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Exploring Next-Generation Electrification Solutions for Aeronautical Engines

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List

1. Introduction

As the aviation industry develops and global pressure for carbon reduction and climate change intensifies, conventional commercial aircraft are increasingly constrained by stricter limits on fuel consumption, noise, and emissions. According to the International Energy Agency, in 2024 the global aviation sector emitted about 1 billion tons (≈1 Gt) of CO_2, accounting for 2.6% of the world total [1]。 With the large-scale adoption of new energy technologies such as electric vehicles, if no changes are made, the aviation industry, one of the hardest to abate sectors could see its share of global CO_2 emissions rise to 11% in the future [2].

To mitigate the environmental impact of the continuing growth in air transport, and according to the targets of the International Civil Aviation Organization (ICAO) and the International Air Transport Association (IATA), the aviation industry plans to achieve net-zero carbon emissions by 2050. Countries are also actively promoting related emission reduction plans, such as the European Commission and the Advisory Council for Aviation Research and Innovation in Europe's (ACARE) "*Flightpath 2050: Europe's Vision for Aviation—Report of the High Level Group on Aviation Research*", the United Kingdom's Jet Zero Council (JZC) "*Jet Zero plan*" and the National Aeronautics and Space Administration (NASA) N+3 program "*Propulsion and power for 21st century aviation*". All of which have set very challenging targets. As a new technology for achieving these targets, aviation electrification is becoming a key trend in the aerospace field and is receiving wide attention, and electric aircraft propulsion systems are the key to the aviation industry's electrification.

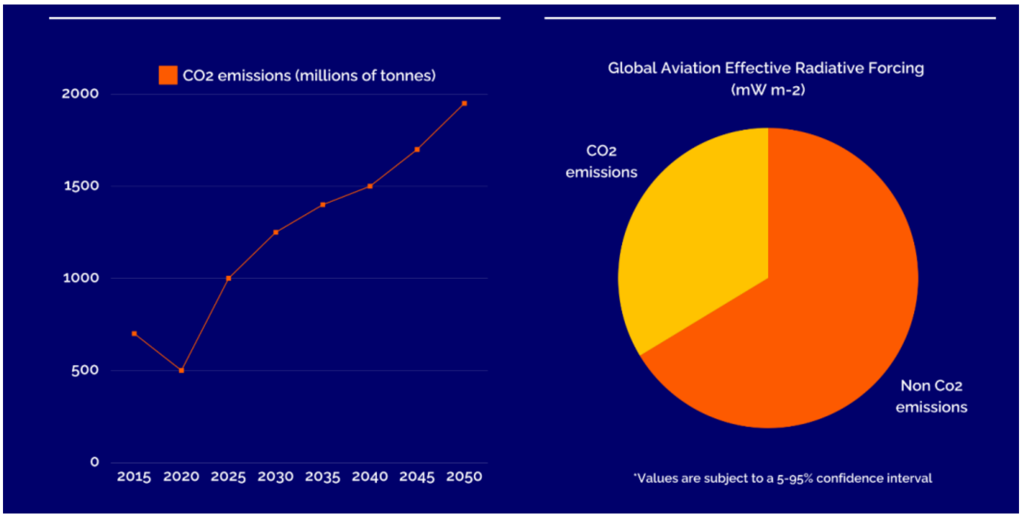

Figure 1.1: Projected global aviation CO_2 emissions and the relative contributions of CO_2 and non-CO_2 emissions to effective radiative forcing (Source:ZeroAvia)

Against the backdrop of "Net-Zero Emissions" and the transition to sustainable aviation, electric aircraft propulsion systems are regarded as the core for achieving cleaner, quieter, and more efficient flight. Unlike conventional fuel powered aero engines, whose thermal efficiency is constrained by combustion and material temperature limits, electric propulsion motors offer notable advantages: high energy conversion efficiency, no local emissions, and low noise. As early as the 20th century, related research had already been undertaken in multiple countries.

Aircraft electrification is mainly divided into two categories. The first is the electrification of non-propulsive systems: engineers replace traditional hydraulic, pneumatic, and mechanical systems with electrical ones, forming the so-called “More Electric Aircraft” (MEA). This technology has been applied on commercial models such as the A380 and Boeing 787, where expanding the electrical architecture improves reliability and maintainability. However, since the propulsion system remains primarily fuel powered, the gains in overall energy efficiency and carbon emissions are limited.

The second category is the electrification of propulsion systems, i.e. Electric-Propulsion Aircraft (EPA). EPAs use electrochemical energy sources such as batteries and fuel cells to supply all or most of the propulsion power, with electric motors driving propellers or fans. Compared with conventional mechanical transmission, electric motors can significantly improve energy conversion efficiency and help reduce carbon emissions and noise. Along this path, three main technical routes have gradually formed: Hybrid Electric Aircraft (HEA), Turboelectric Aircraft (TEA), and All-Electric Aircraft (AEA). Research shows that these electrified solutions can enhance flight performance and operational efficiency while lowering noise and energy losses.

With the accelerating iteration of electric propulsion aero engine technologies, research on high performance electric propulsion aero engines has focused on how to increase motor power density. Power density is related to multiple factors such as machine structure, manufacturing processes, and materials, and the approaches to improving it are diverse. However, systematic reviews of the key technologies for electric propulsion aero engines remain relatively scarce. Therefore, based on the latest research progress from multiple countries, this thesis will focus on the electrification of propulsion systems and will review and assess the key technologies of electric propulsion aero engines for electric aircraft, providing technical references for the future development of electric propulsion aero engines.

2. Current Research Status of Electric Propulsion Aero Engines

Over the past two decades, electric propulsion motors have accelerated from prototype verification toward engineering application: the Pipistrel E-811 became the world's first electric engine to obtain an engine type certificate from the European Aviation Safety Agency (EASA). Its rated system voltage is 345 V DC with a maximum power of 57.6 kW, and it has been put into operation on the Velis Electro trainer (maximum takeoff weight, MTOW, 600 kg) [3], marking that the airworthiness feasibility of small fixed wing aircraft has been validated.

Figure 2.1: Velis Electro trainer and Pipistrel E-811 electric engine

(Source: Pipistrel-aircraft)

In the high-power density direction, Siemens' Extra 330LE demonstrator has already completed public flight and record demonstrations. The onboard SP260D, weighing only 50 kg, delivers about 260 kW of continuous power, meaning that the birth of four seat and larger hybrid electric aircraft will become a reality [4].

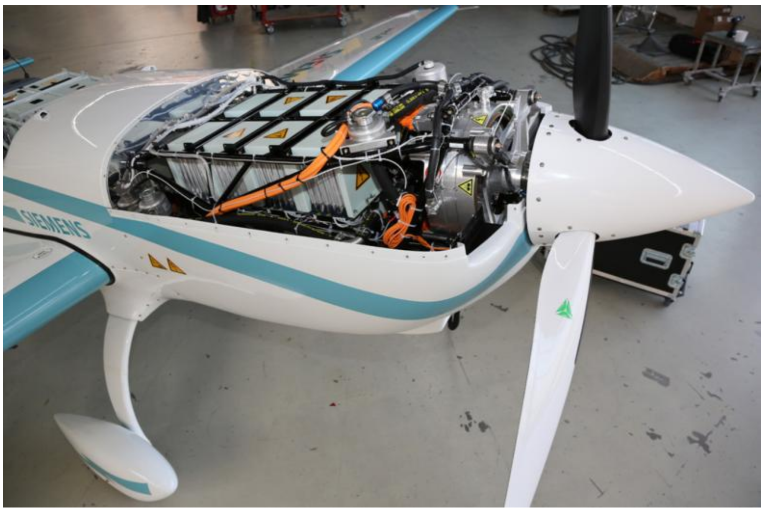

Figure 2.2: Siemens SPD260D electric aircraft engine

(Source:SIEMENS)

Airbus UpNext, an Airbus subsidiary dedicated to future flight technologies, has partnered with Toshiba to jointly develop superconducting electric motors for future hydrogen powered aircraft, with the ultimate goal of a 2 MW class superconducting propulsion system[5].GE Aerospace is collaborating with NASA to develop a hybrid electric demonstrator engine that embeds an electric motor/generator into a high bypass commercial turbofan to supplement power during different phases of operation. This includes modifying the Passport engine to incorporate hybrid electric components and testing it through NASA's Hybrid Thermally Efficient Core (HyTEC) program [6].

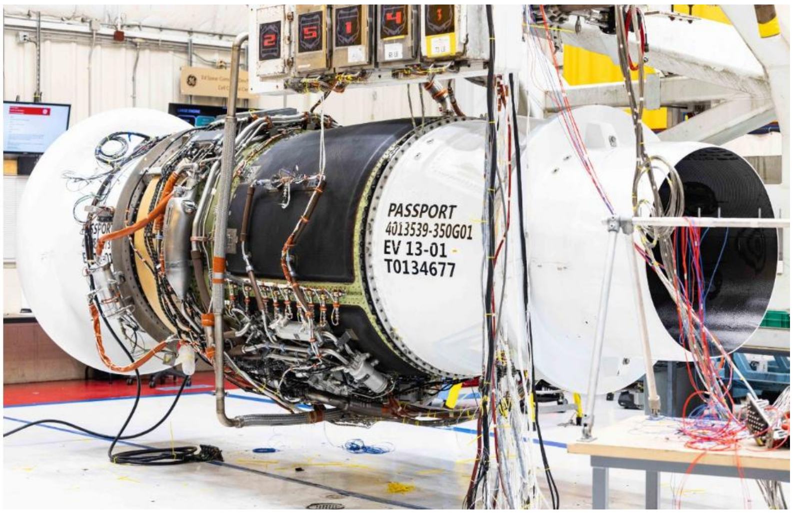

Figure 2.3: Passport engine under testing

(Source:Geaerospace)

In November 2021, UK based Evolito set a new all-electric flight world record of 345.4 miles per hour. The aircraft used a 400 kW electric propulsion system, with three motors each delivering a peak torque of 790 N·m and a peak power of 200 kW. Its axial flux motor, derived from YASA motor technology, has already received UK CAA Design Organization Approval (DOA). Featuring a yoke less design and a segmented magnet architecture, the D1700 model achieves a peak specific torque of ~56 N·m/kg, is tailored for high torque, low speed direct drive applications, and has undergone more than 1,000 hours of flight testing [7].

Safran's world first electric motor for advanced air mobility has received certification from the European Union Aviation Safety Agency (EASA). Its ENGINeUS motor is a self-contained, modular, and scalable propulsion unit that can deliver up to 1 megawatt of power, making it well suited for commuter aircraft operating at around 8,000 meters [8].

Diamond Aircraft is coordinating a pathbreaking Austrian Research Promotion Agency (FFG) funded project to advance understanding of gaseous hydrogen's potential as a fuel source for hybrid powertrains in General Aviation. The 'H2EDT' (Hydrogen based Twin engine Electrification and Digitalization Testbed) project consortium - which unites researchers from FH JOANNEUM (Institute of Aviation and Electronic Engineering), TU Graz (ITnA), HyCentA and IESTA - is designing an experimental, hybrid testbed to explore the challenges hydrogen poses as a fuel for aviation [9].

In January 2023, a 19 seat Dornier 228 equipped with the ZA600 completed its first flight in the United Kingdom, verifying the feasibility of a hydrogen fuel cell plus electric motor powertrain. The system targets 10-20 seat commuter aircraft, with a typical range goal of about 300 nautical miles, uses gaseous hydrogen as fuel, and provides efficient, clean, and quiet propulsion to achieve zero carbon emissions.

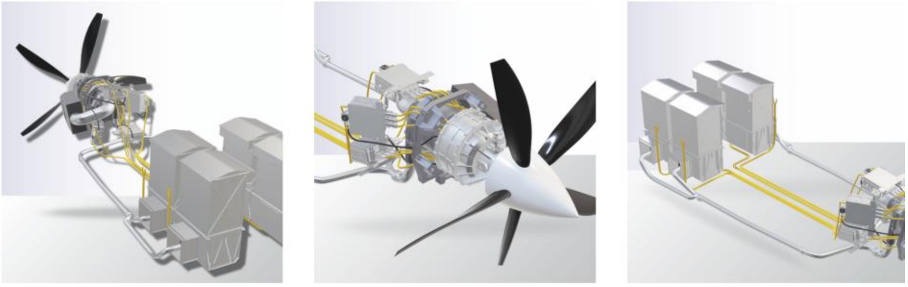

Figure 2.4: ZA600 engine illustration

(Source: ZeroAvia)

Its other engine, the ZA2000, is a 2-5 MW modular hydrogen electric propulsion system aimed at 40-80 seats turboprop regional airliners, with a target range of up to about 700 nautical miles. It is currently being developed in collaboration with Alaska Airlines, which is converting a Q400 into a test platform to advance airworthiness and engineering validation [10].

Figure 2.5: ZA2000 engine illustration

(Source: ZeroAvia)

NASA's STARC-ABL (Single Aisle Turboelectric Aircraft with Aft Boundary Layer Propulsion) retains a conventional turbine and fuselage configuration while adopting a distinctive electrically driven aft propulsor. Power for the propulsor is supplied by two under wing turbofan engines to maximize aerodynamic benefit during flight. The design cruise Mach number is M≈0.785, and with the same range, speed, and airport infrastructure as existing regional jets it can reduce fuel consumption by 7%-12%. Entry into commercial fleets is targeted around 2035 [11].

Sweden's Heart Aerospace is developing the ES-30 hybrid electric regional aircraft, which combines turboprop engines with electric motors. It offers a 200 km all-electric range and an 800 km hybrid electric range (25 passengers), supports fast charging in about 30 minutes, and aims to complete type certification around 2029 [12].

From the above programs, it can be seen that electric propulsion aero engine technology is tending toward maturity. The successful flights of small, manned all-electric aircraft have also accumulated valuable experience for the future development of medium and large-scale electric aircraft, show good prospects and application potential. Next, we will explore the main research routes currently under way for electric propulsion aero engines.

3. Research Approaches for Electric Propulsion Aero Engines

First is hybrid electric, with aviation fuel and batteries as energy sources. The energy transfer can be configured in in series (the gas turbine drives a generator that supplies power, and the motor alone drives the fan) or parallel (the gas turbine and the motor jointly drive the fan). Its main feature is electric assist during takeoff and climb, with fuel as the primary source during cruise, thereby achieving a compromise between range and emissions reduction.

Next is turboelectric, where a gas turbine drives a generator as the energy source. The power flow follows an electrical chain of “turbine → generator → power distribution → multiple motors → fan.” Its hallmark is that propulsion power is distributed electrically along the wings or fuselage, offering flexible layouts but imposing higher demands on high power density motors, power transmission, and thermal management.

Finally, there is all-electric, which relies solely on batteries. The power is transmitted by having the battery drive a motor that directly drives a fan or propeller. It features a simple architecture, zero emissions, and easy maintenance, but is constrained by the current specific energy of batteries, thus, its primary applications are short range general aviation and urban air mobility.

Building on this, a hydrogen electric hybrid propulsion pathway has emerged. This approach uses hydrogen as the primary energy source and can follow two routes: Using fuel cells, which convert hydrogen and oxygen into electricity via electrochemical reactions, with water as the only by product, or using internal combustion engines, where hydrogen is burned and works in coordination with the electric drive. In either case, hydrogen as a fuel does not produce CO_2 itself, however, under high temperature combustion conditions it may generate nitrogen oxides (NO_x). Compared with purely electric systems, hydrogen-based solutions offer higher system level energy density and thus can potentially extend the range and endurance of zero carbon aircraft. They also face challenges such as bulky and heavy fuel cell stacks, hydrogen storage, and safety issues arising from hydrogen’s flammability and explosion risks [13].

Table 3.1. Classification of Electrified Aircraft Propulsion Architectures

Type	Energy Source	Power-Transfer Method	Representative Scheme
Hybrid electric	Aviation fuel + batteries	Parallel or series	NASA STARC-ABL
Turboelectric	Gas turbine driving a generator	Electric motors on the fans	Heart Aerospace ES-30
All-electric	Batteries	Electric motor	Pipistrel Velis Electro
Hydrogen fuel cell	Hydrogen	Electric motor	ZeroAvia ZA600

3.1 Hybrid Electric Propulsion

Hybrid propulsion provides thrust through the coordinated operation of a heat engine (either a gas turbine or a reciprocating/diesel engine), a generator, and an electric motor. From the perspective of energy pathways, hybrid architecture can be categorized as follows: (1) series systems, in which the heat engine drives only the generator and propulsion is provided entirely by the electric motor. This configuration facilitates distributed electric propulsion and enables the heat engine to operate at a fixed, high efficiency operating point, however, the additional energy conversion stage incurs penalties in both mass and overall efficiency. (2) parallel systems, in which the heat engine and the electric motor share a common mechanical drivetrain. Such architectures are retrofit friendly but mechanically more complex, requiring clutches and/or reduction gearing as well as coordinated power coupling management. (3) series parallel (power-split) systems, in which a power coupler dynamically allocates mechanical and electrical power across different flight phases [14].

Unlike "all-electric" propulsion, hybrid propulsion involves continuous energy contribution from the heat engine. The European Union Aviation Safety Agency (EASA) collectively refers to these architectures as Electric/Hybrid Propulsion Systems (EHPS) and has issued the dedicated Special Condition SC E-19. SC E-19 adopts an objective-based compliance philosophy and addresses system architecture, electric machines and controllers, electrical power distribution and monitoring, energy storage, and associated safety requirements. In recent years, EASA has continued to introduce and update supporting Means of Compliance (MOC) to accommodate the diversity of EHPS topologies and integration approaches [15].

Series Hybrid

In a series hybrid propulsion system, the heat engine does not mechanically drive the fan/propeller, instead, it drives a generator. The generator output is conditioned via a rectifier bridge and supplied to the DC bus, while the battery is also connected and can supply the same DC bus. Consequently, the DC bus is jointly supported by the engine generator set and the battery. Power from the DC bus is then converted by an inverter to drive the electric motor, which is mounted coaxially with the propeller and provides the propulsive torque. This architecture is generally well suited to low to medium-speed operating regimes. A supervisory controller (electronic control unit, ECU) regulates the engine to operate within its high efficiency region, any surplus electrical power generated is stored in the battery [16].

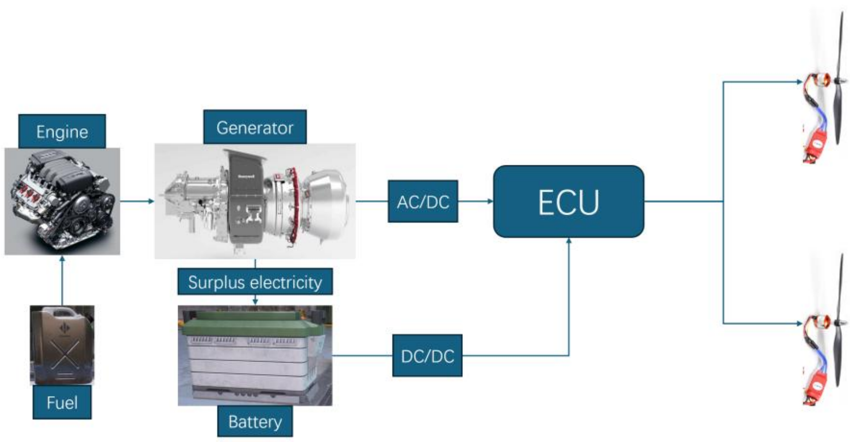

Figure 3.1: Schematic architecture of a series hybrid electric propulsion system

The representative program is VoltAero Cassio 330. Its production configuration adopts a series hybrid architecture: two Safran ENGINeUS electric motors installed in the aft fuselage provide propulsion, while the onboard internal combustion engine located within the fuselage acts solely as a range extender to recharge the aircraft batteries. During taxi, takeoff, and initial climb, the aircraft can operate in a fully electric propulsion mode, whereas during cruise the fuel powered engine replenishes the battery state of charge. The system incorporates dual motor redundancy, notably, each motor is designed with two independently powered stator winding channels, enabling independent operation. The aircraft features a five-seat cabin layout. The production configuration was unveiled at the Paris Air Show in 2025, and the program secured an order from Malaysia's HM Aerospace for 15 firm aircraft plus 15 options [17].

Figure 3.2: VoltAero Cassio 330 concept art

(Source: VoltAero)

Parallel Hybrid

In a parallel hybrid propulsion system, the heat engine and the electric machine constitute two independent power subsystems. Depending on the operating condition and instantaneous power demand, the supervisory controller can command the engine and the electric machine to drive the propeller either independently or in combination. The electric machine may operate as a motor to provide propulsive torque, or as a generator to recharge the battery. Owing to its comparatively high drivetrain efficiency, this architecture is well suited to low and medium speed regimes requiring rapid acceleration, as well as to high-speed operating conditions. In typical parallel hybrid powertrain topologies, the shaft lines of the gasoline/diesel engine, aero engine, and electric machine can be mechanically integrated to provide additive propulsive torque via co-axial coupling, a torque coupler (e.g., a two input/one output parallel gear shaft train), or a planetary reduction gearbox, enabling torque coupling and superposition to drive the propeller [14] [16] .

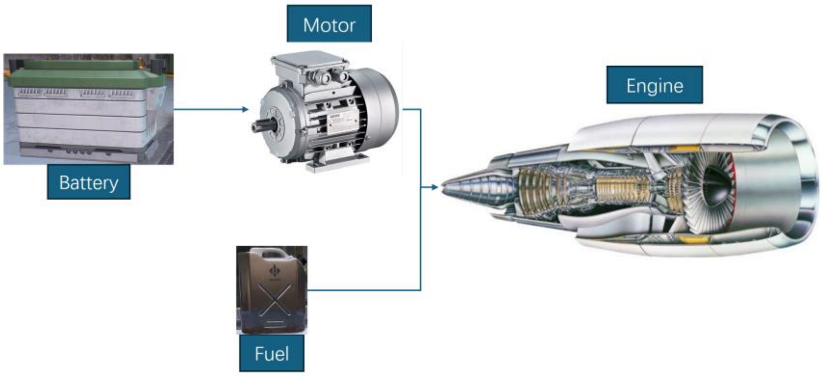

Figure 3.3: Schematic architecture of a parallel hybrid electric propulsion system

A representative program is Ampaire's "Eco Caravan", a hybrid electric retrofit based on the Cessna 208B Grand Caravan platform. The aircraft integrates a combustion powerplant and an electric machine within the same propulsive drivetrain, enabling parallel hybrid operation across the mission profile. The lithium-ion battery modules supplied by Electric Power Systems (EPS) are reported to provide an energy density of 205 Wh/kg and to be designed for >2,000 fast charge cycles under typical operating conditions. The project has completed multiple cross regional demonstrations and long-term test flights and is progressing towards certification and commercial operation via the STC (Special Treatment Capacity) conversion path. It is expected to save 50%-70% on fuel consumption and up to 40% on operating costs [18].

Figure 3.4: Eco Caravan

(Source: Ampaire)

Series-Parallel Hybrid

The series-parallel architecture combines key advantages of both series and parallel layouts, with its defining feature being mode switching across flight phases. In a typical configuration, part of the fan/propeller system is directly driven by a gas turbine through a mechanical transmission, while the remaining propulsors are electrically driven: an inverter draws power from a high voltage DC bus to supply one or more electric motors. In addition, the heat engine supplies electrical power to the DC bus via a generator and operates in parallel with the battery, enabling power splitting and unified energy management on the bus side [14].

Compared with a purely series architecture, a series-parallel system can use the electric branch to provide peak power boost during high demand segments (e.g., takeoff and climb), while relying on the mechanically driven path to deliver the dominant cruise power near an efficient operating point thereby combining electric assist with high mechanical conversion efficiency. Relative to conventional parallel architecture, it also enables the integration of additional electrically driven propulsors, which supports aeropropulsive integration concepts such as distributed propulsion and boundary layer ingestion. This capability for dynamic reconfiguration can improve efficiency over the entire mission profile and is therefore commonly regarded as a pragmatic transition solution for medium to long range aircraft applications [19].

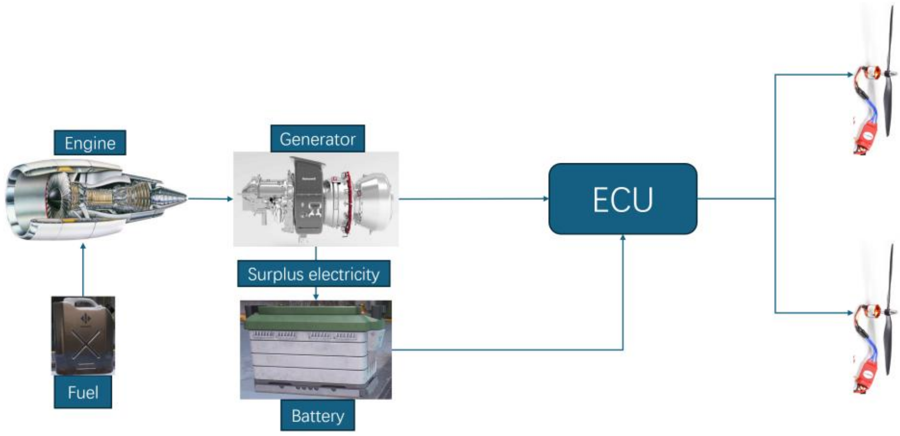

Figure 3.5: Schematic architecture of a series-parallel hybrid-electric propulsion system

A representative program is the Airbus/Daher/Safran "EcoPulse" distributed propulsion demonstrator. The aircraft is based on a modified Daher TBM 900 turboprop platform, retaining the nose mounted turboprop to mechanically and directly drive the main propeller. In parallel, six electrically driven distributed propulsors (e-Propellers/EDP) are installed along the wing leading edge, each unit is driven by a 50 kW Safran ENGINeUS™ electric motor, supplied either by the onboard battery system or by a ~100 kW auxiliary power unit (APU)/turbogenerator. Electrical power from the generator set and the high voltage battery is managed through a DC bus, resulting in a series-parallel (power-split) architecture in which "direct mechanical drive" and "electric drive" branches coexist [20].

Figure 3.6: EcoPulse

(Source: Airbus)

3.2 Turbo Electric Propulsion

A turboelectric aircraft propulsion system uses fuel as the primary energy source. A gas turbine/turboshaft engine drives a high-power generator via a shaft, converting mechanical power into electrical power. The generated electricity is then rectified and aggregated on a DC bus, from which inverters supply power on demand to multiple propulsion motors. Each motor directly drives a small diameter electric fan distributed across the wing or fuselage, forming a distributed electric propulsion (DEP) layout [21]. This arrangement enables fine grained thrust allocation and inherent redundancy and allows fan speeds to be scheduled independently across flight phases to improve aerodynamic efficiency and reduce noise. In this architecture, the main energy pathway is provided entirely by the fuel turbine generator chain, during flight, batteries are generally not intended to serve as the dominant energy source. Instead, onboard energy storage is typically used for ground start/stop functions, transient power buffering, and emergency backup power, rather than for sustaining mission range. With appropriate power electronics and an energy management system, the aircraft can dynamically optimize power allocation during takeoff, climb, cruise, and approach, thereby improving propulsive efficiency and system fault tolerance while preserving operational range and the practical advantages of fuel-based energy replenishment [22].

Partial turboelectric propulsion

In a partial turboelectric configuration, electrically driven propulsors provide only a portion of the total propulsive power, while the remainder is delivered by conventionally fueled turbofan engines.

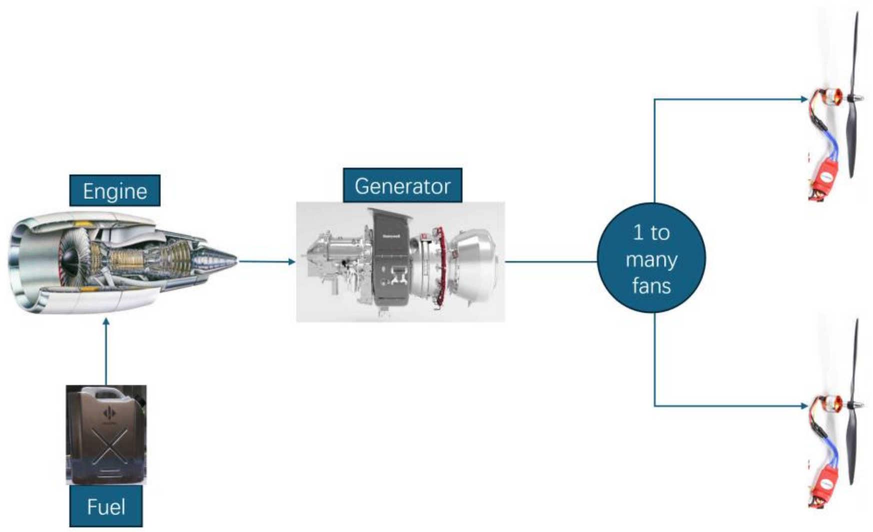

Figure 3.7: Schematic architecture of a partial turboelectric propulsion system

A representative example is NASA's STARC-ABL (Single-Aisle Turboelectric Aircraft with Aft Boundary Layer Propulsion) concept, targeting a ~150 passenger single aisle transport. The baseline arrangement combines two under wing turbofans with an aft, boundary layer ingesting (BLI) electrically driven fan: each turbofan retains its direct propulsive contribution while also extracting shaft power (via fan shaft mounted generators) to supply electrical power to the tailcone fan. Electrical power is distributed on the high voltage bus, and the architecture is not predicated on large capacity batteries as the primary in flight energy source. Reported assessments indicate that, the concept can achieve an approximate 7% reduction in block fuel burn for an economic mission and up to ~12% for a design mission, depending on mission definition and underlying technology assumptions [23].

Figure 3.8: NASA STARC-ABL concept image

(Source:NASA)

Fully Turboelectric System

A fully turboelectric system relies entirely on a conventional internal combustion engine to drive a generator, which in turn powers an inverter and a motor, thereby driving a fan.

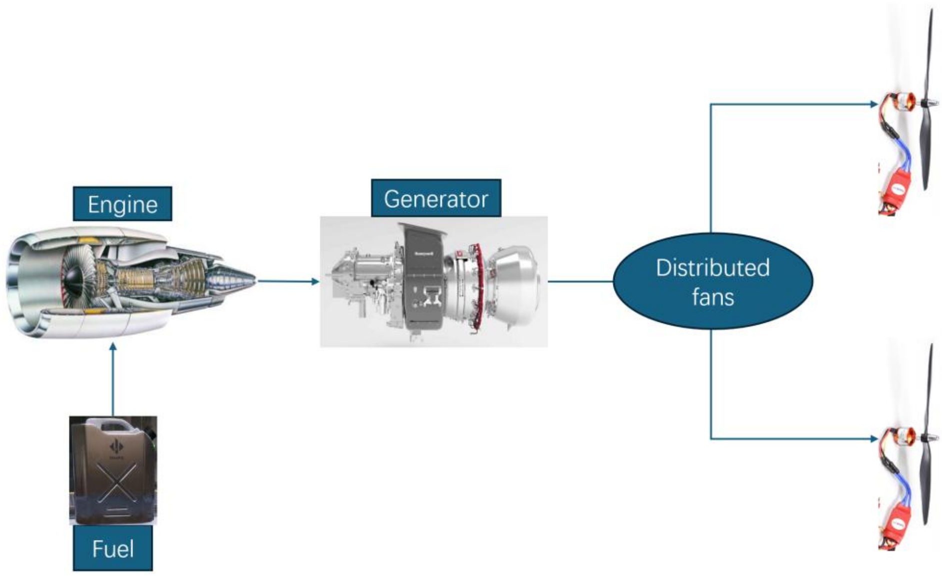

Figure 3.9: Schematic architecture of a fully turboelectric distributed propulsion system

A representative program is Electra aero's EL9 ultra short takeoff and landing (eSTOL) fixed wing aircraft. The EL9 employs a hybrid electric distributed propulsion concept in which a small turbogenerator and an onboard battery system supply electrical power to eight wing leading edge electric propulsors. The engine is not mechanically coupled to the propulsors, instead, generator output is conditioned and distributed via a high voltage DC bus to the individual propulsion motors. The turbogenerator is sized primarily for cruise power, while the battery provides additional boost power during high demand segments such as takeoff and landing. Enabled by an electrically blown flap integration, the EL9 is advertised to achieve takeoff and landing distances on the order of ~150 ft and a cruise speed of approximately ~175 kt, with a planned capability envelope of nine seats and ~330 nm class missions. The program has completed hybrid electric technology demonstrator flight tests and has also reported powered wind tunnel validation of the blown wing performance. Electra has stated a target timeline of initial test flights in 2027 and certification/entry into service around 2029 (under FAA Part 23), while reporting an order pipeline exceeding 2,000 aircraft (including pre-orders) [24].

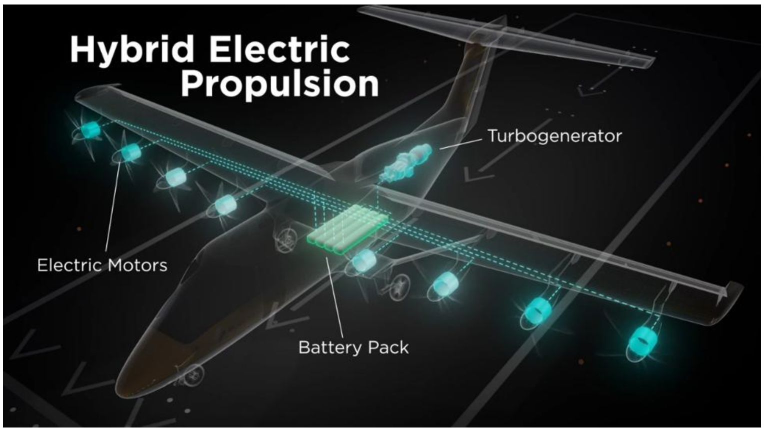

Figure 3.10: EL9 Ultra Short Hybrid-Electric Aircraft

(Source: Electra)

3.3 All-Electric Propulsion

All-electric propulsion relies on electrical energy as the sole onboard energy source during flight. Electrical power is supplied by onboard energy storage systems，currently dominated by rechargeable lithium-ion battery packs integrated with a battery management system (BMS), thermal management, and fault isolation and aggregated on a high voltage DC bus. Inverters then convert DC power into the required AC waveforms to drive distributed propulsion motors and their associated fans or propellers. A typical system consists of a high energy density battery pack, power distribution and protection (HV contactors, fusing/current limiting, insulation monitoring), the motor and its drive, thermal management (cooling for the battery, drive, and equipment cabinet), and energy and state of health monitoring. In the absence of an onboard heat engine, thrust scheduling and low-speed transient response can be more flexible, while noise and local emissions are markedly reduced. However, achievable range and climb capability remain strongly constrained by battery specific energy and thermal limits [25].

Within the airworthiness framework, all-electric propulsion also falls under EASA's Electric/Hybrid Propulsion System (EHPS) scope, as addressed by Special Condition SC E-19.

For eVTOL configurations, compliance is typically addressed in parallel with SC-VTOL and its associated Means of Compliance (MoC) (e.g., system safety, energy storage, and handling of failure conditions), ensuring consistency with aircraft level safety objectives [26].

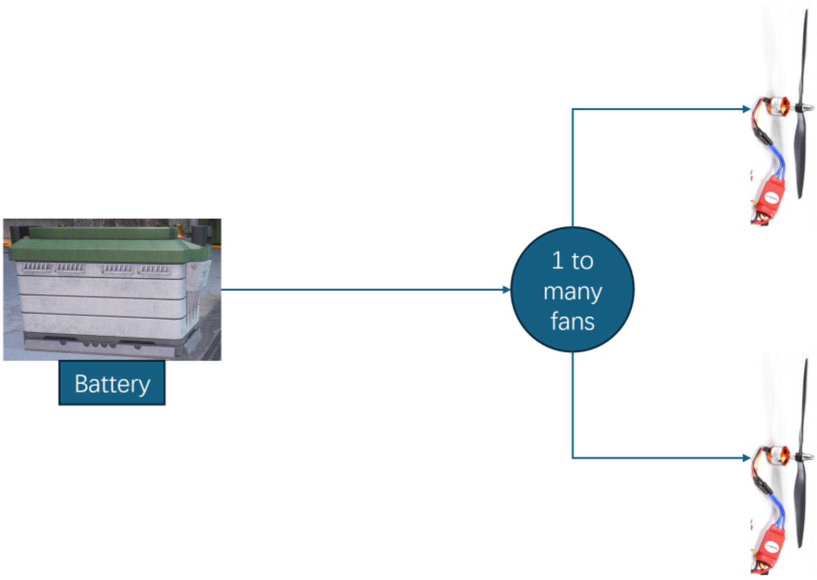

Figure 3.11: Schematic architecture of a all-electric propulsion system

A representative program is the Diamond Aircraft eDA40. Developed as an all-electric derivative of the certified DA40 platform, the eDA40 employs a fully electric propulsion chain in which a Safran ENGINeUS™ electric motor supplied via an inverter directly drives the propeller. The propulsion system is powered by a high voltage battery module provided by Electric Power Systems (EPS) and is designed to support DC fast charging to reduce turnaround time. Diamond's published preliminary figures report >1.2 h endurance, an approximate range of ~117 nm (217 km), and a payload of ~397 lb (180 kg), with an initial two seat training-oriented configuration and an optional 2-3 seat arrangement as battery capability evolves. The program completed its maiden flight on 20 July 2023 and is being advanced toward EASA/FAA CS/Part 23 certification, with positioning focused on the flight training market (i.e., an electric circuit trainer) [27].

As a representative all-electric aircraft, the eDA40 emphasizes reduced noise, zero local emissions during flight, and lower maintenance burden/operating costs relative to conventional piston trainers.

Figure 3.12: Diamond Aircraft eDA40

(Source: Diamond Aircraft)

3.4 Hydrogen Electric Hybrid

Hydrogen electric hybrid propulsion uses hydrogen as the energy carrier. Electrical power is generated steadily by a fuel cell system, most commonly a proton exchange membrane (PEM) fuel cell while a battery and/or supercapacitor provides power-oriented buffering. The nominal power chain is: fuel cell → DC bus → inverter → propulsion motors / distributed fans, with the battery supplying takeoff/climb boost and emergency power. During cruises, the fuel cell operates near a high efficiency, quasi steady operating point while maintaining the battery state of charge within a prescribed SOC window [28].

Hydrogen storage is typically realized either as compressed gaseous hydrogen (e.g., 350-700 bar composite cylinders) or as liquid hydrogen (cryogenic storage at ~20 K, requiring multi-layer insulation, purge provisions, and anti-icing/frost management). The overall system is complemented by balance of plant subsystems, including air compression and humidification, hydrogen recirculation, leak detection and ventilation, as well as water and waste heat management (often driving radiator sizing and thermal integration) [29].

The architecture can also be extended toward a parallel configuration (e.g., a hydrogen internal combustion engine or turbine mechanically coupled with an electric machine). However, current aviation concepts tend to favor a series fuel cell electric path, as it naturally supports distributed electric propulsion and enables decoupled optimization of thermal and electrical subsystems.

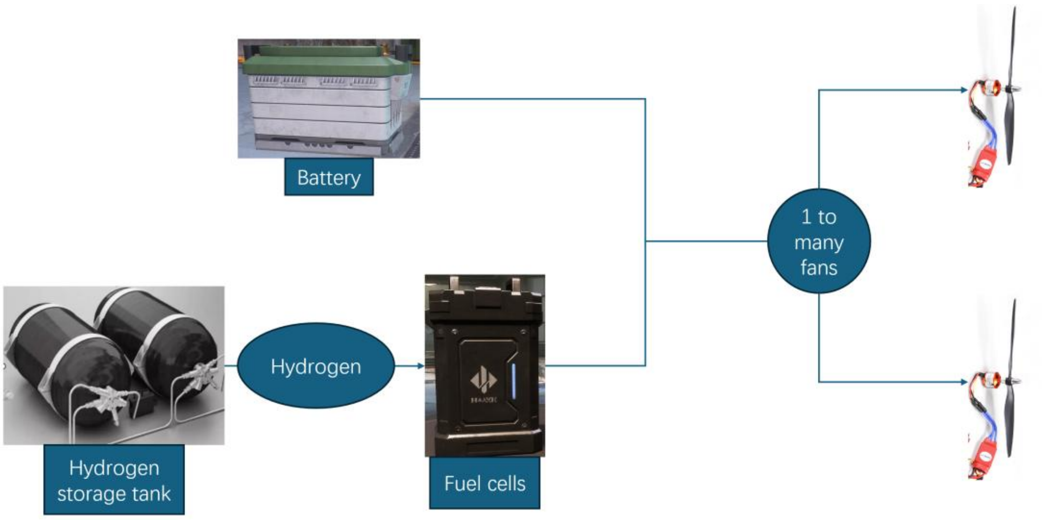

Figure 3.13: Schematic architecture of a hydrogen electric hybrid propulsion system

From an airworthiness and standards perspective, hydrogen-electric hybrid propulsion falls within the baseline scope of EASA Special Condition SC E-19 (EHPS). In support of SC E-19, EASA has also issued and consulted on multiple Means of Compliance (MoC) drafts to clarify acceptable compliance paths.

For hydrogen as an energy carrier, EASA public materials emphasize hydrogen's low volumetric energy density, which imposes significant constraints on aircraft layout and onboard storage volume compared with conventional jet fuels. Hydrogen fuel quality is commonly referenced against ISO 14687 specifications [30].

On the FAA side, the Hydrogen Fueled Aircraft Safety and Certification Roadmap highlight key considerations for liquid hydrogen systems, including purge requirements for

LH_2 lines during connection/maintenance/refueling, ground refueling operations, and crashworthiness of storage solutions. These hydrogen specific hazards and operational aspects must be integrated with EHPS system level safety objectives across the lifecycle, encompassing (at minimum) leak detection and monitoring, hazardous area classification, ventilation and inerting strategies, cryogenic/high pressure protection, and maintenance venting/defueling procedures [29].

A representative program is the H2FLY "HY4" four seat technology demonstrator, which adopts a fuel cell + lithium battery hybrid electric propulsion system. A low temperature PEM fuel cell system is operated in parallel with an approximately 21 kWh battery, through an inverter, the system drives an approximately 80 kW electric motor. Reported continuous power allocation is on the order of ~45 kW (fuel cell) + ~45 kW (battery), with a typical cruise power of about ~26 kW, a cruise speed of approximately 145 km/h, and a maximum speed of roughly ~200 km/h [31].

In September 2023, HY4 achieved what was reported as the world's first piloted, liquid hydrogen powered electric flight, demonstrating practical integration of cryogenic LH_2 storage with a fuel cell electric powertrain. Flight test reporting further indicates that switching from gaseous to liquid hydrogen increased the demonstrator's maximum range from approximately ~750 km to ~1,500 km, materially extending the feasibility envelope for regional missions. The ongoing development pathway is framed toward scaling hydrogen-electric propulsion to regional airliner classes (≈40 seat) applications [32].

Figure 3.14: HY4 liquid hydrogen electric aircraft

Source(DLR Portal)

4. Key Technologies for Electric Propulsion Aero Engines

The core of an electric aero propulsion system can be articulated in terms of four tightly coupled yet mutually constraining objectives: lightweight energy, efficient power transmission, high performance electric machines, and robust thermal management. Together, these objectives form a quantifiable four corner trade off framework. Under a prescribed mission profile and aircraft packaging envelope, higher achievable continuous power and improved range/endurance can be obtained by increasing the available specific energy and specific power at the system level, reducing conversion and distribution losses along the power chain, enhancing motor specific power and fault tolerance, and maintaining temperature rise and thermal transients within certified safety margins.

Using the simple model proposed by Martin Hepperle [33], the mission range associated with a given onboard energy storage mass can be expressed as

$$R = v_{\infty} * \frac{m_{battery} * E^{*}}{P_{battery}} \tag{4.1}$$

After further derivation, the final expression becomes:

$$R = E^{*} * \eta_{total} * \frac{1}{g} * \frac{L}{D} * \frac{m_{battery}}{m} \tag{4.2}$$

R = range [m]

v_{∞} = flight speed [m/s]

E^{*} = mass specific energy content [Wh/kg]

$P_{battery}$ = electric power provided by battery [W]

η_{total} = total efficiency

g = gravity acceleration [m/s^2]

L = lift force [N]

D = drag force [N]

m = mass [kg]

$m_{battery}$ = battery mass [kg]

Building on this equation and drawing on the related studies by Agata Kuśmierek [34], Benjamin J. Brelje [35], on heat rejection in electric propulsion systems, it becomes evident that achieving maximum mission range requires meeting four coupled design objectives. The first is "lightweight energy." Under safety and lifetime constraints, the goal is to maximize the ratio of usable onboard energy to total system mass. Beyond the intrinsic specific energy of the electrochemical cells, this metric is strongly influenced by the degree of modularization, the mass fraction associated with structural components and thermal management hardware, and the chosen voltage level of cables and busbars.

From the proportional relationship

$$I \propto P/V \tag{4.3}$$

The formula for cable cross sectional area and copper weight

$$S = I/J \tag{4.4}$$

$$W = \rho_{\mathrm{Cu}} \cdot L \cdot S \tag{4.5}$$

Where：

I= current [A]

P= power [w]

V= voltage [v]

S= conductor cross sectional area [mm²]

J= allowable current density [A/mm²]

W= copper mass [kg]

ρ_{Cu}= copper density [kg/m³]

L= conductor length [m]

It follows that increasing the DC bus voltage reduces the required current and, consequently, the required conductor cross section and copper mass. This directly lowers wiring/busbar mass and can improve system level gravimetric performance. However, a higher voltage level also elevates insulation demands and exacerbates risks associated with creepage and clearance, electric field enhancement, and partial discharge. Therefore, voltage up scaling must be accompanied by appropriate countermeasures in materials and packaging design to maintain adequate safety margins [36].

"Efficient power transfer" addresses the staged efficiency of the entire energy chain from onboard storage to the propulsor spanning the DC bus/busbars, power converters, magnetics and filters, and the electric machine/mechanical transmission. The dominant loss include: conductor and busbar losses under both DC and PWM harmonic components, comprising I^2R dissipation and AC effects , power semiconductor losses, including conduction loss, switching loss, and reverse recovery and capacitive losses, magnetics and filter losses, such as copper and core losses as well as capacitor ESR dissipation and machine losses, including copper loss, iron loss, and mechanical losses. Increasing the switching frequency typically reduces the size of magnetic components and filters, thereby improving power density. However, it simultaneously increases semiconductor switching losses, magnetic core loss, and AC copper loss, and it generally aggravates electromagnetic interference (EMI). These tradeoffs can be mitigated through soft or quasi soft switching strategies, interleaving, and careful layout optimization to minimize parasitic inductance and capacitance [37].

Adopting three level converter topologies (e.g., NPC, T-type, or ANPC) can reduce device voltage stress and improve output waveform quality by lowering harmonic content. When combined with wide bandgap (WBG) devices such as SiC or GaN, these topologies can enable higher switching frequencies while achieving improved efficiency and power density. Nevertheless, practical implementation must explicitly address neutral point capacitor voltage balancing, gate drive design, thermal design, and EMI suppression [38]. Finally, converter and drive train efficiency should not be evaluated solely at a rated operating point. For aircraft applications, it is essential to report a mission weighted efficiency, as this metric maps more directly to real energy consumption and thus to achievable endurance and range.

"Strong electric machines" refers to the specific power, torque density, and dynamic as well as fault tolerant capability of the propulsion motor/propulsor unit. From $P = \omega T$, increasing rotational speed can, within a certain range, raise specific power rapidly, however, this comes at the cost of higher rotor mechanical stress and increased iron losses, as well as higher aerodynamic noise and end region losses. Torque is fundamentally constrained by the achievable air gap flux density and electric loading, commonly reflected by the scaling [39]:

$$T \propto BAD^2L \tag{4.6}$$

where B denotes the air gap flux density, A the specific electric loading, D a characteristic diameter, and L the active length. Once operation enters the field weakening region, torque is increasingly limited by the DC bus voltage and back EMF, torque decreases, and power no longer grows linearly with ω.

Speed up scaling is accompanied by increasing rotor hoop stress, typically scaling as $\propto \rho r^2\omega^2$, together with higher iron loss and AC conductor loss, and further penalties in fan/propulsor noise and end winding losses. Consequently, achieving "strong" machines requires integrated electromagnetic-structural-control co design. On the electromagnetic side, appropriate pole/slot combinations and winding layouts are used to suppress cogging torque and harmonic content, shorten end windings, and reduce AC loss. For high-speed permanent magnet machines, segmented/laminated magnet designs and high strength retaining sleeves are commonly employed to ensure mechanical integrity. On the control side, current allocation is optimized across the MTPA (maximum torque per ampere, constant torque) region and the field weakening/MTPV (maximum torque per voltage, constant power) region, while explicitly respecting DC bus voltage limits and thermal constraints [40]. To enhance availability and dispatch reliability, propulsion units may adopt multiphase or segmented stator architectures with inverter/control redundancy, enabling graceful degradation under phase faults. In this sense, "strong" is reflected not only in peak performance, but also in sustained capability and reliable operation [41].

"Stable thermal management" constitutes the top-level constraint that enables the preceding three targets to be sustained over the aircraft lifetime. Thermal steadiness can be approximated by

$$\Delta T = Q \cdot R_\theta \tag{4.7}$$

where Q denotes the total heat generation and R_θ is the equivalent thermal resistance from the heat source to the coolant. In practice, R_θ varies with temperature, coolant flow rate, and boundary conditions. For transient operation, junction temperature dynamics are more appropriately described using the thermal impedance $Z_\theta(t)$ or equivalent Foster/Cauer RC networks, which capture the time dependent thermal response [42]. The dominant heat sources include winding copper loss, semiconductor conduction, switching losses, iron loss, and additional stray losses. Their spatial distribution and the resulting hotspots directly govern derating strategies and component life. Winding and device losses convert almost entirely into thermal load. Conversely, temperature rise increases conductor resistance, reduces permanent magnet remanence, and narrows the safe operating area of power semiconductors, creating a coupled electro thermal feedback loop that can accelerate thermal runaway or premature aging if not properly managed [43].

Accordingly, high performance electric propulsion typically relies on advanced cooling and thermal integration measures, such as direct winding cooling or end winding spray cooling, microchannel cold plates, two phase cooling, and appropriately scheduled pump/valve control to reduce junction temperatures and thermal gradients to within material and certification limits while minimizing additional pump power and mass. Maintaining these thermal margins is essential to preserve continuous rated power and service life under representative mission duty cycles [44].

4.1 High energy density storage and energy systems

Benefiting from rapid advances driven by the electric vehicle sector, research on battery technologies is progressing quickly. Nonetheless, on any foreseeable future, electrified aviation remains fundamentally limited by battery system gravimetric specific energy and specific power. The research by Caset et al. indicates that if one attempted to supply an Airbus A320 aircraft with an amount of electrical energy comparable to that required by today's mission using current technology, the required battery mass would exceed the aircraft's maximum take-off weight by roughly a factor of 38[45]. Based on system analyses using typical mission profiles and weight balance, NASA's research indicate that to achieve all-electric or high fraction hybrid propulsion for 4-19 seat general aviation aircraft without significantly sacrificing payload and range, the battery pack specific energy should be at least about 400 Wh/kg; whereas regional aircraft in the 50-70 seat class typically require substantially higher values commonly around 700-800 Wh/kg [46].

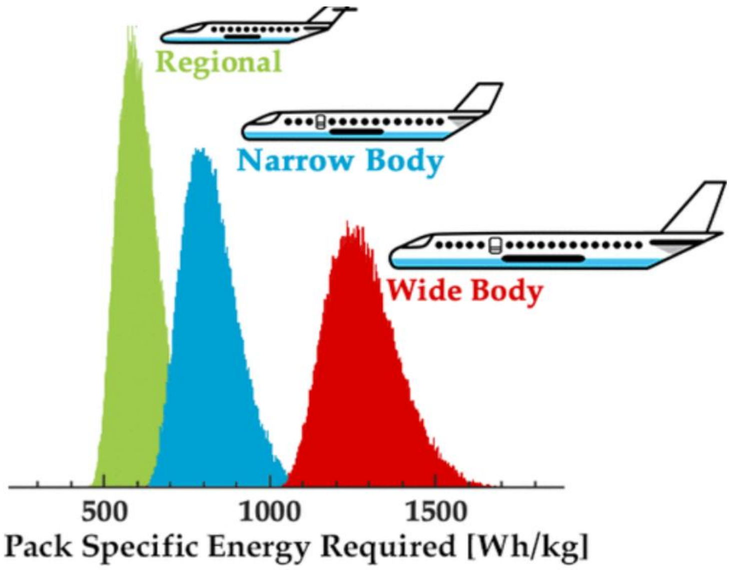

Figure 4.1: Histograms of specific energy for regional, narrow body, and wide body aircraft

(Source: ACS Energy Letters)

4.1.1 Lithium Batteries

An ideal aviation battery must simultaneously satisfy requirements for high specific energy and specific power, rechargeability and long cycle life, safety and thermal stability, manufacturability and maintainability [47]. Given current technology readiness levels and supply chain availability, lithium-based batteries are expected to remain the most practical primary onboard energy storage option in the near to mid-term. With the overarching objective of increasing specific energy while reducing system level penalties, industrial efforts are largely advancing along three pathways[48]:

Continued optimization of lithium-ion (Li-ion) chemistries, including high nickel cathodes, Si/C composite anodes, and solid-state or semi solid-state implementations to improve both cell-level and pack-level specific energy.

Development of lithium-sulfur (Li-S) systems, leveraging their higher theoretical specific energy and potential cost advantages to better address the stringent mass constraints of electric aircraft.

Exploration of ultra-high specific energy concepts, such as lithium-air (Li-Air), which offer very high theoretical energy density but remain at an earlier stage of maturity and face substantial challenges in reversibility, durability, and safety.

The figure below summarizes, for representative lithium-based chemistry, the theoretical energy density, anticipated energy density, and the current state of the art.

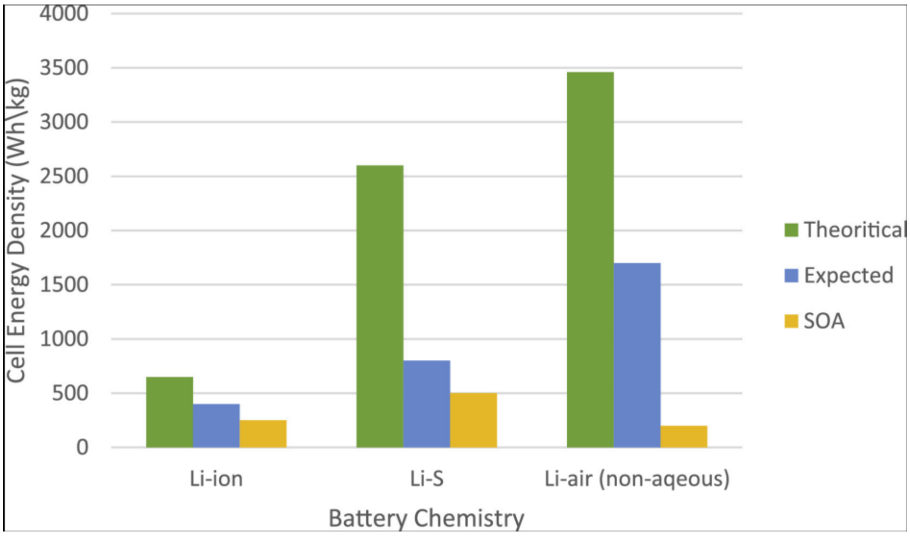

Figure 4.2: Theoretical energy density, expected energy density, and current technological level of lithium battery chemistry systems

(Source: Electric aviation: A review of concepts and enabling technologies)

As illustrated in the figure, once aviation relevant allowances are made for thermal management, structural integration, and safety redundancy, conventional graphite anode Li-ion technology is approaching an engineering ceiling of approximately 250 Wh/kg at the pack level. Meeting the >400 Wh/kg specific energy requirement often cited for electric aviation therefore calls for more aggressive changes in the underlying materials and cell chemistry, rather than incremental optimization alone.

By contrast, the other two chemistries can, in principle, deliver substantially higher energy density. However, both remain constrained by critical barriers to engineering scale deployment, such as polysulfide shuttling, cathode loading and electrolyte management for Li-S, and challenges associated with the oxygen electrode reaction pathways and cycle stability for Li-Air. As a result, the aviation community commonly treats Li-S and Li-Air as longer term, high upside candidates, potentially attractive not only for aerospace but also for large scale energy storage applications [49]. The following sections briefly discuss these three battery categories.

Lithium-Ion Batteries

In current electrified aircraft energy systems, lithium-ion batteries (Li-ion) remain among the most mature and scalable rechargeable technologies for near-term deployment. Leveraging high capacity silicon based anodes with a theoretical specific capacity of up to

3579 mAh/g (based on $Li_{15}Si_4$) [50], utilizing high nickel layered oxide cathodes such as Ni-Co-Mn (NMC) or Ni-Co-Al (NCA) with Ni content exceeding 80% [51], LIB cell-level specific energy is expected to surpass 300-350 Wh/kg while maintaining acceptable cycle life. With further optimization measures such as pre-lithiation, pore closure, and electrode thickening, LIBs are anticipated to reach the >400 Wh/kg class within the next few years [52] [53]. Recent prototype demonstrations suggest that by combining Ni-rich NMC/NCA cathodes (Ni molar fraction x≈0.8 - 0.9), Si/graphite or Si/C composite anodes and high loading electrodes (areal capacity 4 mAh/cm - 10 mAh/cm), measured specific energies of 300 Wh/kg -355 Wh/kg have been achieved in single layer pouch cells, while retaining ≥80% capacity after several hundred to over one thousand cycles [54]. Looking forward, projections indicate that cell-level specific energy could potentially be increased to approximately 380 Wh/kg -420 Wh/kg [55], although at present such figures remain predominantly supported by calculations and prototype level extrapolations rather than large scale mass production.

In anode design, industrial development is progressively shifting from graphite with a small Si additive (typically <10%) toward medium to high Si content composite anodes, such as SiO_X or nano-silicon combined with carbon (approximately 30%-60% Si-based fraction), in order to further extract the remaining headroom in energy density. For instance, some studies have demonstrated composite anodes containing >70 % SiO_X, achieving 600-1000 cycles at C/3 while maintaining a capacity retention of around 80%, suggesting that high silicon chemistries need not be confined to coin cell demonstrations [56]. Consistent with this trend, DOE related project reports indicate that pairing a >50 % SiO_X composite anode with a Ni-rich cathode in 20 Ah pouch cells can deliver 1000 cycles under C/3-1C conditions with approximately 80% capacity retention, while targeting a cell-level specific energy exceeding 300 Wh/kg [57]. In parallel, manufacturing oriented measures including electrode densification, dual layer coating, and high strength current collectors are being pursued to reduce the fraction of inactive materials, thereby expanding the achievable energy density envelope through collaborative optimization of materials and cell/pack structural design [54].

However, a high silicon fraction introduces very large volumetric expansion (often >300%) during lithiation, which in turn drives pronounced stress localization, particle pulverization, disruption of the electronic percolation network, and repeated SEI degradation/reformation, collectively representing a primary bottleneck for high energy Si-based anodes [54] [58].

In response to these coupled failure mechanisms, mitigation strategies can be broadly grouped into three classes:

- **Nanometer/porous architecture engineering:** By employing hollow morphologies, core-shell coatings, or porous scaffolds, researchers construct hierarchical primary/secondary particles that provide internal “buffer space” to accommodate Si expansion and thereby reduce mechanical damage and loss of interparticle contact [59].
- **Polymeric binders and conductive frameworks**: The development of self-healing or highly elastic polymer binders, together with robust 3D conductive networks (e.g. graphene, carbon nanotubes (CNTs), and carbon nanofibers (CNFs)), aims to preserve electronic/ionic transport pathways under repeated volume changes and to mitigate electrode cracking and delamination [55].
- **Prelithiation and electrolyte additives:** Prelithiation introduces additional active lithium into the cell prior to operation to compensate for initial lithium loss and

stabilize early cycle interfacial chemistry [58], In parallel, incorporating small fractions of salt and/or molecular additives in the electrolyte (typically ≤10% by mass or volume, e.g. vinylene carbonate (VC) and fluoroethylene carbonate (FEC)) is widely used to promote the formation of more stable SEI/CEI layers and to suppress continuous interphase growth [55].

For Ni-rich layered oxide cathodes, increasing the Ni fraction can raise operating voltage and reversible capacity, however, it also exacerbates several degradation modes, including particle cracking, residual alkaline surface impurities, and oxygen release at high state of charge (SOC). These phenomena manifest gas evolution, interfacial and bulk impedance growth, a higher propensity for secondary particle fracture, and ultimately reduced thermal stability.

Current mitigation strategies can be broadly categorized into two directions. First, surface protection is widely implemented by depositing dense passivation layers via oxide/fluoride coatings or atomic layer deposition (ALD) to limit electrolyte attack and suppress surface structural reconstruction during high voltage cycling [61]. Second, bulk/surface lattice stabilization can be achieved through targeted doping (e.g. With Mo) to refine grains and to form a disordered layered phase near the particle surface. This approach strengthens the oxygen framework, alleviates radial stress gradients and phase transition heterogeneity, and thereby suppresses intragranular cracking [60].

From the perspective of electrified aviation, the most pragmatic near to mid-term pathway remains a Li-ion chemistry pairing a Ni-rich layered oxide cathode with a high silicon anode. At the laboratory and prototype levels, such cell designs have approached and, in some cases, effectively reached 400 Wh/kg, in cell-level specific energy, with cycle life trends moving toward engineering relevant regimes. Nevertheless, translation to aviation service will require further advances on several fronts like mitigating lifetime degradation driven by high Si volumetric expansion and addressing thermal safety structural and interfacial stability challenges intrinsic to Ni-rich cathodes under high voltage, high SOC operation. In parallel, manufacturing and process optimization must ensure that these high energy designs continue to satisfy aviation's stringent requirements for safety, reliability, and certification compliance under representative duty cycles and failure conditions.

Lithium-Sulfur Batteries

Lithium-sulfur (Li-S) batteries store energy via a multi electron conversion reaction between metallic lithium and elemental sulfur ($S \leftrightarrow Li_2S$), placing them among the rechargeable electrochemical systems with the highest theoretical specific energy. In a typical Li-S configuration, the sulfur cathode delivers a theoretical specific capacity of approximately 1672 mAh/g to 1675 mAh/g, with a volumetric energy density of about 2600 Wh/L, roughly 4 to 5 times that of today's commercial Li-ion batteries (~250 Wh/kg to 300 Wh/kg) [62] [63]. Moreover, sulfur is earth abundant, inexpensive, and free of Co/Ni, offering compelling advantages in cost and sustainability [64] [65]. As a result, Li-S chemistry is widely regarded as one of the most promising engineering pathways for future power supplies in electric aircraft propulsion systems.

In terms of experimental progress, researchers have demonstrated ultra stable Li-S cycling exceeding 1500 cycles, with specific capacities above 1500 mAh/g and excellent rate capability beyond 40 C [66], However, metrics that more directly reflect engineering viability are the performance of pouch cells under practical constraints: high sulfur loading (~5 mg/cm^2) [65], low electrolyte to sulfur ratio (E/S≤2 μL/mg)[6], and limited lithium excess[68].

Representative early achievements include a ~470 Wh/kg class Li-S pouch cell reported by Beijing Institute of Technology [69] and an approximately ~400 Wh/kg cell developed by U.S. national laboratories [70]. NASA's evaluation of Oxis Energy prototype cells indicated a measured cell-level specific energy of ~400 Wh/kg [71], yet cycle life remained strongly limited by polysulfide related phenomena. In more recent high energy pouch cell studies, an interlayer formed by embedding sulfur into polar, lamellar, ordered mesoporous SiO_2 has been introduced. This architecture not only suppresses the shuttle effect of long chain polysulfides but also promotes higher areal capacity, delivering strong performance at high sulfur utilization (>10 mAh/cm²) and stable cycling over 700 cycles [67]. A forward-looking review published in 2025 further notes that record level Li-S pouch cells under laboratory conditions have approached ~695 Wh/kg, whereas a more realistic engineering window lies in the 300 Wh/kg-500 Wh/kg range [72].

Based on the above findings, achieving a true cell level specific energy of at least 400 Wh/kg relies less on simply increasing the sulfur fraction and more on identifying a workable balance among high sulfur loading, low electrolyte to sulfur ratio, and a reasonable negative to positive capacity ratio. Taking typical non aqueous Li-S systems as an example, Meng Zhao and co-workers report that pouch cells are only likely to combine a specific energy of at least 400 Wh/kg with an acceptable cycle life when the electrolyte to sulfur ratio is no more than 2 μL/mg, the sulfur loading is at least 5 mg/cm², and the negative to positive ratio is below 2 [66].

At present, for Li-S batteries to enter the mainstream of electric aviation, several major obstacles still need to be addressed. The key issues are summarized as follows:

- **Poor electronic conductivity, polysulfide shuttling, and volume expansion**: Elemental sulfur and its discharge products are intrinsically electronically insulating. In addition, a range of soluble lithium polysulfides, Li_2S_x ($4 \leq x \leq 8$), formed during cycling can migrate through the electrolyte and undergo shuttle reactions with deposition on both anode and cathode. This process reduces active material utilization, can trigger irreversible capacity fading, accelerates self-discharge, shortens cycle life, increases cell impedance, and lowers coulombic efficiency [73] [74]. Meanwhile, the conversion from S to Li_2S_x is accompanied by volume expansion that can reach up to 76 percent, which compromises electrode integrity and leads to additional capacity loss during repeated charge and discharge [63].

- **Safety and lifetime limitations of lithium metal anodes**: Most high energy Li-S prototypes still employ lithium metal anodes, and metallic lithium is generally required to realize the theoretical energy density of chemistry. This choice introduces well known challenges, including dendrite growth, unstable solid electrolyte interphase formation, and the accumulation of electrically isolated dead lithium. Dissolved polysulfides further corrode the interphase and exacerbate lithium consumption [66] [75]. Moreover, formulations that can deliver 500 to 1000 cycles with 60 to 80 percent capacity retention in idealized coin cells often translate poorly to pouch cells at the 400 to 500 Wh/kg level, where practical lifetimes frequently drop to only several tens to just over one hundred cycles. This remains far below the durability required by the aviation industry [76].

To address the above problems, recent Li-S research has largely converged on the following directions:

- **Sulfur cathode materials and interfacial layer engineering**: Incorporating an appropriate amount of conductive additives into the sulfur cathode, such as acetylene black, carbon black, and Super-P, can improve electronic conductivity and enable high-rate capability and long cycle life [77]. In parallel, three-dimensional conductive frameworks and hierarchical pore networks have been constructed using porous carbon, polar metal compounds (for example metal oxides, sulfides, and nitrides), and structures derived from MOF and COF platforms. In addition, hollow hosts with multilayer shell architectures have been developed as sulfur carriers to mitigate the shuttle effect, increase sulfur loading, and provide void space to accommodate volume expansion [62]. Polar interfaces based on metal single atom catalysts, as well as polar conductive surfaces such as MXenes and MoS_2, further enhance chemical adsorption and catalytic conversion of polysulfides, thereby accelerating the solid phase reaction kinetics of the $S \leftrightarrow Li_2S$ conversion [63].
- **Lithium metal protection and solid-state Li-S systems**: Strategies such as artificial solid electrolyte interphase layers, three dimensional current collectors, and appropriately modified separators can mitigate dendrite growth and the formation of dead lithium, improving cycling reversibility [62]. Beyond liquid electrolyte designs, extending to all solid-state Li-S batteries can leverage sulfide or oxide solid electrolytes to strongly suppress polysulfide shuttling. Under modeled conditions, this approach can deliver a theoretical cell level specific energy above 400 Wh/kg. In addition, solid-state Li-S systems offer clear advantages over conventional Li-S chemistry in safety and sustainability, making them particularly attractive for applications that demand exceptional thermal stability, including electric aviation [78].

Overall, Li-S batteries are highly attractive in terms of energy density and resource sustainability. Their theoretical energy density, low material cost, and sustainability profile align closely with the long-term requirements of electric aviation and large-scale energy storage. Laboratory scale pouch cells have already demonstrated the potential to reach 400 Wh/kg to 500 Wh/kg and, in some cases, even higher, making this chemistry one of the most compelling candidate pathways for future electric aircraft. Nevertheless, substantial challenges remain in electronic conductivity, polysulfide shuttling, volume expansion, and the lifetime and safety of lithium metal anodes. Addressing these issues will likely require at least one to two additional generations of technological iteration. In particular, translating laboratory record performance into aviation grade cycling that is safe, predictable, and sustained for several hundred cycles or more remains a major undertaking. In the near term, Li-S batteries are more likely to emerge in niche aviation applications that offer high value and demand extremely high specific energy while tolerating somewhat relaxed lifetime requirements. Over the medium to long term, variants such as all solid-state Li-S systems may provide a credible route toward adoption in mainstream aircraft propulsion powertrains.

Lithium-Air Batteries

Lithium air batteries store energy through the electrochemical reaction between metallic lithium and oxygen from air. In theory, they can deliver the highest energy density among all rechargeable battery chemistries, reaching about 11400 Wh/kg when referenced to pure lithium, which is nearly comparable to gasoline at about 12800 Wh/kg. For a typical nonaqueous Li-O_2 system whose discharge product is Li_2O_2, the theoretical specific energy is approximately 3500 Wh/kg, which is about an order of magnitude higher than that of today's commercial Li-ion batteries [79].

In terms of experimental progress, a number of prototype cells approaching high specific energy ceilings have emerged in recent years. For laboratory cells based on nonaqueous Li-O_2 chemistry, Shoichi Matsuda in Japan has successfully fabricated a Li-Air battery in the 500 Wh/kg class, which exhibits a stable discharge voltage profile [80]. Zhang Wen and co-workers further increased the energy density of lithium oxygen pouch cells to the 860 Wh/kg class by employing an oxygen rich localized high concentration electrolyte (LHCE) [81]. For aviation-oriented development in solid-state Li-Air systems, Boeing and San Diego State University have reported a series of single layer solid-state Li-Air pouch prototypes. In their second-generation samples, the cell level specific energy has reached about 460 Wh/kg when normalized by the total mass of the gas diffusion layer, solid-state electrolyte, and lithium. At the coin cell level, they reported an energy density of 1150 Wh/kg and a power density of 210 W/kg, together with a continuous power density exceeding 500 W/kg [82]. Compared with Li-S and lithium metal batteries from a similar period, Li-Air clearly offers an advantage in the upper bound of achievable energy density. However, its technical maturity remains at an earlier stage in terms of rechargeability, rate capability, and controllability. The following briefly summarizes several prominent challenges currently faced by Li-Air batteries:

- **High overpotential, sluggish reaction kinetics, and discharge product deposition leading to cathode pore clogging and interfacial deactivation:** In nonaqueous Li-Air cells, the kinetics of the oxygen reduction reaction and oxygen evolution reaction are intrinsically slow, resulting in low energy efficiency, limited cycle life, and poor rate capability. Decomposing discharge products typically requires a high overpotential, which significantly reduces charge and discharge efficiency [79]. Moreover, the high overpotential can in turn accelerate severe degradation of both the electrode and the electrolyte, further constraining battery lifetime [83]. In addition, electronically insulating reduction products such as Li_2O_2 can deposit within porous cathodes and block transport pathways. This progressively lowers porosity, restricts oxygen supply, and promotes gradual electrode passivation during cycling [84].
- **Lithium metal anodes and parasitic reactions:** Like Li-ion and Li-S batteries, Li-Air systems inherit the well-known challenges associated with lithium metal anodes, including dendrite growth, unstable solid electrolyte interphase behavior, and the accumulation of electrically isolated dead lithium within porous separators. As a result, the cycle life of most rechargeable Li-Air batteries remains in the order of several tens to at most one or two hundred cycles [85]. Meanwhile, superoxide and peroxide intermediates generated during cycling, together with the strongly oxidizing high potential environment during charging, continuously decompose organic electrolytes and carbon-based cathode materials. This corrosion of cell components further reduces durability and practical lifetime [79] [86].

To tackle these problems, recent studies have established clearer research directions together with early-stage mitigation strategies:

- **High performance catalysts and soluble redox mediators:** Noble metal catalysts such as platinum and iridium dioxide, as well as transition metal oxides, have been employed to promote the relevant redox reactions and improve the kinetics of the oxygen reduction and oxygen evolution processes [87]. In addition, soluble redox mediators have been introduced into the electrolyte, including TTM (tris (2,4,6 trichlorophenyl) methyl), BDTD (benzo [1,2 b:4,5 b'] dithiophene 4,8 dione), and carbon nanotube-based mediators. Acting as electron and hole carriers, these species facilitate charge transfer between the O_2-Li_2O_2 couple and the cathode, thereby reducing the operating potential and alleviating local interfacial polarization and parasitic reactions [88].
- **Lithium metal protection and solid-state or hybrid solid-state Li-Air systems:** Beyond protection concepts shared with Li-S and Li-ion batteries, lithium anodes in Li-Air cells can be further stabilized via in situ and ex situ protective coatings, the use of three-dimensional porous frameworks, and approaches that anchor lithium within three dimensional current collectors [89]. In parallel, condensed phase electrolytes have been explored, together with cathode structural engineering aimed at optimizing Li_2O_2 storage. These strategies can provide more accessible catalytic sites, improved gas diffusion pathways, and additional accommodation space for discharge products [90].

At present, Li-Air batteries appear to be the rechargeable chemistry that comes closest to the idea of battery-based aviation kerosene. Their theoretical energy density nearly matches that of gasoline and is far beyond that of current Li-ion and Li-S systems, offering a compelling vision for long range and heavy payload electric aircraft. However, severe limitations remain, including sluggish reaction kinetics, material and electrolyte decomposition driven by high overpotential, cathode pore clogging, and the safety and lifetime challenges of lithium metal anodes. As a result, the technology readiness level is still far from engineering deployment. In the near term, Li-Air batteries are unlikely to serve as a mainstream aviation power source and are better positioned as a long horizon, high risk and high reward strategic technology reserve.

Overall, from the perspective of aviation electrification, high nickel and high silicon Li-ion batteries represent the most realistic near-term technology and the closest option to large scale airworthiness deployment. They are capable of supporting short range and part of the medium range electric aviation mission set. Li-S batteries offer stronger advantages in specific energy and resource sustainability and may serve as a medium-too long-term upgrade pathway. However, they must first overcome two fundamental barriers, namely polysulfide shuttling and the safety and lifetime limitations of lithium metal anodes. Li-Air batteries, in contrast, define an upper bound of theoretical energy density that approaches aviation fuel and therefore represents an ultimate long-range vision for electric aviation. Yet their current gaps in kinetics, safety, and controllability remain substantial, leaving them far from engineering adoption.

Taken together, electric aviation is better understood as a long cycle process of coordinated evolution across three battery generations. One generation makes flight feasible in practice, another extends range and efficiency through incremental but sustained upgrades, and a third continues to mature in laboratories, accumulating the capability required for a future step change.

4.1.2 Fuel Cells

As noted earlier, lithium-based batteries are constrained by the tradeoff among specific energy, specific power, and thermal management. From the cell level to the pack level, they also incur additional penalties associated with structural mass, thermal provisions, and safety related redundancy. Based on currently available public technology, lithium batteries can primarily support shorter range missions and smaller seat class aircraft. Even if cell specific energy advances toward 400 Wh/kg to 500 Wh/kg, fully electrifying medium range missions or aircraft with larger payload requirements is still unlikely in the near term. Before large scale electrification and the development of fully electric propulsion systems, the use of low carbon alternative fuels with high energy density has been widely viewed as another pathway to meet emissions reduction targets [91] [92]. Fuel cells are not limited by the Carnot cycle and can convert the chemical energy of a fuel directly into electrical energy, enabling high efficiency power generation [93]. A typical hydrogen fuel cell propulsion system combines hydrogen, a chemical fuel with very high specific energy (about 33.3 kWh/kg), with a high efficiency electric drive chain [91] [92]. Even after accounting for the engineering penalties associated with hydrogen storage and the balance of plant (all equipment required to control and regulate fuel, air, temperature, water, and electrical power delivery), the usable system level specific energy is still typically substantially higher than that of a contemporary Li-ion battery pack. In addition, near zero emissions can be achieved during flight, with water as the primary product, making hydrogen fuel cells a key pathway to compensate for the insufficient energy density of batteries [94]. At the system level, electric and hybrid electric aircraft based on hydrogen fuel cells can maintain zero local emissions while delivering a usable specific energy that is clearly higher than current Li-ion battery systems. This makes them particularly suitable for 4 to 19 seats general aviation aircraft and short-range commuter platforms [95]. With continued maturation of liquid hydrogen technologies and system integration, the field generally expects the concept to extend toward 30 to 80 seats regional passenger aircraft, enabling longer stage lengths and higher payload capability [96].

Fuel cells convert hydrogen and oxygen from air directly into electrical energy and water through electrochemical reactions. Current research in this area primarily focuses on two pathways, namely proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC). PEMFC are commonly categorized by operating temperature into low temperature proton exchange membrane fuel cells (LT-PEMFC) and high temperature proton exchange membrane fuel cells (HT-PEMFC). Among them, LT-PEMFC are often viewed as the most attractive option because of their relatively low operating temperature, rapid start up and shut down, high power density, and straightforward coupling to high voltage direct current buses [94]. Compared with LT-PEMFC, SOFC and HT-PEMFC operate at much higher temperatures, typically in the range of about 600°C to 1000°C, and they generally have larger physical footprints. These characteristics enable operation in the megawatt class power range. As a result, SOFC are often considered more suitable for propulsion systems of larger aircraft. However, because their technology readiness remains lower, they are not yet well suited for near term deployment [97]. The following sections provide a brief introduction to these two pathways.

Proton exchange membrane fuel cells (PEMFC)

Proton exchange membrane fuel cells, also referred to as polymer electrolyte membrane fuel cells, consist of two bipolar plates (BP), two gas diffusion layers (GDL), two catalyst layers (CL), and a proton exchange membrane (PEM) [98]. The electrolyte membrane is most commonly based on perfluorosulfonic acid polymers (PFSA), such as Nafion®, which provide sufficient proton conductivity while maintaining strong gas barrier performance. In parallel, membranes based on graphene oxide (GO) have also attracted attention [99]. Through functionalization, GO-based membranes can improve proton transport and water retention under elevated temperature and low relative humidity conditions [100]. In addition, GO can enhance mechanical robustness through the construction of nano hybrid composite membranes and is therefore considered a promising carbon-based membrane platform for future development.

Depending on operating temperature and the membrane electrolyte system, PEMFC are typically classified into low temperature and high temperature variants. LT-PEMFC uses a hydrated polymer electrolyte membrane as the pathway for proton migration and transport, with a typical operating temperature of 50°C to 80°C. In engineering practice, the temperature is often kept below about 80°C to preserve membrane hydration and stability [101]. These fuel cells offer advantages such as rapid start up, high power density, and zero local emissions. As a result, substantial research and development has been carried out across transportation, portable power, stationary power, aviation, and underwater applications, and the technology has already been deployed in multiple sectors. Current research priorities include reducing platinum group catalyst loading, increasing the activity of low platinum catalyst layers, advancing hydrogen storage, transportation, and safety infrastructure, and improving water and thermal management as well as cold start characteristics. These efforts aim to extend system lifetime and reduce total life cycle cost [98].

HT-PEMFC employs high temperature stable polymer membranes, most commonly Phosphoric Acid-Doped Polybenzimidazole (PBI) membranes [102]. Under low relative humidity conditions, typically in the range of about 25% to 50%, they can operate at temperatures above 120°C. The elevated operating temperature provides multiple benefits. First, it accelerates electrode reaction kinetics and weakens carbon monoxide adsorption on platinum catalysts, thereby improving carbon monoxide tolerance. Reduced adsorption coverage on platinum surfaces can also enhance tolerance to other impurities [104]. Second, the higher temperature substantially simplifies water management and facilitates efficient integration with thermal subsystems such as gas turbines and waste heat recovery. This broadens opportunities for waste heat utilization and can improve overall system efficiency and fuel flexibility [103] [104]. Nevertheless, relative to LT-PEMFC systems, HT-PEMFC still face significant challenges. Beyond issues such as higher required platinum loading [104], limitations remain in the performance and long-term stability of high temperature membrane electrode assemblies (MEA) [102], phosphoric acid loss, structural evolution at the electrode membrane interface, and pore scale as well as multiscale modeling and design methodologies [104] [105]. As a result, the technology readiness level and accumulated engineering experience still require further improvement before widespread deployment.

Overall, PEMFC constitutes a hydrogen fuel cell architecture built from multilayer electrodes coupled with a proton conducting membrane. At present, PFSA remains the dominant technology, while research is progressively moving toward new membrane materials that can operate under higher temperature and lower humidity conditions, including GO-based systems. From an engineering standpoint, two main pathways are commonly distinguished, namely low temperature and high temperature PEMFC. Low temperature systems are relatively mature and have already been demonstrated in transportation and selected aviation pilot programs, offering a practical zero local emission propulsion option for light electric or hybrid electric aircraft and unmanned aerial vehicles. High temperature systems, by contrast, leverage elevated operating temperature to achieve improved tolerance to fuel impurities and to enable more effective integration with waste heat recovery and gas turbine-based subsystems. They are therefore often viewed as a promising route toward future aviation fuel cell systems with higher power capability and higher overall efficiency.

However, substantial gaps remain in membrane electrode assembly stability, phosphoric acid retention, and multiscale modeling and design. Bridging these gaps will require sustained advances in both materials development and system level research before HT-PEMFC can credibly support large scale electric aviation deployment.

Solid oxide fuel cells (SOFC)

Solid oxide fuel cells are all solid-state fuel cells that operate at elevated temperatures and employ an oxide ion conducting ceramic electrolytes, a perovskite-based cathode, and a nickel cermet anode. The electrolyte is most commonly Yttria-Stabilized Zirconia (YSZ), used together with ceramic or metal-ceramic composite electrodes to form a single cell [106]. The typical operating temperature range is approximately 400°C to 1000°C. Within this temperature window, the electrolyte exhibits high oxide ion conductivity, which supports rapid internal electrochemical reactions and high overall efficiency [107].

Owing to high temperature operation, SOFC offer several attributes that are advantageous relative to low temperature fuel cell technologies. Elevated temperature improves electrode kinetics and gas phase reaction rates, which can significantly reduce reliance on noble metal catalysts. In addition, SOFC provides strong fuel flexibility. Beyond pure hydrogen, they can operate on natural gas, biogas, biomethane, syngas, bio alcohols, ammonia, and other carbon or nitrogen fuels contained. For some hydrocarbon fuels, internal reforming can even be achieved within the cell, simplifying system architecture and improving fuel utilization [108] [109]. Because solid oxide fuel cell systems are not constrained by Carnot cycle limits, electrical efficiency can reach about 60%. When integrated into hybrid cycle configurations with gas turbines or waste heat boilers, combined heat and power efficiency can exceed 90%. These characteristics give solid oxide fuel cells clear advantages for medium and high-power distributed energy applications and industrial waste heat utilization [107].

At the system level, SOFC are particularly well suited for integration with gas turbine engines to form SOFC GT hybrid cycles, enabling high efficiency power generation systems in the range of several hundred kilowatts up to the megawatt class [110]. In such hybrids, the SOFC provides high electrical efficiency, while heat exchangers recover a portion of the thermal energy from the exhaust stream and transfer it to the working air flow to raise the inlet temperature to the combustor. This architecture can significantly improve overall generation efficiency while producing almost no pollutant emissions [111] [112].

For large aircraft propulsion and onboard power systems, the combination of high efficiency, near zero pollutant emissions, fuel flexibility, and the ability to operate close to steady state during cruise makes SOFC technology attractive for medium and long-range missions [113]. However, SOFC manufacturing often requires costly materials, including rare earth or otherwise scarce elements, together with demanding fabrication processes, which substantially slows commercialization [109]. In addition, high power aviation and propulsion applications still face multiple challenges, including stringent volume and mass constraints, system thermal management and cooling requirements, long start up times, slow response to load transients, and the need for rigorous reliability and safety validation. As a result, the overall technology readiness of SOFC systems remains lower than that of low temperature PEMFC [108].

Elevated operating temperature also introduces substantial materials and engineering challenges. High temperature operation of SOFC requires electrodes, electrolytes, interconnects, insulation layers, and seals to be fabricated from costly materials. It further raises issues related to the chemical and mechanical stability of electrolytes and electrodes under thermal cycling, metal and ceramic joining and sealing reliability, resistance to thermal shock, and the added system level cost and reliability pressure associated with complex thermal management [108] [109]. To reduce thermal stress and material degradation, and to simplify insulation requirements and the start-up process, one major recent research focus has been to lower the SOFC operating temperature toward the vicinity of about 600℃. This shift motivates the development of alternative electrolyte materials such as gadolinium doped ceria (GDC) and samarium doped ceria (SDC), together with matched electrode architectures [114]. A central challenge in current SOFC materials science and engineering is therefore to maintain sufficiently high ionic conductivity and interfacial electrochemical activity while operating at reduced temperature.

Overall, SOFC operate at high temperatures, typically between 400℃ and 1000℃. They offer very high electrical efficiency, can be integrated with gas turbines to form highly efficient SOFC-GT hybrid cycles, and can utilize a wide range of hydrogen based or carbon containing fuels. These attributes make technology, in principle, highly attractive for medium and long-range aircraft propulsion and onboard power generation. However, the engineering challenges associated with high temperature operation, including materials selection, packaging and sealing, thermal management, start-up procedures, and dynamic load response, make current systems expensive and complex, and their overall technology readiness remains clearly behind that of PEMFC. Even so, driven by the vision of higher efficiency, the potential to directly use aviation fuel or synthetic fuels, and deep coupling with gas turbine systems, SOFC technology continues to be regarded as a valuable medium-to-long-term pathway for future hybrid electric and large-scale electrified aircraft platforms. If breakthroughs can be achieved in intermediate temperature materials and system integration, SOFC based architectures could become an important enabling technology for improving long range flight energy efficiency and reducing carbon emissions.

In summary, from the perspective of electric aviation, fuel cell development is gradually converging toward a dual pathway in which PEMFC serve as the primary option in the current and near to mid-term, while SOFC represents a high efficiency opportunity over the mid to long term. The former is anchored by mature PFSA membranes together with continued advances in emerging membrane materials such as GO-based platforms. Along the low temperature route, proton exchange membrane systems have already entered light electric and hybrid electric aircraft as well as unmanned aerial vehicles through multiple demonstration programs, offering a relatively practical zero local emission pathway for short range and regional mission platforms. High temperature proton exchange membrane systems, by contrast, show advantages in impurity tolerance and in integration potential with waste heat recovery and gas turbine-based subsystems. They are therefore often viewed as a route toward future aviation fuel cell systems with higher power capability and higher efficiency, although progress still depends on sustained breakthroughs in membrane electrode assembly stability, mechanisms of phosphoric acid transport, and multiscale modeling and design.

In comparison, SOFC enabled by high temperature solid electrolytes and broad fuel compatibility, outline a different vision for medium to long range flight and for large commercial or military platforms. They offer the prospect of high efficiency SOFC-GT hybrid cycles and, in principle, the ability to directly utilize a variety of future aviation fuels, including hydrogen and ammonia. However, engineering challenges associated with elevated temperature, including materials cost, sealing and packaging, thermal management, start-up procedures, and dynamic response, make SOFC systems more suitable in the near term as an exploratory direction for future large-scale electric or hybrid electric aircraft.

Looking ahead, coordinated advances in membrane materials, solid electrolytes, system integration, and safety certification standards are expected to further clarify the respective roles of these technologies. PEMFC may enable electric aviation to move from simply achieving flight to achieving operation that is more stable and cleaner on a relatively short timescale, whereas SOFC could, over a longer horizon, emerge as an important candidate technology for improving long range mission energy efficiency and enabling deeper decarbonization.

4.1.3 Other Energy Storage Devices

Beyond fuel cells and lithium-based batteries, including Li-ion, Li-S, and Li-Air systems, electric aviation is also actively exploring a range of non-traditional energy storage technologies to compensate for the limitations of stand-alone electrochemical storage in specific power, cycle life, and safety. These approaches are most often deployed in hybrid energy storage system (HESS) architectures that operate alongside a primary energy source. The following sections briefly discuss these technologies.

Supercapacitor energy storage (SC)

Compared with conventional Li-ion batteries, supercapacitors offer markedly higher specific power and power density, with output power that can exceed batteries by more than an order of magnitude. They can also sustain up to millions of charge and discharge cycles and enable rapid charging and discharging on the order of seconds [115]. However, the specific energy of commercially available supercapacitors is typically only about 1 Wh/kg to 10 Wh/kg, which is far below the roughly 150 Wh/kg to 265 Wh/kg level of mainstream Li-ion batteries [116]. For this reason, supercapacitors are generally not considered a standalone primary energy source. Instead, they are commonly integrated with batteries or fuel cells in hybrid energy storage system architectures, where supercapacitors function as power buffering or power assist units on the electrical supply side [117]. In such configurations, supercapacitors can first reduce peak power demand and thereby lower the required rated output of the propulsion powertrain during short duration high power phases such as takeoff, climb, and acceleration, which can improve overall thermal cycle characteristics. Second, by reducing the frequency of extreme operating conditions, they can mitigate battery aging and lower maintenance requirements and operating costs. Third, their second level power response and wide operating temperature range can help overcome the power ramp rate limitations of conventional aviation engines. This improves the dynamic response speed and control redundancy of propulsion and onboard electrical power systems, thereby expanding mission capability and safety margins in highly dynamic scenarios such as rapid maneuvering, gust rejection, and go around events [118] [119]. In the context of electric aviation, battery and supercapacitor hybrid energy storage systems are widely viewed as a promising architecture. Through appropriate energy management strategies, power can be dynamically allocated between the two devices across different flight phases to improve acceleration performance and safety margins under stringent mass constraints. This can enhance the overall safety and economic viability of the energy system and open additional design space for future electric aircraft platforms at higher thrust classes.

Flywheel energy storage systems (FESS)

Flywheel energy storage stores electrical energy as rotational kinetic energy in a high-speed rotor and releases it on demand through bidirectional conversion via a motor generator unit. It is a representative form of mechanical energy storage. Because the process is purely physical and not constrained by electrochemical reactions, modern flywheel systems can transfer large amounts of power within seconds. They can achieve round trip energy efficiencies on the order of 90% to 95%, deliver millisecond to second level power response, provide service lifetimes beyond 20 years, sustain hundreds of thousands of charge and discharge cycles with essentially no performance fade, and produce no emissions during operation [120]. With advances in high strength composite rotors, magnetic bearing technologies, and vacuum containment, the specific energy and specific power of modern flywheel systems have improved substantially, and some performance parameters can now be competitive with electrochemical storage. Flywheels have already been deployed in selected ground transportation applications. However, significant engineering challenges remain for onboard aviation use. First, a high-speed, high-energy rotor that becomes unstable or fractures can release a large amount of kinetic energy in a very short time. To satisfy aviation safety and airworthiness requirements, robust mechanical protection and fragment containment are necessary, typically involving high strength thick casings and multi compartment structures. This can substantially increase structural mass and installation volume. Second, the large angular momentum carried by a high-speed flywheel can generate pronounced gyroscopic effects during roll, pitch, and yaw maneuvers, introducing additional coupled moments and disturbances to the flight control system. Mitigation may require symmetric arrangements of multiple flywheels, gimbal mounting, or compensation loops in the control laws, and the associated analysis and control design complexity is significantly higher than that of fixed, non-rotating onboard batteries [121].

Under these coupled constraints, a central challenge for aviation adoption is how to integrate flywheels with batteries, supercapacitors, and other storage elements to form coordinated hybrid energy storage architectures. This integration problem will largely determine whether flywheel systems can be engineered and scaled for broader aeronautical applications.

Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage stores electrical energy directly in a magnetic field by maintaining a large direct current in a superconducting coil. This is achieved by cooling the conductor below its critical temperature so that the coil enters a superconducting state. Because the energy is stored electromagnetically without intermediate conversion steps, and the effective resistance of the coil is nearly zero in the superconducting state, SMES can provide near instantaneous power response and very high round trip efficiency, while also supporting an essentially unlimited number of charge and discharge cycles [122]. Existing studies have proposed hybrid energy storage system architectures that combine SMES with batteries. In electric or hybrid electric aircraft power systems, SMES can be assigned to handle short duration peak power demands and to compensate for fault induced disturbances, while the battery provides the primary energy supply. This division can reduce the required capacity of conventional generator sets and lower fuel consumption without compromising safety[123]. In parallel, the aviation community is exploring the coupling of liquid hydrogen propulsion concepts with superconducting power distribution. For megawatt class electric propulsion, liquid hydrogen can serve not only as a fuel for fuel cells or gas turbines, but also as a cryogenic source for high temperature superconducting machines, superconducting cables, and superconducting magnetic energy storage components. Some design oriented studies in other transportation related domains, such as accelerator or marine systems, have already indicated the feasibility of using liquid hydrogen to provide cooling in the 20K to 60 K range for MgB_2 coils or REBCO tape based SMES devices [124]. If future electric or hydrogen electric aircraft can carry liquid hydrogen tanks and associated cryogenic thermal management hardware, the cooling and heat management infrastructure required by SMES could potentially be shared with the propulsion system. This could improve the mass and cost of cryogenic subsystems at the system level and make onboard SMES a viable option for short duration power balancing, peak shaving, and support under highly dynamic operating conditions. At present, the main factors limiting SMES adoption in electric aviation include the complexity and mass penalty of cryogenic systems, the cost of high temperature superconducting materials, and the reliability of these materials under vibration and radiation environments [122].

Metal air batteries

Beyond the widely discussed lithium-air concept, metal air batteries such as Aluminum-air, Zinc-air, Magnesium-air, and Iron-air systems are being considered as potential candidates for future medium and long-range electric aviation. This interest is driven by their very high theoretical specific energy and by an operating mode that resembles a fuel cell in key respects. Theoretical specific energies for these chemistries can reach several thousand Wh/kg, far exceeding present commercial Li-ion batteries. In addition, metals such as aluminum and zinc are abundant, and their extraction and refining processes are mature, which can be translated into comparatively low cost [125]. For electric aviation, because the metal electrode is consumed during discharge and electrodeposition-based recharging is generally inefficient, aviation-oriented metal air systems are often discussed in a mechanically rechargeable mode. In this approach, replenishment is achieved on the ground by rapidly replacing the metal anode material, such as anode slurry, or the electrolyte. The operational logic is therefore closer to conventional refueling than to time-consuming plug-in charging [126]. Such systems could function either as a primary power source or as a range extender, supplying high specific energy during cruise. In principle, this could satisfy the high energy density requirement of cruise flight while also reducing the burden of high-power charging on airport electrical infrastructure.

However, key bottlenecks remain in rechargeability and power characteristics. For Aluminum-air systems, the aluminum anode can undergo severe self-corrosion and hydrogen evolution in alkaline electrolytes, which lowers coulombic efficiency and increases self-discharge. At the same time, oxide and hydroxide passivation layers form on the surface and hinder access to active areas, causing practical specific capacity to fall far below the theoretical value [127]. Zinc-air batteries face challenges such as zinc dendrite formation during charging, nonuniform deposition morphology, and the strong sensitivity of alkaline electrolytes to carbon dioxide. The latter can lead to carbonate precipitation that clogs pore in the air electrode [126]. For emerging systems such as Iron-air batteries, unresolved issues include sluggish iron redox kinetics, electrode volume expansion and pulverization during cycling, and, in high temperature solid oxide type iron air configurations, the stability of electrolyte and electrode interfaces [128].

As a result, the engineering feasibility of metal air batteries for electric aviation largely remains at the level of conceptual analysis and small-scale experimental validation. Substantial interdisciplinary progress is still required before such systems can satisfy airworthiness expectations and full life cycle operational requirements.

In summary, to overcome the intrinsic coupling between energy density and power density that constrains conventional Li-ion batteries, aviation energy storage is increasingly moving toward diversified and hybridized solutions. Supercapacitors, flywheel energy storage, and superconducting magnetic energy storage are representative power-oriented technologies. Owing to their very high-power density and fast response, exceptionally long cycle life, and stable operation over a relatively wide temperature range, they are well suited to serve as power buffering elements within hybrid energy storage system architectures. In this role, they can address peak power demands during highly dynamic flight phases such as takeoff and climb, improve the operating conditions of the primary energy source, and enhance overall aircraft dynamic performance, reliability, and safety. In parallel, metal air batteries represent a highly promising energy-oriented storage pathway. Their ultrahigh theoretical specific energy opens new possibilities for medium and long-range electric aviation. If safety can be ensured, such systems could substantially extend the economically viable range envelopes of electric aircraft and support step change improvements in decarbonization and noise mitigation for civil aviation.

However, major challenges remain. For power-oriented storage, onboard integration and demonstrable reliability under aviation constraints are still demanding. For metal air systems, critical bottlenecks persist in corrosion, self-discharge, charging reversibility, and electrolyte management. Addressing these issues will require sustained, coordinated progress across materials, structural design, control strategies, and systems engineering so that large scale deployment can be achieved while meeting airworthiness requirements and maintaining full life cycle economic viability.

4.2 Thermal management and high temperature control technology

As aircraft propulsion systems undergo a deep transition toward electrification, electric aviation integrates substantially higher power density per unit mass. A direct consequence is a pronounced increase in heat flux density per unit volume and per unit surface area, which further intensifies thermal management challenges. Existing studies indicate that the target power density for aviation class electric machines and power electronics systems often exceeds 10 kW/kg to 20 kW/kg, far above the heat rejection levels typical of liquid cooled electronic equipment in conventional civil aircraft [129]. In addition, conventional aircraft architecture relies on centralized hydraulic systems and bleed air systems that use gas or liquid working media, offering favorable heat capacity and heat transfer characteristics. By contrast, in electric propulsion systems the corresponding actuated mechanisms are not driven by a fluid working medium, which limits the ability to remove thermal loads effectively through exhaust flow. Furthermore, as machine power and voltage levels continue to increase, winding designs tend to adopt a larger number of turns and thicker insulation layers, which can further degrade the effective thermal conductivity of the windings [130]. This creates an unprecedented multivariable optimization problem for the thermal management system. Aircraft mass sensitivity imposes strict constraints, requiring sufficient heat exchange capability at minimal added weight. At the same time, aircraft operating conditions vary rapidly. Takeoff and climb, cruise, descent, ground taxi, and even cross region operations correspond to different ambient temperatures and cooling conditions. The thermal management system must therefore remain stable and efficient across a wide operating envelope. In addition, aviation safety and reliability requirements are stringent. Overheating of critical components can trigger severe consequences such as thermal runaway or demagnetization, potentially leading to catastrophic outcomes. Accordingly, stricter temperature limits and redundancy-oriented design become necessary.

4.2.1 Promoting thermal management of motors and power systems

To achieve higher thrust to weight ratio and lower energy consumption, electric aviation propulsion is increasingly converging on the tight integration of high specific power electric machines with high power density power electronic hardware. However, this trend also drives a substantial rise in waste heat loads, while the dominant heat sources are characterized by low quality, spatially dense distribution, and locally high heat flux. As a result, thermal management is no longer an auxiliary subsystem. Instead, it becomes a primary design constraint that directly governs propulsion system mass, aerodynamic drag, and airworthiness driven reliability. In particular, during peak power segments such as takeoff and climb, temperature margin often determines short duration overload capability and lifetime limits.

Therefore, thermal management for electric aviation must be optimized against the mission profile as a whole, rather than being treated as a steady state cooling check of individual components [131].

From the perspective of heat source composition, losses on the machine side mainly include alternating current copper losses in the windings, time varying core losses, and stray losses. On the power conversion side, heat generation is dominated by semiconductor conduction and switching losses, with additional contributions from busbars, filtering components, and packaging related parasitic heating [132]. Hot spots are typically concentrated in stator slot windings and end windings, in the tooth and yoke regions of the magnetic core, and along the thermal resistance path between the junction region of power modules and the cold plate [133]. Under the trend toward integrated motor drive architectures, the motor and inverter share a common housing and cooling circuit, leading to stronger thermal coupling. This co-integration can increase power density, but it also amplifies the complexity of thermal design and the potential for thermal fault propagation [132].

Among the solutions available today, ram air cooling is the most common and the most mature approach. In this architecture, a closed loop liquid cooling circuit combined with a ram air heat exchanger serves as the baseline thermal management framework for the propulsion system. Cold plates extract heat from electrical components and transfer it to the coolant, and the collected heat is then rejected to the external air flow through a compact hexagonal heat exchanger that incorporates rectangular flow channels. A diffuser is typically included to reduce the cooling air velocity, thereby lowering the cold side pressure loss across the compact heat exchanger [134] [135]. The system penalties of this approach mainly arise in three categories. First, the heat exchanger and the associated inlet and outlet ducting introduce aerodynamic drag and pressure losses. Second, the coolant pump, and in low speed, ground, or hot day conditions potentially an auxiliary fan, impose additional parasitic power consumption. Third, sizing the piping network, cold plates, and heat exchanger leads to mass and volume penalties [131] [136]. Consequently, the thermal management system often must be co-optimized with propulsion power class, mission profile, including off design conditions such as hot day takeoff, the flight speed envelope, and the overall aerodynamic configuration of the aircraft.

For propulsion motor cooling, the dominant optimization strategy is to continuously shorten the thermal resistance path from winding hot spots to the cooling medium. External air cooling or fan assisted cooling offers the simplest structure and lower airworthiness risk, but heat rejection is typically insufficient because of limited air side heat transfer coefficients and the high heat flux associated with high power density operation. Indirect liquid cooling through a housing jacket is mature and reliable, yet winding hot spots remain constrained by the thermal conduction chain through slot insulation, impregnation layers, and the stator core. To move closer to the hot spots, current research is focusing on embedded heat pipe cooling and direct liquid cooling, which can shorten the conduction path from the winding to the coolant and thereby enable higher current density and improved thermal performance [133] [137]. However, these more hotspot proximate approaches also introduce additional engineering constraints, including nozzle placement and return flow management, sealing and leakage risks, contamination control, and maintainability. Existing studies on numerical have investigated the effects of liquid flow rate and coolant properties, demonstrating their potential to improve overall heat transfer performance as well as their influence on the hydrodynamics of oil film flow [138].

As power density continues to increase, conventional single phase liquid cooling may approach its practical limits under locally high heat flux conditions. As a result, enhanced heat transfer concepts such as jet impingement cooling, spray cooling, and two-phase microchannel heat exchangers are increasingly being investigated for high heat flux electronics thermal management [139] [140] [141], However, the maturity of these techniques remains relatively low, and publicly available experimental datasets and engineering case studies are still limited. Much of the existing work therefore remains focused on early-stage theoretical analysis and numerical simulation-based validation. Consequently, these approaches are better positioned as medium to long term technology reserves and development directions rather than solutions that can be directly deployed in near term engineering practice. It is also important to emphasize that aviation systems impose substantially stricter requirements on safety, reliability, and maintainability than most ground-based equipment. For onboard adoption, advanced cooling technologies must therefore achieve a higher level of controllability and predictability, including monitorable operating states, manageable fault modes, and the ability to isolate abnormal conditions. In addition, they must pass systematic verification and certification processes within a stringent airworthiness regulatory framework before they can transition from laboratory research into practical engineering application.

4.2.2 Thermal Management of Energy Storage Systems

In electric aviation propulsion, the energy storage system is not only the largest contributor in terms of mass and volume, but also the heat source associated with the highest safety risk. Its thermal management objectives therefore extend beyond simply lowering the maximum temperature. They must simultaneously address multiple goals, including the substantial increase in cell heat generation driven by high current transients during operating conditions such as takeoff, climb, and vertical takeoff and landing, as well as the isolation of thermal runaway events and the capability for continued safe flight and landing [142]. In the context of megawatt class electric propulsion, NASA related thermal studies for electric aviation have characterized the relevant waste heat as low quality heat below approximately 200°C [143], at this power level, the heat generated can quickly drive air cooled battery thermal management systems to require large heat exchange area, which in turn increases aerodynamic drag and system mass. Compared with air cooling, liquid cooled battery thermal management systems offer higher cooling effectiveness and stronger heat removal capability. They also enable a more compact overall architecture, which is attractive under the tight packaging constraints of aircraft design. The corresponding liquid cooling systems must account for additional concerns such as leakage risk and fluid contamination. Moreover, the added plumbing can introduce new cost and weight penalties. Even so, their superior overall performance has led to wide adoption.

A more forward leaning research direction is to employ thermoelectric cooling as a heat pump technology. This approach uses solid-state Peltier elements, typically flat square modules with characteristic dimensions of a few centimeters. When a voltage is applied across the element, heat is pumped from one side to the other. With this solid-state heat pump mechanism, a cold side temperature below ambient can be maintained even under extreme conditions where ambient temperature is well above the allowable upper limit for battery operation, such as hot day takeoff, hover, or prolonged climb. This enables precise temperature control of critical regions and can cover operating scenarios that are difficult to handle with conventional air cooling or liquid cooling alone. Thermoelectric cooling offers several practical advantages, including small size, low mass, the absence of moving parts, compact structure, and ease of modular integration. It can also provide localized hot spot temperature regulation and can rapidly switch between cooling and heating modes through current reversal. These attributes give it strong potential for onboard applications in space constrained environments and in architectures where multiple heat sources are tightly coupled [144] [147].

On the other hand, when electric aviation adopts a fuel cell and hydrogen-based pathway, the boundary conditions for energy storage thermal management change substantially. Liquid hydrogen storage is intrinsically a cryogenic thermodynamic system. On one side, minimizing boil off losses and ensuring safety require measures such as thick-walled tanks, vacuum insulation, and pressure control, which significantly increase structural mass and overall system complexity. On the other side, liquid hydrogen naturally provides a powerful cold source and a potential platform for coupled cold sink and heat sink integration. For example, hydrogen can be used as a heat absorbing working fluid through heat exchangers to precool the fuel cell stack, the electric machine and drive system, and selected onboard power electronics. Alternatively, within a system level thermal integration framework, appropriately arranging cold and hot loops and the associated heat exchange nodes can reduce the required external radiator area and the associated aerodynamic drag [145] [146].

4.2.3 Thermal Isolation, Heat Conduction, and Heat Rejection Technologies

In electric aviation, the most prominent application of thermal isolation is safety protection for energy storage systems and high-power electronics, particularly for high specific energy batteries. The design objective is to suppress or delay thermal runaway propagation and to confine high temperature conditions and vented products to controlled pathways [148]. Consequently, thermal isolation typically requires a parallel design of an operational heat conduction path and a fault mode insulation path. Under normal operation, heat should be transferred efficiently toward cooling components to minimize temperature gradients. Under fault conditions, thermal barrier materials and structures are introduced between adjacent cells to increase thermal resistance and reduce heat flux. Recent reviews and experimental studies on the suppression of multi cell thermal runaway propagation consistently emphasize that passive insulation barriers can significantly delay temperature rise in neighboring cells and reduce the probability of propagation. In particular, experiments have directly demonstrated that nanofiber aerogel thermal barriers can markedly suppress heat propagation within high energy density battery modules, providing evidence for the effectiveness of introducing insulation layers to mitigate thermal runaway propagation[1]. In addition, combinations of flame-retardant phase change materials and aerogel felts have been explored to further enhance propagation resistance in battery modules [149]. However, the thickness of insulation layers, their compressed assembly state, and their aging conditions can strongly influence effectiveness. Thermal isolation design therefore must be coordinated with the overall energy storage system structure and venting path architecture.

In contrast to thermal isolation, heat conduction and heat spreading technologies address a different class of problems. Hot spots such as motor winding end turns and electrical interconnects often occupy a small volume but exhibit very high local heat flux. If cooling relies only on convection, a typical failure mode can occur in which the average temperature remains moderate while a localized hot spot exceeds its allowable limit. The core objective of thermal conduction design in electric aviation is therefore to transform highly concentrated points like hot spots into area distributed heat sources as much as possible, and to transport the heat to the most appropriate sink location with minimal temperature rise. This can reduce radiator size and the associated drag penalties [150]. Under higher heat flux conditions or when longer distance heat transport is required, passive two phase heat transfer devices such as heat pipe networks and loop heat pipes have attracted increasing attention because of their high effective thermal conductivity and their inherent ability to homogenize temperature. Existing studies on loop heat pipes for avionics and high acceleration environments indicate that such devices can transport substantial heat loads with relatively small temperature differences. However, their stability under vibration, attitude changes, and repeated start up and shut down cycles must be validated under application specific operating conditions, and redundancy-oriented design is often required [151].

Heat rejection technologies define the upper bound of thermal management in electric aviation, because regardless of how heat is isolated and conducted internally, it must ultimately be rejected to the ambient environment. The most widely adopted architecture remains the combination of a liquid cooling loop, a liquid to air heat exchanger, and ram air. Its advantages include technical maturity, straightforward control, and the ability to leverage existing onboard ducting and heat exchange resources, such as those associated with the environmental control system. In the HEATheR concept, part of the waste heat is rejected by convection from selected regions of the aircraft outer mold line (OML cooling), reducing reliance on pumped loops and centralized heat exchangers [152]. Sozer and co-workers performed a computational assessment of this concept and highlighted that conventional pumped loops and heat exchangers impose penalties in parasitic power, aerodynamic drag, and weight. In their analysis of the OML approach, they used outer surface temperature limits based on typical transport aircraft materials, including aluminum alloys and carbon fiber composites, as engineering constraints [153].

Beyond conventional inlet duct heat exchangers, electric aviation is also exploring skin heat exchangers that reject heat through the external aircraft surface. The underlying idea is to utilize direct heat transfer between the wing or fuselage surface and the external flow, thereby reducing internal ducting and heat exchanger volume [154]. Research on the feasibility of skin heat exchangers for hybrid electric aircraft have used computational fluid dynamics to evaluate convective heat transfer capability and aerodynamic impacts across different flight phases. These results suggest that skin-based heat rejection may be particularly promising in high altitude, low temperature environments [155], but practical implementation requires careful assessment of how surface temperature rise affects the boundary layer, drag, and aerodynamic efficiency, and it must address engineering issues such as lightning protection, anti-icing provisions, and maintainability [154].

Overall, the rapid increase in power density in electric aviation propulsion systems has driven a pronounced rise in heat flux per unit area. This trend requires thermal management architectures that can deliver stable and efficient temperature control at low mass, while also incorporating redundancy to meet stringent safety requirements. In current engineering practice, liquid cooling loops paired with liquid to air heat exchangers remain the dominant solution. In parallel, driven by the thermal safety demands of onboard energy storage, ongoing development is emphasizing more refined hot spot mitigation, thermal isolation strategies, and novel heat rejection pathways, with the aim of enabling safe and sustainable integration of high-power electric aviation systems.

4.3 High performance power electronics and electric power system architecture

As MEA continue to evolve toward hybrid electric and fully electric propulsion architectures, onboard electrical power systems are shifting from traditional auxiliary subsystems to core systems of comparable importance to the propulsion unit itself. From the perspective of the energy chain, regardless of whether the primary energy source is electrochemical energy storage, such as batteries or fuel cells, or electrical power generated by a turbine-driven generator, both propulsion and onboard loads typically undergo a power processing sequence involving DC bus integration, multi-stage power conversion, and electric motor drive. In this process, power electronic converters serve not only as energy interfaces, but also as carriers of system level functions, such as bus voltage conversion, zonal power supply and power scheduling, fault detection and isolation, including circuit interruption and current limiting, power quality and harmonic control, as well as coordination with thermal management and health monitoring, all rely heavily on the co-design of power electronics and power distribution architectures [156] [157].

The increase in power rating further intensifies these challenges. In MEA platforms represented by the Boeing 787, the onboard non-propulsive electrical power capacity and demand have already reached the megawatt level. For single aisle aircraft and configurations with higher levels of electric propulsion penetration, system level studies and conceptual designs frequently involve electrical power requirements of 1-3 MW or even higher, together with higher distribution voltages and more stringent constraints related to high altitude insulation and electrical discharge [158]. Therefore, whether power electronics and electrical power system architectures can achieve an optimal balance among weight, efficiency, reliability, and airworthiness will determine whether advanced energy storage technologies can be translated into range and payload advantages at the aircraft level. This also implies that conventional onboard power supply technologies based on silicon devices and low-voltage 115 V/400 Hz architectures are increasingly inadequate for future electric aviation. Innovations must therefore be pursued simultaneously at both the device level and the system level.

4.3.1 High Performance Power Electronic Devices

At the device level, wide-bandgap (WBG) semiconductors are becoming a key enabling technology for improving the specific power, efficiency, and high temperature reliability of onboard power electronics. Compared with conventional silicon devices, SiC and GaN devices offer stronger electric field withstand capability, lower specific on-resistance, and a wider high temperature operating window due to their larger bandgaps. These advantages allow power converters to achieve lower losses and higher power density at higher switching frequencies and higher voltage levels [159], thereby driving the evolution of aircraft electrical systems toward higher frequency operation, miniaturization, and increased power density.

In terms of device selection, current studies generally suggest that SiC devices offer greater advantages in voltage rating, thermal capability, and engineering maturity for applications above 650 V and even at the kilovolt level. By contrast, in low voltage, high frequency DC/DC conversion and local drive applications below 650 V, GaN devices are more competitive due to their faster switching characteristics and potential for high frequency integration [159]. In existing aviation applications, experimental validation has been conducted using 1200 V SiC power modules in a three-phase inverter prototype based on a 540 V DC bus, demonstrating the engineering feasibility of SiC devices in high voltage bus interfaces and high-power density inverter systems [160]. For bidirectional DC/DC power converters, topology reviews for future hybrid electric and fully electric aircraft have systematically compared device combinations such as SiC/Si and SiC/GaN in terms of efficiency and loss distribution, highlighting the value of WBG devices in high efficiency and lightweight designs. Meanwhile, several megawatt-class prototypes for electric aviation have already been developed, including megawatt level hybrid Si/SiC multilevel inverters for electric propulsion [161], megawatt-class medium voltage three-level ANPC inverters for hybrid electric propulsion [162], and 3 kV, 4 MW high power medium voltage active rectifiers for demonstration systems [163]. These developments indicate that the combination of medium voltage DC distribution, WBG devices, and multilevel topologies represents one of the main pathways for achieving a step change in power rating. From a broader statistical perspective, WBG devices can significantly improve the power density of typical conversion equipment such as motor drives, reaching approximately two to three times higher power density in certain representative categories. This further supports the industry expectation that WBG technologies can reduce the volume and mass of passive components and thermal management systems while improving overall system efficiency [159].

4.3.2 Voltage Levels and Electrical Power System Architecture

For electric and hybrid electric propulsion in large aircraft, once propulsive electrical power reaches the megawatt range, electrical power system design is primarily governed by the choice of voltage level. Increasing the bus voltage can significantly reduce current magnitude and conductor weight, while also alleviating thermal management requirements. However, this also comes at the cost of thicker insulation layers, increased cable weight, and other associated penalties. Therefore, research on electric propulsion for large aircraft emphasizes the need to establish new aviation power distribution voltage standards, since voltage selection simultaneously affects the configuration and sizing of almost all related equipment, including protection devices, distribution systems, control systems, power converters, generators, and cooling systems [164]. At present, standardized voltage levels have been established for onboard DC microgrids, such as 28 V, 270 V (±135 V), and 540 V (±270 V). Driven by the requirements of electric propulsion, these architectures are being further extended toward kilovolt level MVDC/HVDC systems. The objective is to reduce transmission current, cable size, and mass penalties in high power applications while keeping insulation requirements within a manageable range [165].

For electric and hybrid electric propulsion, research attention is further shifting toward onboard DC microgrids centered on high voltage DC distribution. In such architectures, multiple controllable power converters are employed to connect generators, fuel cells, batteries, supercapacitors, and other multi source energy supply units, as well as various electric propulsion drives and onboard loads, to one or more HVDC/MVDC buses. This enables zonal power distribution, power sharing, and network reconfiguration control. This type of converter dominated power network elevates power electronics from being merely energy conversion components to becoming the core of system stability and reliability design [166].

For large aircraft MVDC architectures, the major engineering challenge is often not whether energy can be transmitted, but whether faults can be rapidly and selectively isolated while the system continues to supply critical loads. Since DC systems lack natural current zero crossings, fault interruption relies more heavily on solid-state or hybrid solutions. Under assumed high voltage and high current operating conditions for turboelectric propulsion power networks, NASA has systematically compared and evaluated three technological routes for DC circuit breakers: mechanical, cryogenic solid-state, and cryogenic hybrid approaches. Based on this analysis, NASA further proposed standardization recommendations for medium voltage DC power systems in future aerospace propulsion applications. However, from the perspective of engineering maturity, this field remains at a developmental stage. At present, more mature and widely applied DC interruption and protection solutions are mainly concentrated in the marine sector. The main reason is that aviation platforms are extremely sensitive to weight, volume, and integration density. As a result, device redundancy, cooling capacity, and structural mass that may be acceptable in shipboard applications are often difficult to tolerate in aviation scenarios. This has caused the two application domains to gradually diverge in terms of requirement constraints and technological development pathways, forming relatively independent fields of application [164].

In addition, high altitude and low-pressure environments can significantly reduce insulation margins. Relevant studies have clearly indicated that a reduction in ambient pressure leads to a decrease in the partial discharge inception voltage of insulation systems, thereby increasing the likelihood of partial discharge during aircraft or spacecraft operation. Therefore, any increase in bus voltage must be accompanied by a coordinated assessment of insulation structures, creepage and clearance distances, and material systems [167].

Overall, for the megawatt class development of electric and hybrid electric propulsion, onboard power electronics and electrical power systems are shifting from improving the efficiency of individual components toward system level reconfiguration driven by voltage level selection. Owing to their high voltage blocking capability, low losses, and high frequency operation, WBG devices provide engineering feasibility for power converters operating at higher switching frequencies and higher power densities. As propulsive power enters the megawatt range, increasing the DC bus voltage will become a key pathway for reducing current levels and cable mass while alleviating thermal management pressure. However, this will also substantially increase the challenges associated with insulation design, electromagnetic compatibility, and DC fault interruption. Based on current prototype development trends, the foreseeable technical pathway can be summarized as "medium voltage DC architecture + WBG devices + multilevel/modular topologies + converter dominated DC microgrid control." Whether this pathway can be implemented at scale will depend on the engineering maturity of DC protection and selective fault isolation, including lightweight solid-state or hybrid circuit breakers, rapid fault detection, and network reconfiguration strategies, as well as high voltage insulation and partial discharge lifetime assessment standards, high power density packaging, and thermal management at the system engineering level.

4.4 High power density motor technology

In electrification schemes for aircraft engines, high power density electric machines are not designed merely to pursue higher output power. Rather, their objective is to achieve comprehensive optimization of torque per unit rotor volume, specific power, low vibration, and low torque ripple under stringent constraints on mass, volume, and reliability [168]. Compared with ground transportation systems, aviation applications are far more sensitive to specific power and system integration. Therefore, electric machine design cannot rely simply on the scaling up of conventional industrial motors, but must instead involve targeted optimization at the levels of electromagnetic topology, magnet utilization, winding configuration, and slot pole combination [169]. In current research on more electric and fully electric aircraft propulsion, permanent magnet machines remain the most practically feasible mainstream option due to their high efficiency and high-power density. However, their final performance is not determined solely by magnet materials, but depends strongly on structural topology, rotor magnet arrangement, and the matching relationship between the number of pole pairs and the number of stators slots [168] [169].

For aircraft engine electrification, the core design issues of high-power density electric machines can be summarized along three main dimensions. First, different machine structural topologies determine the fundamental pathways of electromagnetic energy conversion and the corresponding modes of mechanical integration. Second, the arrangement of permanent magnets affects the air gap flux density, field weakening capability for high-speed operation, mechanical strength, and magnet utilization. Finally, the number of pole pairs and the slot pole combination further influence the winding factor, harmonic content, cogging torque, and additional losses [169] [170]. Therefore, this section focuses on these three design dimensions, which directly determine the upper limits of electromagnetic performance, in order to establish an analytical framework for high-power density electric machines suitable for aircraft engine electrification scenarios.

4.4.1 Electric Machine Structural Topologies

From the perspective of structural topology, radial-flux permanent magnet machines (RFPMs) and axial-flux permanent magnet machines (AFPMs) remain the two most important research directions in aircraft propulsion and aircraft engine electrification.

In radial-flux machines, the stator and rotor are arranged in a cylindrical configuration, which can be further classified into three main types: inner-rotor, outer-rotor, and dual-rotor structures [171]. As a type of permanent magnet synchronous machine, the RFPM offers several advantages, including mature manufacturing processes, robust mechanical structure, high rotor integrity, and better suitability for high-speed operation. Its efficiency and power density are also higher than those of machines using other excitation methods [172] [173]. Therefore, when the electric machine needs to be coupled with the shaft system of a conventional aircraft engine and operate over a relatively high-speed range, the RFPM is generally regarded as a more realistic engineering solution. The dual-rotor machine, however, exhibits more pronounced performance advantages over the former two configurations. Under the same machine outer diameter, axial length, and efficiency, the dual-rotor configuration can achieve the lowest overall machine mass and the highest power density, with a power factor close to unity. But, due to its more complex structure, the dual-rotor machine is not as widely adopted as the inner-rotor and outer-rotor configurations [171].

Axial-flux machines employ disc-shaped stator and rotor structures and can be classified into single-rotor and dual-rotor configurations [174], in addition to the high efficiency and high-power density inherent to permanent magnet synchronous machines, AFPMs also offer several distinctive advantages. First, compared with radial-flux machines, axial-flux machines close their magnetic flux paths in the axial direction, which typically enables higher torque density and a more compact disc-type structure within a shorter axial length. As a result, they are particularly attractive for applications with limited installation space, flattened layout requirements, or distributed propulsion architectures. Second, axial-flux machines are favorable for increasing the number of pole pairs. These advantages allow AFPMs to offer superior power-density potential compared with radial-flux machines [175]. Furthermore, under comparable dimensional constraints, the rotor moment of inertia of an axial-flux machine is lower than that of a radial-flux machine. This enables faster dynamic response and objectively facilitates the design of higher bandwidth controllers. Such controllers can effectively drive the propulsor over the entire operating range and help prevent stalling during operation [176]. However, the advantages of AFPMs do not imply that they are superior to RFPMs in all aviation scenarios. Axial-flux machines generally have larger rotor diameters and require more complex bearing arrangements, which makes it difficult to increase rotational speed. In addition, their structural characteristics are not inherently favorable for heat dissipation and cooling. For systems involving the electrification or retrofit of conventional turbofan or turboshaft engines, axial-flux structures still face engineering challenges related to axial force control, rotor-disc strength, manufacturing complexity, and assembly tolerances. Moreover, the power level of axial-flux machines has not yet reached the megawatt-class scale required by civil aviation fuel-based aero-engines. Therefore, AFPMs are more appropriately regarded as an advanced topology with high potential, rather than a direct replacement for radial-flux solutions in all application scenarios [168] [169] [177].

In addition to radial-flux permanent magnet machines and axial-flux permanent magnet machines, transverse-flux machines (TFMs), flux-switching machines (FSMs), and superconducting machines are also frequently considered as potential complementary solutions for aircraft electric propulsion. The main attraction of TFMs lies in their high theoretical torque density and power density, making them particularly suitable for low-speed direct drive applications. However, TFMs suffer from relatively large leakage flux, low power factors, pronounced cogging torque, many structural components, and high manufacturing and system integration complexity. These limitations continue to restrict their large-scale engineering application [178]. By contrast, FSMs place both the permanent magnets and windings on the stator side, while the rotor contains no windings and has a relatively robust structure. This configuration provides relatively high-power density, favorable potential for stator side thermal management, and considerable design flexibility for fault tolerant operation. As a result, FSMs are attractive for high-reliability aviation electric drive applications. But such machines typically belong to the doubly salient topology, which can lead to relatively large cogging torque and torque ripple. They also face design challenges related to local magnetic saturation, phase decoupling, and control under fault conditions [179]. As for superconducting machines, they exhibit the highest potential specific power in megawatt class aircraft electric propulsion. Some studies have shown that fully superconducting high temperature superconducting machines (HTSMs) can achieve power densities as high as 25 kW/kg [180]. However, their performance advantages depend heavily on the support of cryogenic systems. AC losses, cooling penalties, safety concerns, and whole-aircraft integration remain key issues that have not yet been fully resolved [181]. Therefore, although these topologies are attractive in certain specific performance indicators, such as higher theoretical torque density or stronger fault tolerance, from the perspective of current engineering maturity they are more appropriately regarded as reserve solutions for specific missions and medium to long term development, rather than mainstream routes capable of broadly replacing RFPMs or AFPMs in the near term.

4.4.2 Permanent Magnet Arrangement

If structural topology defines the overall design envelope of an electric machine, permanent magnet arrangement further determines whether high power density can be effectively converted into usable electromagnetic output. The permanent magnet configurations commonly used in aircraft electric propulsion machines can generally be classified into surface mounted and interior arrangements. Surface mounted permanent magnet (SPM) rotors are often regarded as a fundamental option for high power density designs because of their simple magnetic circuit, direct establishment of the air gap magnetic field, and relatively straightforward manufacturing process. By contrast, interior permanent magnet (IPM) rotors can not only generate permanent magnet torque, but also introduce reluctance torque, thereby providing superior field-weakening capability and a wider constant-power operating region under the same voltage constraints [182]. This feature is particularly important for aircraft engine electrification, since practical operating conditions often require the machine to operate stably over different speed ranges. Merely pursuing high static peak torque is therefore insufficient to demonstrate system level applicability. As a result, IPM solutions generally offer more comprehensive advantages in terms of high specific power, wide speed range operation, and compatibility with high-speed operation.

In designs aimed at further increasing power density, the spoke-type permanent magnet structure represents a typical flux-concentrating configuration. By modifying the orientation of the magnets inside the rotor, this structure increases the effective air gap flux density, making it particularly attractive for applications seeking higher torque density [183]. However, it should be noted that flux concentration does not provide a “free gain.” Relevant studies have shown that while spoke-type structures can achieve higher air gap flux density, they are also more prone to larger cogging torque and harmonic effects. Therefore, compensation measures such as rotor slotting, structural shaping, or other suppression techniques are required [184]. From the perspective of aviation applications, spoke-type structures offer significant potential for improving power density. But their implementation depends on whether the system can accommodate higher design complexity. In addition, dedicated optimization and control strategies are required to mitigate vibration and torque ripples.

Another technical route worthy of attention is the Halbach array. A Halbach array is typically approximated by multiple permanent magnets segments whose magnetization directions rotate spatially according to a prescribed pattern. Its defining characteristic is that it strengthens the magnetic field on the working side while significantly weakening the flux on the back side, which is known as the one-sided flux-concentration effect. Based on this mechanism, Halbach rotors can help increase the air gap flux density and improve the sinusoidal characteristics of both the air-gap magnetic field and the back electromotive force waveform [185]. Based on this mechanism, Halbach rotors can help increase the air-gap flux density and improve the sinusoidal characteristics of both the air-gap magnetic field and the back electromotive force waveform [186]. In topologies that emphasize lightweight design and high specific torque, such as axial flux, coreless, or yokeless machines, the Halbach configuration can also reduce or even eliminate the need for rotor back iron. This further releases the potential for higher torque density and specific power and therefore continues to attract attention in high end applications such as electric aircraft propulsion and urban air mobility [186] [187]. However, Halbach solutions usually require a larger number of magnet segments, more complex magnetization processes, and more demanding assembly and mechanical design. In many designs with comparable dimensions, they may also increase the amount of permanent magnet material required. Therefore, compared with conventional surface mounted structures, Halbach configurations generally involve higher material and manufacturing costs.

Against the background of continuing concerns over rare earth permanent magnet price fluctuations and supply security, the consequent pole structure has attracted considerable research interest because it can improve magnet utilization and reduce rare earth material consumption. Its main advantage lies in replacing part of the permanent magnet poles with iron poles, thereby significantly reducing the required magnet volume. Some studies even indicate that conventional consequent-pole designs can achieve approximately 50% magnet savings [188], However, due to the inherent asymmetry in pole arrangement and magnetic circuit distribution, this structure can easily lead to asymmetrical air gap magnetic fields and back EMF waveforms, accompanied by larger cogging torque, torque ripple, and even more pronounced electromagnetic vibration. Therefore, improvements are usually required through rotor geometric optimization, hybrid pole design, or harmonic-suppression structures [189] [190]. This indicates that, in aircraft electric machine design, the optimization of permanent magnet arrangement should not focus solely on maximizing flux density. Instead, magnet utilization, losses, vibration, and manufacturing complexity must also be considered simultaneously. In other words, the permanent magnet configuration truly suitable for aircraft engine electrification is not the one that optimizes a single performance indicator, but rather the one that achieves a comprehensive balance among output capability, wide speed range operation, vibration constraints, structural reliability, and magnet economy.

4.4.3 Pole Pair Number and Slot Pole Combination

In the design of high-power density permanent magnet machines, the number of pole pairs and stator slots are not merely geometric parameters for winding arrangement, but important design variables that determine the boundaries of electromagnetic performance. This is because the slot pole combination affects the magnetomotive force, the harmonic spectrum of the air-gap magnetic field, cogging torque, radial electromagnetic forces, and vibration levels [191].

Fractional-slot concentrated windings (FSCWs) have continued to attract attention in high-power density permanent magnet machines. One important reason is that their non-overlapping coil structure can significantly shorten the axial length of the machine, making them more suitable for space constrained applications. This structure also facilitates a higher slot fill factor, thereby helping to reduce copper losses and improve output capability per unit volume. In segmented stator structures, these advantages in compactness and manufacturability are usually even more pronounced [192].

For aircraft propulsion applications, where reliability, specific power, and power density requirements are particularly stringent, the compact and lightweight characteristics of FSCWs have greater engineering value. Therefore, FSCWs are often regarded as one of the important candidate solutions for high-pole number, high-power density permanent magnet propulsion machines [193].

However, FSCWs and high-pole number designs also involve non negligible trade-offs. First, if the slot–pole combination is not properly selected, the magnetomotive force harmonics generated by concentrated windings may be intensified, further aggravating torque ripple, radial electromagnetic force fluctuations, and the resulting noise and vibration problems [192]. Second, at a given mechanical speed, an increase in the number of pole pairs makes stator iron loss, permanent magnet eddy current loss, and other high frequency additional losses more sensitive. This can lead to overheating and may further result in thermal demagnetization, which is particularly critical in high-speed permanent magnet machines [192] [194]. Therefore, high-power density design does not imply that a higher number of pole pairs is always preferable. Instead, the pole-pair number should be jointly optimized according to the target speed range, power supply frequency constraints, cooling capability, and allowable loss limits.

In summary, from the perspective of aircraft electrification, FSCWs and high-pole number designs offer clear advantages in shortening end windings, increasing slot fill factor, and improving output capability per unit volume. These characteristics align well with the requirements of aircraft propulsion systems for lightweight design and high integration. However, such solutions do not achieve optimal performance simply by increasing the number of pole pairs. If the slot–pole combination is not properly designed, stronger magnetomotive force harmonics, larger torque ripple, more pronounced radial electromagnetic forces, and higher iron losses and rotor additional losses may be introduced, thereby adversely affecting noise, vibration, thermal management, and operational reliability. This issue is particularly critical for high-speed aviation electric machines, where these increase can rapidly amplify losses and thermal risks, offsetting part of the advantages gained in static power density. Therefore, high-power density electric machine design for aircraft electrification should not aim at maximizing a single electromagnetic indicator. Instead, it should pursue system level comprehensive optimization among output capability, efficiency, cooling conditions, vibration constraints, and structural reliability.

4.4.4 Trent 1000 and Aircraft Electrification

The Trent 1000 is a three spool, high bypass ratio turbofan engine developed by Rolls-Royce for the Boeing 787 Dreamliner. It is not an electric propulsion engine, but a high bypass ratio turbofan optimized for the MEA architecture. As such, it represents one of the most realistic, mature, and engineering feasible pathways for the electrification of large civil aero engines. According to official Rolls-Royce materials, the Trent 1000 was specifically designed and optimized for the Boeing 787. Its three-spool architecture provides improved compatibility with the 787's "all electric" bleedless engine system, thereby enabling more stable engine cycle operation.

In the bleedless architecture of the Boeing 787, aircraft systems no longer rely heavily on compressor bleed air from the engines, as is typical in conventional airliners. Instead, electrical power is supplied by engine-driven generators, which can provide up to approximately 500 kW of electrical power for aircraft systems. The total generator output from the two engines is about 1 MW, supporting functions such as cabin air conditioning and wing anti-icing, which traditionally depend on pneumatic bleed air. This medium power shaft power extraction approach not only supplies energy to the aircraft electrical system but also improves engine handling and operational stability under low power operating conditions [195].

From the perspective of aircraft systems, the electrified architecture of the Boeing 787 converts many functions traditionally performed by pneumatic systems into electrically driven functions. This architecture eliminates the conventional pneumatic system and bleed air manifold, replacing bleed air dependent functions such as air conditioning packs and wing anti-icing with electrically powered alternatives. Its electrified functions also include engine starting, high-capacity hydraulic pump driving, and power supply for the cabin environmental control system, while improving the efficiency of secondary power extraction. Relevant sources indicate that this architecture is expected to deliver approximately 3% fuel savings and improve engine fuel consumption by about 1%–2% under cruise conditions [196].

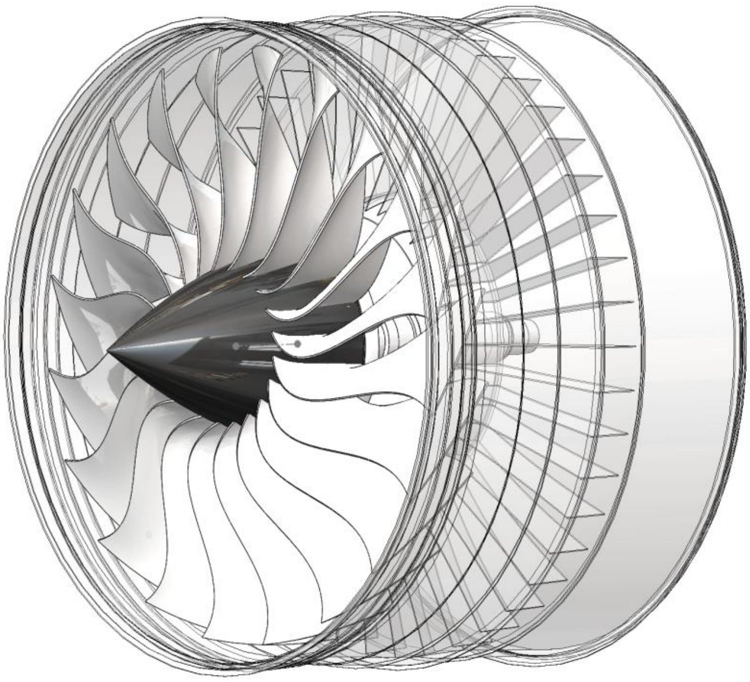

Figure 4.3: Fan system for Trent 1000

The figure illustrates the front fan of the engine and its relative position with respect to the engine core. The fan system generates most of the propulsive thrust by accelerating a large mass flow of bypass air, making it a critical component for maintaining high propulsive efficiency in large civil aero engines. Rolls-Royce states that the Trent 1000 has a bypass ratio of 10:1, and that its 2.8m diameter fan produces more than 85% of the engine's total thrust [195]. Therefore, in the field of large commercial aircraft, the current direction of electrification does not primarily imply directly eliminating the fan system or completely replacing the gas turbine with an electric motor. Instead, it focuses on electrification upgrades to engine accessory systems, power extraction methods, and aircraft energy distribution architectures while retaining the propulsive advantages of high bypass ratio fan propulsion.

This case demonstrates that the near-term application focus of high-power density electric machine technologies in the electrification of large civil aero engines is not the immediate replacement of gas turbine main propulsion with electric motors. Instead, it is first reflected in high power generators, starter generators, motor driven accessories, power electronic conversion systems, and electrified energy management systems. For large commercial aircraft, the requirements for range, payload, safety, and airworthiness certification are extremely demanding, and fully electric propulsion still faces significant engineering challenges. Therefore, the technological route represented by the Trent 1000 and Boeing 787, namely "high bypass ratio turbofan propulsion combined with a bleedless more electric system," is currently one of the most realistic, mature, and scalable pathways for achieving aircraft electrification in large civil aviation. By using high-power density electric machines, advanced generation systems, and power electronic technologies to electrify aircraft accessory systems and secondary energy systems, this approach not only satisfies the current requirements of large commercial aircraft in terms of range, payload, and reliability, but also lays an engineering foundation for future hybrid electric propulsion engines and higher levels of aircraft electrification.

5. Conclusion and Outlook

In summary, the electrification of aero engines represents an important technological pathway for the aviation industry to achieve low carbon, low noise, and high efficiency development. As global pressure to reduce aviation emissions continues to increase, conventional fuel-based propulsion systems alone are becoming increasingly insufficient to meet the future requirements of air transportation in terms of both environmental performance and operational efficiency. Electrified aero engines provide a new direction for the development of aircraft propulsion systems and offer greater potential for optimization in energy utilization, noise reduction, system redundancy, and aircraft configuration design.

From the perspective of current development, electric aero engines have gradually progressed from early-stage concept validation toward engineering flight testing and airworthiness verification. Representative projects have emerged in areas such as small fully electric aircraft, hybrid electric commuter aircraft, turboelectric distributed propulsion concepts, and hydrogen fuel cell aircraft. These developments indicate that electric propulsion technology is expanding from low power, low payload platforms toward higher power systems, longer ranges, and more complex mission scenarios. However, the applicable scope of different technological routes varies significantly. Fully electric propulsion is more suitable for short range flights, flight training, and urban air mobility. Hybrid electric and turboelectric propulsion are more appropriate as medium to short term transitional solutions, while hydrogen electric hybrid propulsion shows considerable potential for medium- and long-term regional aviation. Therefore, the future development of electric aero engines will not be dominated by a single technological pathway. Instead, it will require systematic matching according to aircraft seating capacity, range, mission profile, and infrastructure conditions.

At present, the core constraints limiting the further development of electric aero engines do not arise merely from insufficient performance of individual components, but from the system level trade-off among lightweight energy storage, efficient power transmission, high performance electric machines, and stable thermal control. High energy density energy storage determines aircraft range and payload capability; high performance power electronics determine energy transmission efficiency and system reliability; high power density electric machines determine the miniaturization and integration capability of propulsion units; and thermal management technologies determine whether these performance advantages can be maintained stably over long operating durations and with sufficient safety margins. This is particularly critical in aviation applications, where any improvement in power density simultaneously introduces new challenges related to heat dissipation, insulation, structural strength, redundancy design, and airworthiness certification. Therefore, future research should shift from the optimization of individual performance indicators toward multidisciplinary collaborative design integrating electromagnetic, thermal, structural, control, and airworthiness considerations.

In terms of energy storage technologies, Li batteries remain the most engineering feasible solution in the near term. However, their limited system level specific energy restricts the application of fully electric aircraft in large capacity and long-range scenarios. Although Li-S and Li-Air batteries offer higher theoretical energy densities, they still face challenges related to cycle life, safety, and engineering scale up. Hydrogen fuel-cell systems have advantages in terms of system level energy density and zero carbon emissions, but they also require solutions to issues such as hydrogen storage volume, cryogenic or high-pressure safety, fuel-cell power density, and airport refueling infrastructure. It can therefore be seen that future aviation energy systems are likely to develop into a multi energy configuration. In the short term, development will rely mainly on high performance Li batteries and hybrid electric systems; in the medium term, hydrogen fuel cells and hybrid electric propulsion will become increasingly important; and in the long term, higher-potential technologies such as Li-Air batteries, solid-state batteries, and superconducting electric machines may be further explored.

Overall, electric aero engines represent an important direction in the transformation of aviation power systems from conventional thermomechanical propulsion toward electrification, intelligent operation, and system level integration. Although current technologies remain clearly insufficient for the large-scale replacement of conventional civil turbofan engines, their application prospects in small aircraft, commuter aviation, regional transport, and special purpose flight missions are becoming increasingly evident. In the future, with the continuous advancement of high specific energy storage, high efficiency power conversion, high power density electric machines, lightweight thermal management, and airworthiness certification standards, electric aero engines are expected to play an increasingly important role in aviation emission reduction and the development of next-generation aircraft.

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