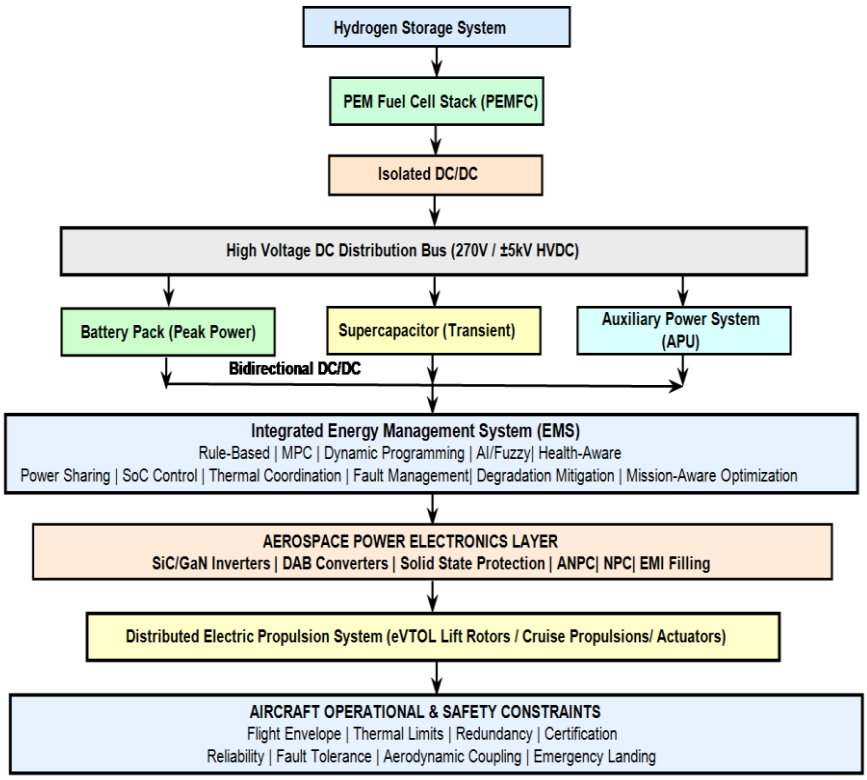

Fig. 3: Electrical and control architecture for a fuel-cell–battery eVTOL aircraft. Hydrogen powers the fuel-cell stack, and electrical output is delivered to the DC bus via a converter. Bidirectional storage interfaces store temporary loads, and separate bus branches provide propulsion and auxiliary loads. The EMS communicates commands and information with the electrical subsystems. Thermal, redundancy, and emergency conditions determine the design. The bus voltages shown are examples
Source: created by the authors

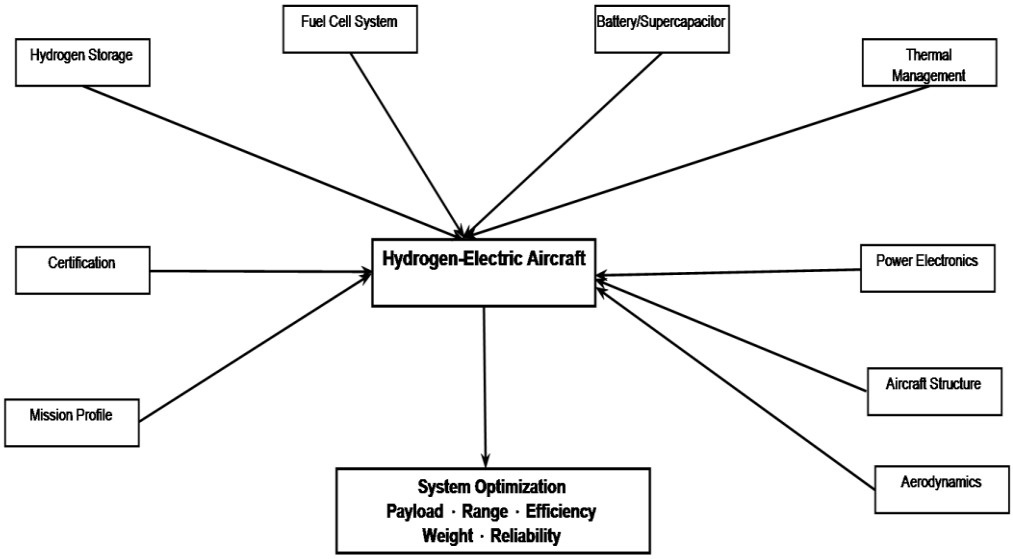

Fig. 4: Conceptual map of design factors for hydrogen-electric aircraft. The inbound arrows represent design influences and constraints from energy storage, fuel-cell size, power electronics, thermal management, airframe integration, mission requirements, and certification. The outbound arrows represent the aircraft outcomes to be assessed, including payload, range, efficiency, mass, and reliability.
Source: created by the authors.

Table 1. Concise Comparison of Key Hybrid Architectures

S/N	Architecture Type	Main Power Path & Role of Fuel Cell	Typical Applications/ Pros & Cons	Citations
1	Series hybrid (FC or engine–generator)	All propulsive power electric; FC/gen feeds DC/AC buses	High layout flexibility, supports distributed propulsion; heavier electrical system; well-suited to small/regional FC aircraft	[21], [22], [25], [26]
2	Parallel hybrid (FC/engine + EM on shaft)	Mechanical + electrical torque on same shaft; FC often primary or assist	Lower MTOM and mission energy vs series; good for retrofits and light aircraft; more limited propulsion integration freedom	[7], [26], [27], [28], [29], [30]
3	Turboelectric (engine-driven generators)	Turbines → generators → electric fans/props; FC may supplement or power subsystems	Enables BLI and distributed propulsion; promising for regional/narrow-body; relies on advanced high-power-density machines and cooling	[21], [23], [26], [31]
4	Fuel-cell electric (with battery buffer)	FC provides most energy; batteries/SCs handle peaks	No direct CO_2 from fuel-cell operation. Lifecycle emissions depend on the hydrogen supply pathway; best for GA/commuter; volume/mass of H_2 and FC stack critical	[4], [25], [30], [32], [33], [34]
5	eVTOL all-electric / hybrid	Multiple distributed motors; battery-only or battery + FC/turbogenerator	High redundancy and control; battery-limited range; FC hybrids proposed for long-endurance eVTOLs	[1], [7], [21], [22]

Source: created by the authors.

Table 2. Technology Maturity and Expected Impact of Key Hydrogen-Electric Aircraft Technologies

Technology	Qualitative maturity*	Expected aircraft impact	Principal bottleneck	Supporting references
Rule-based EMS	High	Moderate–High	Limited optimality and adaptability	[8], [13], [18], [47], [48], [51]
MPC-based EMS	Medium–High	High	Computational complexity and model fidelity	[49], [51], [54], [55], [57]
ECMS/fuzzy-ECMS	Medium–High	High	Calibration and adaptability to changing mission conditions	[8], [17], [18], [50]
AI/learning-based EMS	Emerging	High	Explainability, computation, data availability and certification	[108], [109]
PEM fuel-cell propulsion	Emerging–Medium	Very High	Specific power, degradation and thermal management	[5], [32], [33], [40], [87], [91], [92]
Hydrogen storage systems	Emerging–Medium	Very High	Mass, volume, safety, insulation and integration	[5], [32], [86], [89]
SiC/GaN power electronics	Medium–High	High	Reliability, protection and thermal management	[20], [76], [78], [80], [83], [84], [85]
HVDC electrical distribution	Medium–High	High	Insulation, fault protection and certification	[74], [75], [76], [77], [79], [80]
Distributed electric propulsion	Medium–High	High	Propulsion-system weight, cooling and integration	[21], [22], [25], [26], [30], [31]
Bidirectional DC/DC converters	Medium–High	High	Efficiency, EMI, thermal management and reliability	[20], [79], [80], [81]
Solid-state/WBG protection	Emerging–Medium	High	High-voltage faults, DC arcs and reliability	[74], [76], [77], [83], [84], [85]
Advanced thermal management	Emerging–Medium	Very High	Heat rejection, system mass and integration	[2], [20], [32], [40], [78], [80], [82]

Source: created by the authors.

* Qualitative maturity is the authors' synthesis of the technologies and evidence reviewed in this paper; it is not intended to represent a formal numerical Technology Readiness Level (TRL) unless explicitly reported by the cited source.