Energy & Environmental Science

ROYAL SOCIETY OF CHEMISTRY

REVIEW

View Article Online
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Cite this: *Energy Environ. Sci.*, 2025, **18**, 9786

Sustainable propulsion and advanced energy-storage systems for net-zero aviation

Ningaraju Gejjiganahalli Ningappa, Karthik Vishweswariah, Sabbir Ahmed, Mohamed Djihad Bouguern, M. R. Anil Kumar and Karim Zaghib *

The transition of the aviation industry toward sustainable propulsion requires transformative shifts in energy systems, storage technologies, and emission strategies. This review critically assesses sustainable aviation fuels (SAFs), hydrogen fuel cells, advanced batteries, and hybrid-electric powertrains in pursuit of net-zero goals. SAFs provide up to 89% lifecycle CO_2 reduction and are compatible with the existing infrastructure but face limitations in terms of feedstock supply, production cost, and global scalability. Hydrogen, with a gravimetric energy density of $\sim$120 MJ kg^{-1}, exhibits long-term potential but is constrained by cryogenic storage and airframe redesign requirements. Electric aviation has been advancing through lithium-ion, lithium–sulfur (400–600 Wh kg^{-1}), and solid-state chemistries; however, current energy densities limit the range and payload. Hybrid-electric propulsion systems with series, parallel, or turboelectric configurations, exhibit enhanced emission reduction and energy management, particularly when paired with SAFs or hydrogen. Demonstrators such as Airbus EcoPulse, Rolls-Royce E-Fan X, and Ampaire Electric EEL have validated hybrid-electric and SAF feasibility, while hydrogen-powered flights are being advanced by H2FLY's HY4 and ZeroAvia's Dornier 228. Lifecycle assessments show 57–88% per-revenue passenger-kilometer (RPK) emission reduction. Future scalability depends on improved safety, thermal management, recyclability, material innovation, dual certification, and harmonized policies. This roadmap underscores the need for coordinated technological, regulatory, and industrial efforts to realize a resilient and sustainable aviation ecosystem.

Received 23rd May 2025,
Accepted 9th October 2025

DOI: 10.1039/d5ee02865e

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Broader context

The aviation sector faces an urgent challenge in balancing global connectivity demands with the imperative to reduce greenhouse gas emissions. While contributing 2–3% of global CO_2 emissions, the sector's overall climate impact is significantly amplified due to non-CO_2 effects at high altitudes. With air traffic expected to double by 2050, emissions could grow unchecked without technological intervention. Unlike ground transport, aviation is constrained by strict energy-to-weight and safety requirements, making decarbonization far more complex. This review addresses this critical challenge by evaluating the technological maturity, energy efficiency, lifecycle emissions, and integration feasibility of emerging propulsion and storage technologies, sustainable aviation fuels, hydrogen fuel cells, lithium-based batteries, and hybrid-electric systems. We highlight how demonstrator aircraft, hybrid architectures, and solid-state batteries pave the way toward cleaner skies. Our analysis integrates insights from lifecycle assessment, safety, certification, and recycling, making it highly relevant for policy, industry, and research communities. The work is a timely roadmap for aligning technological innovation with regulatory and infrastructure developments, offering actionable strategies for achieving net-zero aviation within a rapidly evolving energy landscape.

1. Introduction

Aviation is a crucial enabler of global mobility and economic development; however, it is also a principal cause of climate change. Although this sector contributes only 2–3% of global CO_2 emissions, its net radiative forcing effect, encompassing contrails, nitrogen oxides (NO_x), and cirrus clouds, is estimated to be 1.5 to 2 times higher than that due to CO_2 emissions alone.[1] In 2023, aviation emissions were nearly 882–950 million tons of CO_2, representing about 2.05% of global anthropogenic CO_2 emissions, and reached more than 90% of pre-COVID-19 levels. With global air traffic anticipated to grow by 3.6–5% per year, emissions are projected to double or triple by 2050, potentially contributing up to 10–11% of global CO_2 emissions unless dramatic shifts in power plant and storage technologies are implemented (Fig. 1a).[2,3] Despite improvements in fuel

Department of Chemical and Materials Engineering, Concordia University, 1455 De Maisonneuve Blvd. West, Montreal, Quebec H3G 1M8, Canada. E-mail: karim.zaghib@concordia.ca

efficiency averaging around 1.25% annually, growth in demand has outpaced efficiency gains, with notable emissions growth from private aviation rising by 46% between 2019 and 2023, further intensifying the sector's climate footprint. In contrast to terrestrial transport, where electrification is already advanced, aviation faces inherent constraints related to energy density, weight, and long-range flight requirements, making decarbonization a uniquely difficult challenge (Fig. 1b).[4,5] Current solutions heavily rely on fossil-based jet fuels, necessitating an immediate shift to renewable energy-storage systems that facilitate long-range flight while maintaining high performance and safety levels.[6]

Achieving net-zero aviation demands a paradigm shift to alternative low-gravimetric-mass carriers with high gravimetric energy density, efficiency, and regulatory acceptability. Today, sustainable aviation fuels (SAFs) are the best short-term options available, with drop-in compatibility with the current aircraft and lower life-cycle emissions (Fig. 2a).[8] Recent technological

Ningaraju Gejjiganahalli Ningappa

Ningaraju Gejjiganahalli Ningappa is a doctoral researcher at Concordia University, specializing in advanced energy storage systems. He earned his master's in chemistry from JSS Science and Technology University (JSS STU), India, in 2023. His research focuses on developing polymer electrolytes for lithium batteries and beyond to enhance their safety and performance. He has published articles on advanced polymer electrolytes in solid-state batteries (2024) and addressing critical aspects of electrolyte design, interfacial behavior, and safety strategies for dendrite-free metal anodes in next-generation battery chemistries (2025). His research addresses significant challenges in lithium-ion transport and electrolyte stability, with a strong dedication to advancing efficient and sustainable battery technologies.

Karthik Vishweswariah

Karthik Vishweswariah is currently engaged as a doctoral researcher at Concordia University, where his research endeavors encompass advanced energy storage systems. He acquired his Master of Science in Chemistry from JSSSTU, India, in 2023. His research primarily focuses on the development of ionic liquid electrolytes for lithium batteries, with the objective of enhancing their safety and performance metrics. Karthik has contributed to the academic discourse through publications detailing ionic liquid electrolytes for lithium-ion batteries (2024) and investigations into lead complexes as energy storage devices utilizing Quantum Theory of Atoms in Molecules (QTAIM) studies (2023). His scholarly work addresses significant challenges associated with lithium-ion transport mechanisms and electrolyte stability, thereby advancing the field of more efficient and sustainable battery technologies.

Sabbir Ahmed

Sabbir Ahmed is a graduate researcher (MSc) at Concordia University. He obtained his degree in Chemical Engineering from Shahjalal University of Science and Technology in Bangladesh and has several years of experience as a process engineer in chlor-alkali plants. Recently, he published a paper discussing the transformation processes of critical lithium ores into battery-grade precursors (2024). His research primarily focuses on lithium mining and the precursors used for lithium-ion battery cathode materials. Mr. Ahmed addresses the challenges associated with lithium extraction methods and explores sustainable solutions. He is dedicated to advancing efficient, sustainable, and environmentally friendly practices in lithium mining.

Mohamed Djihad Bouguern

Mohamed Djihad Bouguern is a PhD researcher in chemical engineering, specializing in lithium-ion batteries and energy storage technologies. His work focuses on dry electrode processes, solid-state batteries, and interface engineering. He has published several papers, including The Critical Role of Interfaces in Advanced Li-Ion Battery Technology (2024) and Engineering Dry Electrode Manufacturing for Sustainable Lithium-Ion Batteries (2024). His research also covers perovskite-based photo-batteries and the evolution of solid electrolyte interphase thickness. Bouguern is dedicated to advancing sustainable and efficient battery solutions.

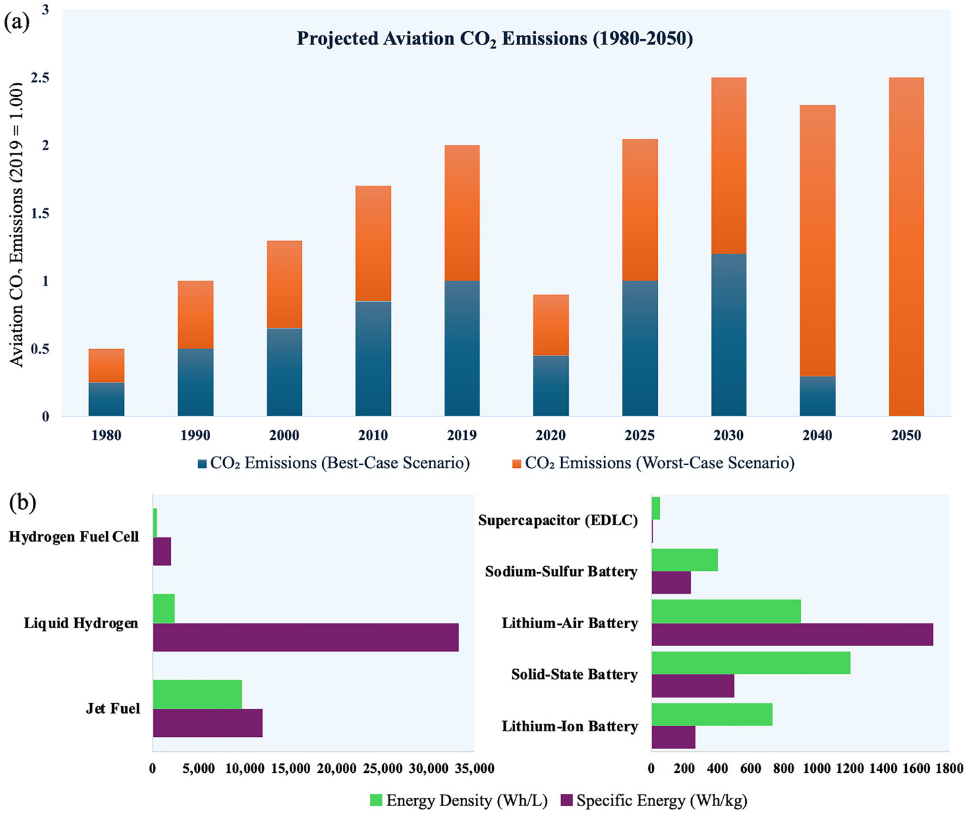


Fig. 1 (a) Aviation CO_2 emission trends under best-case (1.6 °C) and worst-case (2.3 °C) scenarios, highlighting historical data and future projections. Adapted with permission from ref. 7. Copyright 2023, International Council on Clean Transportation. (b) Comparison of energy-storage technologies for aviation.

advancements in SAFs have led to carbon-neutral solar-fuel production, such as Synhelion's development of solar-driven fuel synthesis with up to 20% conversion efficiency. While SAFs remain the most viable near-term solution, expert consensus increasingly suggests that if challenges related to cost, feedstock scalability, and indirect land-use impacts are resolved, SAFs could serve as the primary pathway to decarbonizing long-haul aviation. However, the resolution of these barriers remains

M. R. Anil Kumar

Dr Anil Kumar Madikere Raghunatha Reddy received his PhD degree in Chemistry, his secure research experience of more than 12 years, He published 85 research papers in the reputed international peer reviewed Journals, published 6 books, 8 book chapters, published two Indian Patent, reviewer for Elsevier journals and he also the member of various committees for the inspection of new as well as old engineering institutions. He served as a Member, Board of Examiners, chemistry Composite Board & Board of Examiner and thesis evaluator. His research areas of interest Nano Science & Technology, Lithium-ion battery and beyond, Materials Science and photocatalysis.

Karim Zaghib

Professor Karim Zaghib is a globally recognized expert in electrochemistry, lithium-ion and solid-state batteries, carbon materials, and energy transition. He is a professor at Concordia University and the Director of the Collaboration Centers on Energy and its Transition, following a 28-year career at Hydro-Québec. There, he led the development of LFP cathodes and graphite/nanotitanate anodes, now used by Tesla, Ford, and others. He pioneered the first two-electrode photobattery and high-capacity LFP/graphite storage systems. Dr Zaghib holds 970 patents, 62 licenses and has co-authored 450 publications with over 25 000 citations and an h-index of 87, shaping global battery innovation.

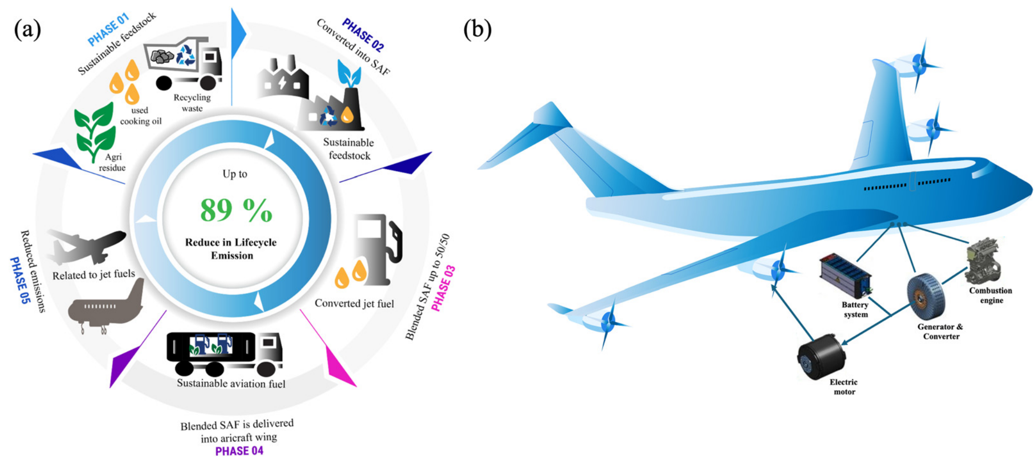


Fig. 2 (a) Overview of SAFs, illustrating emission-reduction potential and renewable feedstock usage. (b) Schematic of a hybrid-electric aircraft with engine, generator, battery, and electric motors.

uncertain, making it essential to concurrently explore and invest in alternative energy storage and propulsion strategies.[9,10] Hydrogen, with its high gravimetric energy density (33.3 kWh kg^{-1}) and carbon-fuel–free combustion mode, is an excellent long-term option; however, limitations in infrastructure, storage, and aircraft geometry limit its growth.[11,12] Hydrogen fuel cells, though exhibiting more excellent energy-to-weight ratios, need to be supplemented by breakthroughs in cryogenic storage materials and lightweight thermal insulation to become realistically practical solutions for commercial air transport.[12] International aviation organizations, such as ICAO, IATA, and the European Commission, have established ambitious emission-reduction targets (*e.g.*, CORSIA and Flightpath 2050), but technological and economic challenges still discourage mass adoption.[13]

Although battery technologies, especially in lithium-ion, solid-state, and lithium–sulfur chemistries, are advancing, they still lack the energy density needed for transcontinental commercial flights (target >800 Wh kg^{-1}).[14] Lithium-ion batteries, as the current technology for regional and short-range electrified aircraft, exhibit limited gravimetric energy density (150–260 Wh kg^{-1}) compared to jet fuel (12 000 Wh kg^{-1}), necessitating the development of novel next-generation solid-state and lithium–air chemistries.[15–18] Supercapacitors and structural batteries also offer promising potential to increase the power output and reduce weight, making hybrid-electric aircraft configurations more efficient.[19,20] As shown in Fig. 2b, hybrid-electric powertrains combine fuel-based and battery-based power sources, utilizing combustion engines, generators, and electric motors for improved efficiency and lower emissions. Owing to these constraints, hybrid-electric configurations combining batteries, hydrogen fuel cells, and ultrahigh-energy-density storage systems have been established as a promising means for aviation decarbonization.[13] Supply-chain sustainability remains a pressing concern, as lithium, cobalt, and nickel mining for aviation-sized batteries suffer from geopolitical, environmental, and ethical trade-offs.[17,21] In response to this, research into blended-wing-body (BWB) aircraft is underway to minimize drag and maximize fuel efficiency, with JetZero's BWB demonstrator, supported by Delta Air Lines, set to start testing in 2027, which is estimated to reduce emissions by as much as 50%.[22] Overcoming these hurdles will involve cross-sector cooperation among aircraft manufacturers, power suppliers, policymakers, and research institutions.[23] Standardization of processes for safety, increased efficiency in terms of energy use, and provision of economic incentives will be key to driving deployment, while innovation in high-energy-density storage, increased scalability of manufacturing, and recycling strategies at the end-of-life will drive the feasibility of the large-scale implementation of electric, hydrogen, and hybrid-electric aviation.[24] With intensified global commitments to decarbonization, the coming decade will be a make-or-break decade in shaping the future of sustainable air travel.

This review comprehensively evaluates the key technological pathways essential for achieving net-zero aviation, focusing on sustainable aviation fuels, hydrogen fuel cells, advanced battery technologies, and hybrid-electric propulsion systems. It examines their performance limits, integration challenges, lifecycle environmental impacts, and certification considerations, drawing insights from recent flight demonstrators and policy frameworks. Organized in a pathway-based structure, the paper guides readers from fuel production through propulsion integration and safety evaluation, providing a strategic roadmap to inform research, development, and policymaking for sustainable aviation.

2. Sustainable aviation fuels (SAFs)

SAFs contribute a critical part to the environmental impact of the aviation industry. SAF is a jet fuel produced from nonbiological or biological nondepletable feedstocks that meet stringent ASTM specifications and are compatible with the current

Table 1 Overview of SAF feedstocks, associated conversion technologies, and notable sustainability or performance benefits

Biomass source	Conversion technology applied	Notable attributes and benefits	Reference
Urban waste streams	Thermochemical (gasification-FT)	Converts municipal refuse into value-added aviation fuels, decreasing landfill dependency and supporting integrated waste-to-energy frameworks Prioritizes sustainable disposal over incineration or landfilling	28
Recycled cooking oils	HEFA	Technologically mature (TRL 9), widely commercialized for SAF use, efficient use of waste lipids Low-cost, readily available nonfood-based oil stream	29
Agricultural residues	Gasification-FT/ATJ/pyrolysis	Post-harvest straw offers uniform chemical profiles and minimal contamination; avoids food system competition (except fodder varieties like oat/barley) Rich in carbohydrates (cellulose, hemicellulose) supporting efficient biochemical conversion	30
Energy-dedicated crops	Multiple: FT/ATJ/pyrolysis	Crops such as algae, jatropha, and camellia thrive in arid, saline, or marginal soils, avoiding land-use conflicts with food production High oil content and fast growth rates improve biomass productivity; Camellia is suitable for rotation farming with cereals	31
Forest-derived residues	Gasification-FT/ATJ	Underutilized lignocellulosic streams with wide availability; supports production of low-carbon SAF Proven ability to reduce lifecycle greenhouse gas emissions *via* advanced conversion processes	32
Industrial wood waste	Gasification-FT/ATJ/Pyrolysis	Abundantly available throughout the year; often has negative feedstock cost depending on region	30

aircraft engines and fuel infrastructures, as illustrated in Table 1. Its core benefit is that it can close the carbon loop using the biomass or waste-based carbon sequestered in developing feedstocks, thereby reducing the net lifecycle CO_2 emissions to a much lower level than traditional jet fuel.[25] Because SAF is a "drop-in" fuel that can be used without modification to aviation or fueling infrastructure, it can be easily and affordably integrated into existing aviation practices.[25] Feedstocks comprise lignocellulosic biomass, municipal solid waste, algae, agricultural residues, nonfood oils, and wet waste.[26] Even though it exhibits great promise SAF currently accounts for less than 1% of the available aviation fuel and is approximately four times more expensive than conventional jet fuel, posing considerable economic challenges.[27] As proposed by ICAO, reaching the net-zero target of the aviation industry by 2050 can lead to a 63% reduction in emissions. However, this will need wide political backing and substantial investment in SAF infrastructure.

SAF production technologies are classified into three categories: chemical, biological, and thermochemical routes.[33] Chemical conversion processes, such as hydroprocessing of esters and fatty acids (HEFA) and Fischer–Tropsch (FT) synthesis, are the most advanced (Fig. 3a and b). HEFA relies on hydrogenating lipids, such as animal fat and vegetable oil, to yield paraffinic hydrocarbons. By contrast, FT relies on gasification of biomass (CO and H_2 syngas) to produce synthetic kerosene (FT-SPK).[34] Bioprocesses, such as alcohol-to-jet (ATJ) and synthesis of iso-paraffins (SIP), integrate microbial fermentation in the process of fermenting sugar to alcohols or farnesene and converting them into jet fuel through hydrogenation (Fig. 3c and d). Pathways provide customized solutions based on cost, feedstock availability, and desired fuel parameters. For example, catalytic fast pyrolysis (CFP) exhibits highly efficient conversion conversion of lignocellulosic biomass to aviation-grade fuel.[35] Hydrothermal liquefaction (HTL) of wet waste is another promising SAF feedstock production technique that meets the performance standards of the aviation industry.[26] However, commercial-scale deployment is limited by slow approval procedures and feedstock-supply logistics, for which more than 400 L of samples are commonly required for certification.[26]

Numerous recent research studies have demonstrated the benefits of SAFs in terms of operation and climate. For instance, the burning of 100% HEFA-SPK fuel decreases ice-particle content by 56% and soot emissions by 35% in contrails, compared to those in the case of Jet A-1, diminishing the total radiative forcing.[36,37] A combination of carbon capture and storage with FT-SPK synthesis is capable of generating negative carbon fluxes and mitigating fossil-fuel – based emissions by 37%, in authorized blends.[38] Strategic implementation of SAF in flights with high-contrail-warming potential can enhance climate gains (reducing the environmental impact) by 9–15 times, compared to that using equal-dispersal ones, maximizing the minimal availability for the highest impact.[37] However, blend ratios, *i.e.*, a 50% cap for FT-SPK with Jet A-1 fuel, limit their climate-mitigation potential without additional technical progress.[38] Additionally, the physical characteristics of SAF depend on raw materials, influencing combustion, pollutant formation, and engine compatibility, highlighting the importance of careful assessment of individual operating conditions.[39,40]

Despite its environmental promise, SAF faces numerous deployment challenges. Its high production cost, for example, £5.16 per kilogram of PtL SAF with a global warming potential of 21.43 g of CO_2 equivalent per megajoule, is a barrier to its adoption.[41] For instance, the deployment of SAF in Africa would require subsidies in the range of \$3.49–3.78 billion in a 50% blending scenario. SAF can reduce emissions by 69.3–113.5 million tons in South America by 2070, depending on high carbon prices above \$0.273 per unit.[42] The use of e-fuels,

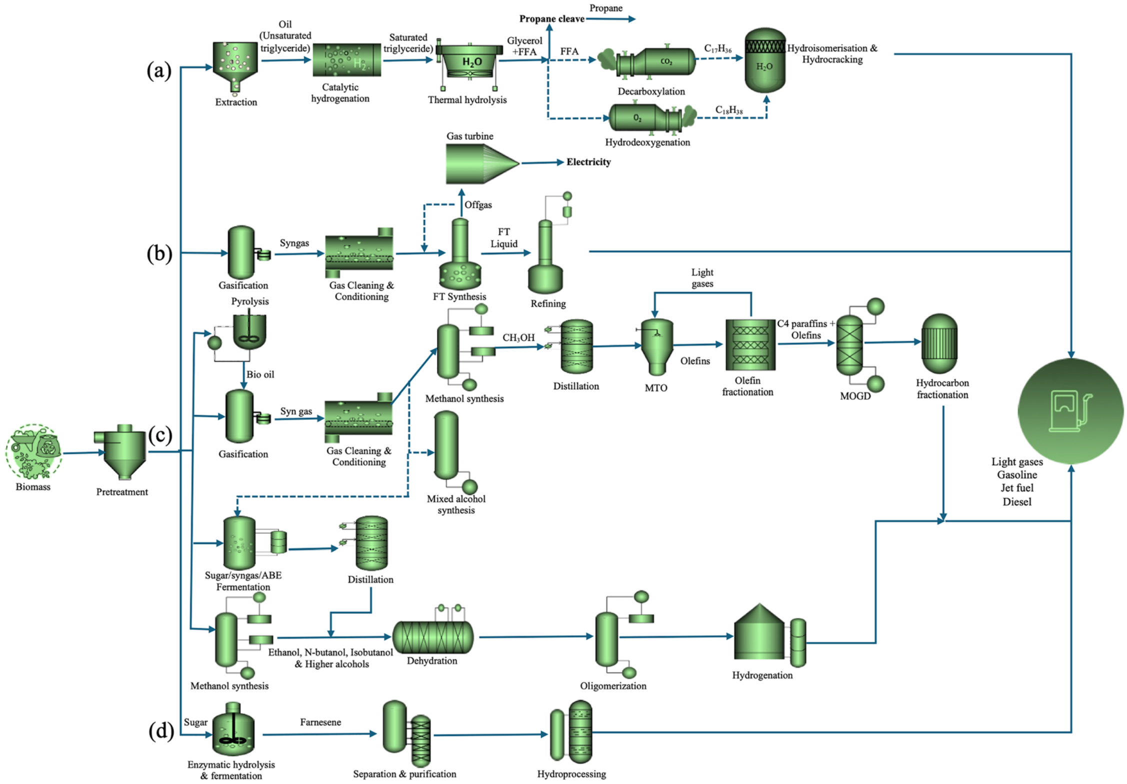


Fig. 3 Schematic representation of key SAF production pathways: (a) HEFA, (b) FT, (c) ATJ, and (d) SIP, showing process steps for the conversion of biomass to jet fuel.

such as e-kerosene produced using direct air capture and electrolysis, has increased from 1.9 to 15.8 million gallons in six years. It is expected to be cost-competitive with the traditional fuels by 2050.[43] However, its scaling up is highly contingent upon renewable electricity growth and supply-chain development.[44] Social sustainability is another necessary pillar, which has been under-researched. Stakeholder cooperation is necessary to achieve fair commercialization; in this respect, research has focused on incorporating social indicators into SAF-assessment systems.[45] The transition toward complete integration of SAF is an interdisciplinary, multifaceted procedure involving research and development (R&D) consolidation, infrastructural investment, supportive policy measures, and global synchronization to resist technological, economic, and societal threats.[46,47]

The economic feasibility of SAF deployment is multi-faceted because it depends on intercorrelated variables like biomass supply chain size, conversion pathway maturity, policy support, and lifecycle environmental impacts.[48] Feedstock prices are highly variable, from negative for wastes to premium for dedicated crops, impacting SAF's minimum selling price (MSP).[49] Although deployable in the near term with mature technologies such as HEFA, the consumption of limited waste oils poses a problem compared to the ATJ and FT routes, which offer greater flexibility, albeit at a higher capital expense, longer certification, and more burdensome feedstock logistics.[50] In addition, lifecycle carbon benefits also rely not only on the selected feedstock but also on land-use change, coproduct allocation, and methodological decisions within LCA boundaries (*e.g.*, cradle-to-gate *versus* cradle-to-grave). Strategic deployment of SAF on high-contrail-impact routes and coproduct valorization can realize maximum climate gain at lower cost. Real-world scalability is, nevertheless, contingent on secure infrastructure, regulatory confidence, regional cooperation, and robust policy support, including carbon pricing and subsidization, to close today's price gap with fossil jet fuels.[51] These complex economic, environmental, and social concerns necessitate a concerted, region-specific strategy for aviation decarbonization, which includes the inclusion of SAF.

Scaling up SAFs like HEFA, FT-SPK, and ATJ faces significant manufacturing and supply chain challenges that limit their role in achieving net-zero aviation. The global supply of feedstocks such as used cooking oil and animal fats is insufficient to meet jet fuel demand, raising competition concerns with food industries.[52] Establishing new biorefineries takes two to five years and substantial capital investment, hindering short-term growth. Pathways like ATJ and next-generation FT face high costs and low yields, scaring away investors.[53] Infrastructure at airports and refineries is not equipped for large-scale SAF operations, adding further costs. Additionally, the geographical variability of feedstocks leads to high transport costs. Current SAF prices are two to five times higher than conventional Jet-A, driven by high feedstock costs and slow technology advances. Policy uncertainties and delays undermine investor confidence, slowing deployment. These obstacles limit SAF adoption mainly to major hubs, raising worries about meeting IATA's

2050 net-zero targets without improvements in logistics, infrastructure, and policy.[54]

Several strategies have been developed to address the significant challenges associated with SAFs, particularly concerning their high production costs and issues related to land use change. One promising approach is the establishment of modular and decentralized biorefineries located in proximity to existing agricultural or industrial facilities, which can significantly reduce capital expenditures and improve logistical efficiencies. The advancement of feedstock technologies, including the cultivation of saline-tolerant halophytes, short-rotation woody crops, and macroalgae, facilitates the growth of a sustainable biomass supply without competing for arable land designated for food production.[55,56] Furthermore, the incorporation of machine learning and artificial intelligence tools is being utilized to enhance the optimization of SAF supply chains at various stages, including feedstock harvesting, process regulation, and product distribution, particularly in pathways such as ATJ and FT synthesis.[57] From a policy standpoint, various technical interventions, including carbon pricing, feed-in tariffs, and SAF blending mandates, have shown measurable success. A notable example is the California Low Carbon Fuel Standard, which promotes low-carbon alternatives by generating tradable credits that help mitigate the price differential with Jet A-1 fuel.[58] The synergistic effect of these policies and technical incentives has the potential to improve the cost-effectiveness of SAFs and minimize environmental impacts.

3. Hydrogen fuel cells

Hydrogen is a green aviation-energy carrier with extremely high gravimetric energy density ($\sim$120 MJ kg^{-1}, $\sim$33 336 Wh kg^{-1}), approximately three times higher than that of conventional jet fuel ($\sim$43 MJ kg^{-1}, $\sim$11 955 Wh kg^{-1}).[59] However, its low volumetric energy density ($\sim$8 MJ L^{-1} compared to $\sim$35 MJ L^{-1} of jet fuel) places massive design constraints, which require substantial onboard storage tanks that make the aircraft heavier and increase the aerodynamic drag and fuel consumption.[60,61] Hydrogen can be produced by thermochemical processes (*e.g.*, gasification, pyrolysis, steam reforming) or electrolysis, which is sustainable only when powered with renewable energy.[59,62] Hydrogen aviation has been demonstrated as practically viable since the early NACA and Tupolev flights.[63] Recent research has set up hydrogen combustion engines and fuel-cell power systems, providing zero-carbon alternatives to the current aviation fuels[64,65] (Fig. 4a and b). Hydrogen combustion reduces CO_2, SO_x, and soot emissions with $>$70% reduction in NO_x emissions.[66,67] Emission of water vapor at high altitudes (11 km) is uncertain as they can form contrails, although it has been estimated that soot-free combustion of hydrogen can reduce this effect.[68,69] Hydrogen-powered aircraft with fuel cells are more accurately defined as completely electric systems, with much lower maximum take-off weight (MTOW) and refueling times than battery-electric aircraft. The onboard batteries are usually small and used as buffers or for transient power increases, and not as primary energy-storage systems.

Hydrogen-storage integration is a fundamental challenge in aviation. As shown in Fig. 5, current methods include physical storage (compressed or liquefied hydrogen or cryo-compressed tanks) and chemical storage (metal hydrides and chemical hydrides).[70] Compressed hydrogen requires high-strength pressure vessels, while cryogenic liquid-hydrogen storage requires high thermal insulation to minimize boil-off losses and pressure rises, resulting in increased energy consumption.[71] Different tank geometries (*e.g.*, spherical and cylindrical) optimize

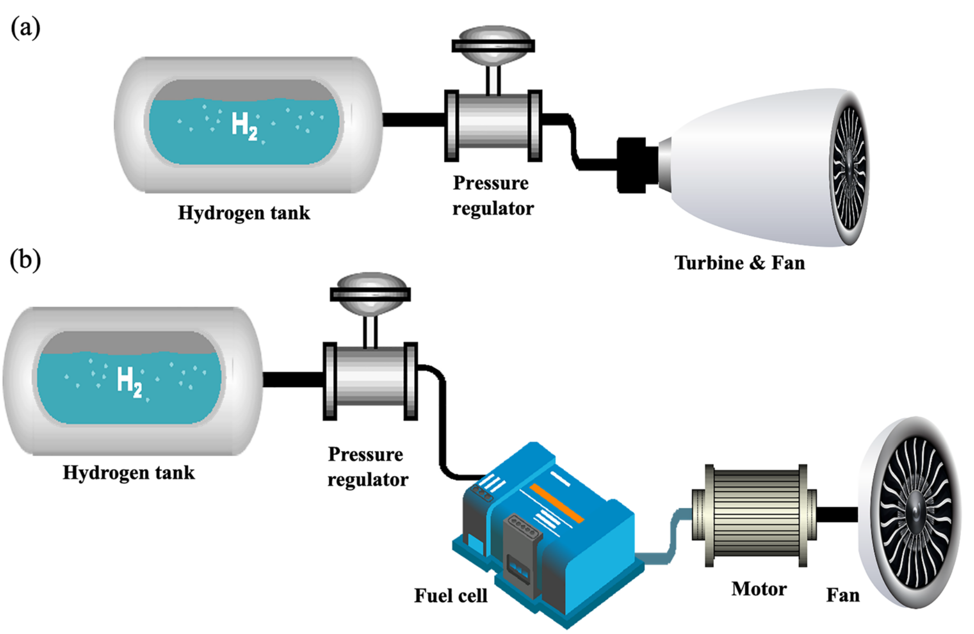


Fig. 4 (a) Hydrogen-fueled combustion-based propulsion layout. (b) Hydrogen fuel-cell electric powertrain showing key components, including motor and fan.

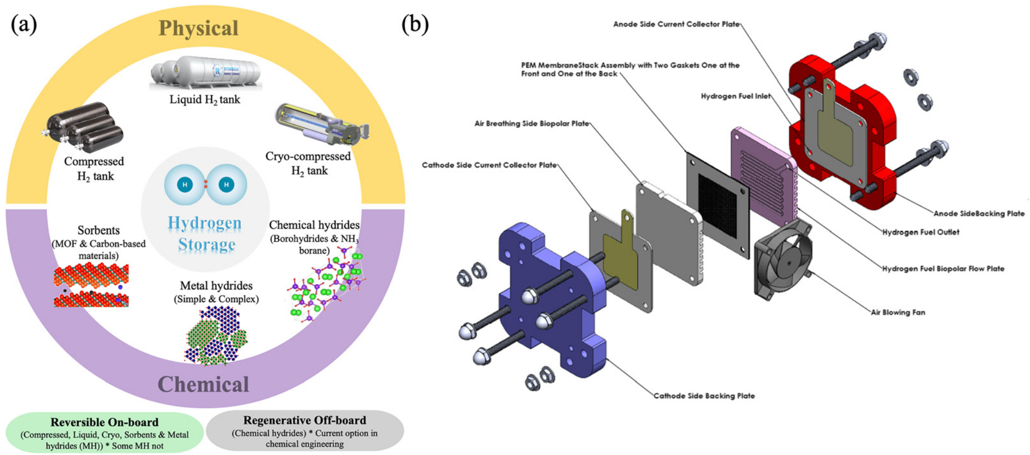


Fig. 5 (a) Classification of hydrogen-storage technologies. (b) Exploded view of a proton exchange membrane (PEM) fuel cell showing its key structural components. Adapted with from ref.[75] Copyright 2017, Elsevier.

the aerodynamic efficiency and reduce heat-transfer loss.[70] Chemical storage methods, such as, metal hydrides represent a promising alternative, where hydrogen is stored in the solid phase, improving thermal management and safety.[72] Hydrogen embrittlement poses a severe challenge, necessitating corrosion-resistant alloys and hybrid protective coatings to supply structural integrity under cryogenic and high-pressure conditions.[71] Storage systems must balance weight, volumetric density, and integration feasibility. Liquefaction achieves $\sim$0.070 kg L^{-1} density, outperforming compression ($\sim$0.030 kg L^{-1}), but incurs higher complexity, evaporation losses (0.1–1% per day), and cryogenic system mass. Integration into aircraft also complicates the storage design, requiring BWB structures or fuselage-mounted tanks to be as spacious as possible for storage, increasing the aerodynamic cost.[12] Table 2 provides a performance trade-off summary between various hydrogen-storage systems, crediting their impact on aircraft weight, fuel economy, and safety concerns. The Cryoplane project evidence shows that large hydrogen tanks contribute to fuel consumption by approximately 10%, but optimized designs would save as much as 12% of the energy on long-range flights.[73,74] Material choices such as carbon-fiber-reinforced polymer and aluminum–lithium alloys offer practical engineering trade-offs in tank construction, balancing low weight, strength, and resistance to hydrogen permeation. Future developments in additive manufacturing, lightweight insulation technologies, and high-strength alloys should make hydrogen propulsion more efficient and lighter overall.[71,72]

Fuel cells are a zero-emission propulsion alternative technology that burns hydrogen to produce electricity through electrochemical reactions. The most promising new technologies are proton exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs).[76,77] PEMFCs are low-temperature (<100 °C) systems with quick startup capability, suitable for unmanned aerial vehicles (UAVs) and small electric air vehicles, but with CO and sulfur contamination sensitivity and the need for high-purity hydrogen.[77] SOFCs operate at 600–900 °C with approximately 60% conversion efficiency and represent a realistic option for long-distance flights.[216] Boeing's demonstration 2008 test flight of a fuel-cell-powered aircraft proved this concept with a two-seater Dimona glider driven by a PEMFC–Li-ion hybrid system, flying level for 20 min at 3300 ft (Fig. 5b). The German Aerospace Center's HY4 aircraft was the first hydrogen fuel-cell four-seater, with a range of 470–930 miles, depending on altitude, speed, and payload.[78] Unlike battery-electric aircraft that rely entirely on scaled battery systems, hydrogen fuel-cell aircraft retain compact battery modules primarily for buffering, thereby avoiding mass and center-of-gravity issues inherent to full-battery systems. Despite this advantage, fuel cells remain hampered by power density, with PEMFCs producing only 600–800 Wh kg^{-1}, which is well short of the 8–10 kW kg^{-1} target for commercial transport.[77] Eliminating this shortfall requires new, lightweight bipolar plates, high-efficiency membranes, and high-power-density designs.[77] Table 3 is a tabulation of the performance characteristics and challenges associated with aviation fuel-cell technologies.

Current research has been focusing on fuel-cell–driven flight-system simulations for high efficiency, new electrochemical concepts, and power maximization for fuel-cell-powered flights.[79] Research on PEM fuel cells for commercial aircraft (*i.e.*, LM-100J freighter) has been conducted to successfully utilize hydrogen storage, replacing battery needs and utilizing byproducts of oxygen for ancillary uses.[80] Hydrogen aviation designs are optimized to minimize weight, increase electrochemical efficiency, and improve hydrogen storage balance, improving the energy efficiency of the propulsion system by 10%.[81] Thin SOFCs prepared through sputtering methods also achieved a specific power of up to 1.17 kW kg^{-1}, marking a turning point in electric flights.[82] Developments in multistack fuel-cell systems (MFCSs) have improved the power-distribution efficiency, curtailing energy instability and improving system-life expectancy, thus making them suitable for high-power electric propulsion.[83] Fuel cells generate low-voltage DC power ($\sim$1–1.1 V per cell), scalable *via* modular connections,

Table 2 Performance trade-offs and integration challenges of hydrogen-storage methods for aviation applications

Storage method	Gravimetric density (MJ/kg)	Volumetric density (MJ/L)	Weight penalty (%)	Storage volume required (L kWh^{-1})	Aircraft integration	Safety considerations
Cryogenic liquid hydrogen (LH_2)	33.3	8.5	Moderate (~10–20%, varies with insulation needs)	~12–15 (varies with tank design & aircraft size)	Requires insulated tanks; impacts fuselage design; allows longer flight range	Risk of material embrittlement; boil-off management needed
Compressed hydrogen (700-bar H_2)	33.3	4.5–5.6	High (~15–25%, dependent on pressure-vessel materials)	~20–25 (influenced by tank reinforcement needs)	Bulky tanks; impacts payload & aerodynamics	Explosion risk from high pressure; requires reinforced tanks
Metal hydrides	1–8	10–14.8	Very high (~25–40%, material-dependent; advanced alloys may reduce impact)	~8.5–12 (high density but adds system weight)	Heavy storage systems; useful for unmanned aerial vehicles & auxiliary power units but are impractical for full-scale aircraft	Safer storage; weight constraints limit applications

Table 3 Comparison of fuel-cell types, including their operational conditions, efficiency, applications, and associated challenges

Fuel-cell type	Common electrolyte	Operating temperature (°C)	Typical stack size	Electrical efficiency	Aviation applications	Advantages	Challenges
PEMFC	Perflurosulfonic acid	50–100	<1–100 kW	53–60% (transportation)	Small electric aircraft, UAVs, and hybrid-electric propulsion	Lightweight, quick start-up, high efficiency	Expensive catalysts, sensitive to fuel impurities
SOFC	Yttria-stabilized zirconia	500–1000	1 kW–2 MW	35–60%	Hybrid-hydrogen propulsion, aircraft APUs	High efficiency, fuel flexibility, and hybrid cycle compatibility	High-temperature operation, long startup time, and material degradation
Alkaline fuel cell (AFC)	Aqueous potassium hydroxide	90–100	10–100 kW	60%	Spacecraft power systems, possible aerospace applications	Lightweight, high efficiency	CO_2 sensitivity limits real-world aviation use

Table 4 Comparative evaluation of hydrogen combustion vs fuel cell propulsion for aviation

Criterion	Hydrogen combustion	Hydrogen fuel cells	Ref.
Efficiency	30–40% (lower due to combustion losses)	50–60% (PEMFC); up to 82% (SOFC)	87–89
Emissions	Water vapor + low NO_x; contrail concerns remain	Zero CO_2/NO_x; minor by-products; water vapor only	90
Integration complexity	Easier for retrofits; similar to existing turbines	Requires new electric architectures; heavy BOP	91
Power density	High power output and thrust (suitable for large aircraft)	Lower; requires modular stacking	92 and 93
Scalability	Best for large jets and long-haul missions	More suitable for small aircraft and regional jets	94
Thermal management	High exhaust temps; simpler cooling	Requires precise thermal control systems	89
Fuel logistics	Can adapt to existing gas turbine infrastructure	Requires new storage, humidifiers, and safety infrastructure	88
Safety considerations	Flammable but well-studied; needs NO_x suppression	Sensitive to fuel purity and thermal overshoot (Kadyk *et al.*, 2018)	90

and do not consume internal reactants, resulting in extended lifespan and higher reliability than that of conventional batteries.

NASA's FUEL initiative (Fostering Ultra-Efficient Low-Emitting Aviation Power) is a strategy to advance SOFC-based propulsion, with objectives of >75 kW power levels, >300 W kg^{-1} system power densities, and $>60\%$ conversion efficiencies.[77] Boeing's analysis shows that SOFC-based power systems can reduce fuel expenses by 50%, making them an affordable choice for regional aviation. However, power-density breakthroughs, heat management, and onboard hydrogen storage are required for commercialization.[82] Airbus is also aggressively working on the next-generation SOFC designs, focusing on high-temperature electrochemical performance and hybrid-hydrogen configurations for zero-emission aviation.[84] Other developments in porous metal substrates and thin-film coatings have demonstrated the enhanced efficiency of SOFCs, providing solutions to increase cell lifespan, stability, and thermal cycling performance. The coupling of SOFCs with bio-liquid-natural gas hybrid power systems has demonstrated high specific energy density and power, making SOFCs a strong candidate for long-range electric flights.[82] Hydrogen-electric aircraft technologies are also being researched intensively to meet environmental sustainability demands, and studies have indicated new energy-management strategies for the optimal distribution of power in fuel-cell-electric aircraft.[85] PEMFCs, built using acidified Teflon membranes and operating below 70 °C at modest pressures ($\sim$2 bar), offer simplicity, low emissions, and fast start-up features that are being actively refined for broader aviation applications. It is of high priority to develop high-performance SOFC stacks, lightweight cell structures, and novel thermal management techniques for the next generation of fuel-cell aircrafts, requiring more research and funding in hydrogen-electric propulsion.[81]

Hydrogen combustion and hydrogen fuel cells are two different methods for using hydrogen as a propulsion source. Combustion systems burn hydrogen in gas turbines, producing water vapor and some NO_x emissions, while fuel cells convert hydrogen into electricity with near-zero emissions and higher efficiency (60–82%).[86] However, fuel cells are heavier and more complex. Combustion systems have higher power density and are easier to integrate into existing platforms, making them ideal for long-range, large aircraft, but they still produce emissions and require NO_x mitigation strategies.[87] Overall, hydrogen combustion and fuel cell propulsion offer distinct trade-offs in scalability, emissions, integration complexity, and mission suitability. A side-by-side comparison of these systems is presented in Table 4 to guide application-specific technology choices.

4. Battery technology

Aviation electrification is widely regarded as a crucial step in decarbonizing the sector, potentially capable of offering zero direct CO_2 emissions when powered by renewable energy.[95–97] However, the potential is currently hindered by fully electric aircraft being limited by low energy density, weight restrictions, and infrastructural shortcomings.[98,99] Compared to liquid hydrocarbon fuels, which have high energy content per unit mass, the current battery technologies produce only a minute percentage of the energy density required for extended-range flights. At the pack level, lithium-ion batteries have an energy capability of approximately 250 Wh kg^{-1}, which is approximately 50 times less than that of traditional Jet-A fuel (Fig. 6a).[98] This inherent limitation, combined with the high mass of battery packs and their associated power electronics, limits their use to short flights (50–200 miles).[100] More conservative analyses suggest that cutting-edge battery technology would increase the takeoff weight of an aircraft by a factor of 1.7 to 3.8 for short- to long-range flights, respectively, to render full-electric propulsion, which is impractical without significant breakthroughs.[99]

To facilitate the mass electrification of aviation, a step-change in the energy density of batteries is required (Fig. 6b). Recent studies have projected a six-fold increase in the battery performance as an economic all-electric commercial flight requirement.[104–107] Estimates are that next-generation batteries with an energy density of 800 Wh kg^{-1} will be on the market by 2050 (Fig. 6c), allowing mid-size jets such as the Airbus A320 or Boeing 737 to travel to up to 1100 km.[97] This, however, is likely to approximately double the MTOW, thus posing serious engineering and regulatory issues. Sustainability is also an issue, with its dependence on lithium, cobalt, and nickel putting

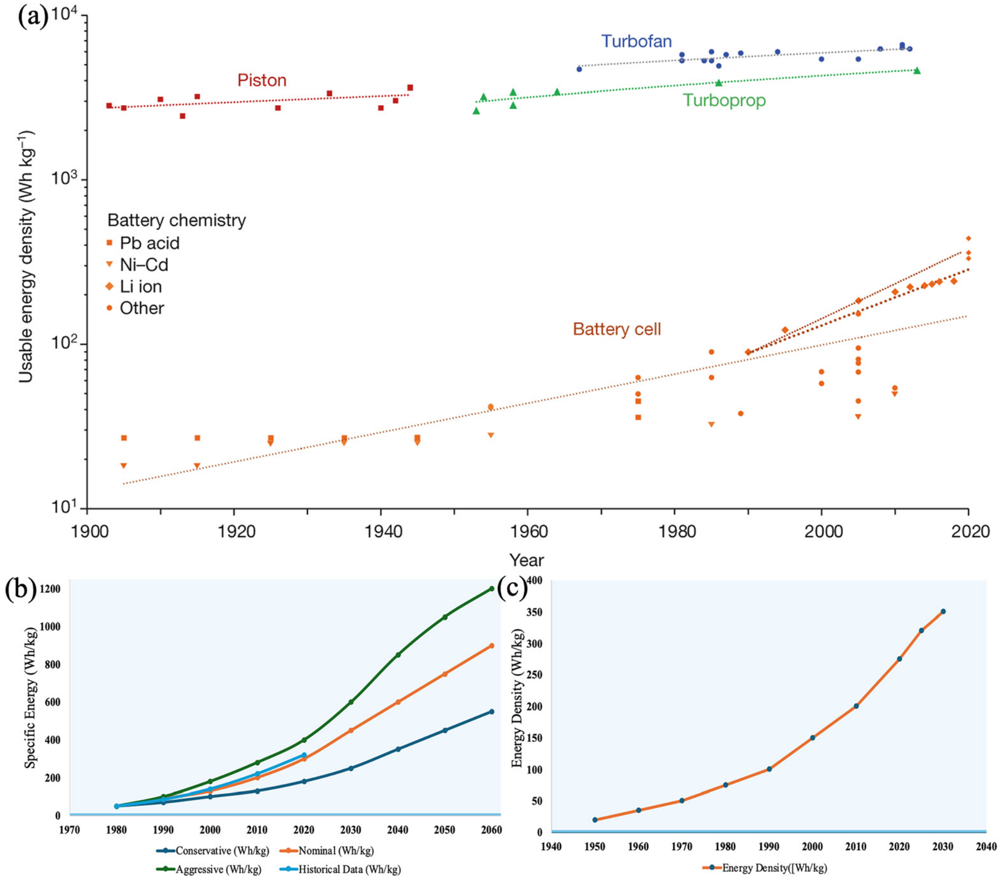


Fig. 6 (a) Evolution of usable energy density in aviation over time. Adapted with permission from ref. 101. Copyright 2022, Springer Nature. (b) Predicted advancements in battery-specific energy across various future scenarios, based on forecast models and values from ref. 102. (c) Progress in battery technology concerning energy-density enhancement, based on values from ref. 103.

additional pressure on an already strained supply chain.[108] A global evaluation of lithium availability has prompted concerns regarding its long-term sustainability, prompting research into new battery chemistries.[109] Moreover, the International Energy Agency (IEA) has highlighted circular economic interventions with suggestions of recycling activities to cut virgin battery material usage by 10% by 2040.[110] Although currently existing processes, such as pyrometallurgy and hydrometallurgy, support the recovery of metals, these processes are environmentally detrimental owing to emissions and the production of toxic waste.[111] Improved processes, like bacterial leaching, are also in the pipeline, but must be enhanced to improve the efficiency and reduce the cost.[112,113]

In addition to material and technological issues, the economic viability of battery-electric flights is also questionable. The levelized cost of electricity (LCOE) of electric flights is still not close to the levelized cost of hydrocarbon fuel or even drop-in biofuel.[99] Current studies have shown that batteries should be below \$100 per kWh, with a carbon taxing policy for electric flights to become commercially attractive.[97,114] Although electric propulsion potentially has lower operating costs through increased powertrain efficiency, upfront investment in infrastructure and aircraft redesign is a high hurdle.[99] In contrast to drop-in sustainable fuels, which involve minimal adjustment to current aircraft and fueling infrastructure, battery-powered aviation necessitates a radical aircraft design overhaul, *e.g.*, increased fuselage volume to store batteries and pervasive regulatory adjustments. These limitations imply that the immediate future for aviation batteries will be restricted to regional and short-range applications, with long-range electrification depending on advances in energy storage, aircraft design, and regulatory policies. However, ongoing investment in high-energy-density battery chemistries, new production processes, and recycling infrastructure will be instrumental in deciding whether all-electric propulsion can become ubiquitous in the next few decades.[115,116]

4.1. Li-ion batteries

Lithium-ion batteries (LIBs) have become prevalent in industries owing to their high energy density and technological readiness, and are a strong contender for electric aviation applications.[117] Demand for LIBs is still rising because of advancements in material sciences and the drive for decarbonization. The US Battery 500 Consortium has also established the ambitious goal of delivering 500 Wh kg^{-1} energy density, which is close to twice the commercial LIB performance, though well beyond practical application in aviation.[118] Even so, they are limited in their use within aviation, and only a small number of commercial aircraft, *e.g.*, the Boeing 787 and Airbus A350, utilize LIBs for APUs instead of propulsion.[119] LIBs operate on the principle of lithium-ion movement between a petroleum coke or graphite anode and a lithium–metal–oxide cathode (*e.g.*, $LiCoO_2$, $LiNiO_2$, $LiMn_2O_4$), with efforts focused on replacing the cathode and anode materials, for example, metal oxides,[120,121] carbon,[122] and polymer electrolytes,[123] to achieve better energy density and efficiency. Key challenges persist, however, such as low gravimetric energy density, sustainability of supply chains, and safety risks.[124] Overcoming such limitations involves optimizing production processes, improving charge–discharge cycle life, and optimizing recyclability to reduce resource depletion, as noted by Oliveira *et al.*[125] With the IEA forecasts of a 30-fold increase in lithium and cobalt demand, sustainability issues related to mining toxicity, disposal, and battery lifecycle management have become paramount.[126,127] While second life uses maximize the application of LIBs, ascertaining battery health and complexity in remanufacturing are barriers to its large-scale application.[128] The absence of standard recycling protocols and regulatory norms also contributes to sustainability concerns, raising costs and restricting end-of-life management opportunities.[124,129]

However, although LIBs are the dominant type of batteries in portable electronics and electric vehicles, they face fundamental limitations in aviation, particularly regarding energy density. Current LIBs reach 250–300 Wh kg^{-1} (vs Jet-A fuel: ~12 000 Wh kg^{-1}) and thus, offer a minimal range (Fig. 7a).[130] The low energy density of batteries means they will always need to be much heavier than the existing aviation power sources, to meet the energy requirements of the aviation sector, starving aircraft of performance and viability. Restrictive interplays of electrochemical stability confine cathode voltages to 4.3 V, and even though the graphite anode is a proven contender, it is limited to 370 mAh g^{-1}, thus limiting further improvements.[131,132] To overcome these limitations, other advanced electrode materials have been introduced to achieve better capacity, including silicon anodes and lithium–metal anodes, which show higher capacities but also challenge the cycling stability and dendrite formation .[132,133] Thermal safety is one of the main factors, as overheating can initiate thermal runaway (TR) at high voltages, resulting in battery failure.[134,135] The hazards of uncontrolled heat generation and exothermic reactions that may result in catastrophic failures in an aviation context were illustrated by the Boeing 787 Dreamliner battery fires.[125]

In aviation environments, the risk of TR is amplified due to the high specific energy required, compact battery pack configurations, and the severe consequences of in-flight failures. Next-generation lithium-ion cells, despite rigorous manufacturing controls, remain susceptible to unpredictable TR triggered by latent internal defects or physical abuse.[136] The challenge is intensified by aircraft weight and volume restrictions, which limit the inclusion of heavy protective housing or bulky cooling systems, thereby requiring lightweight but highly effective safety measures.[137,138] Experimental studies on Samsung 30Q

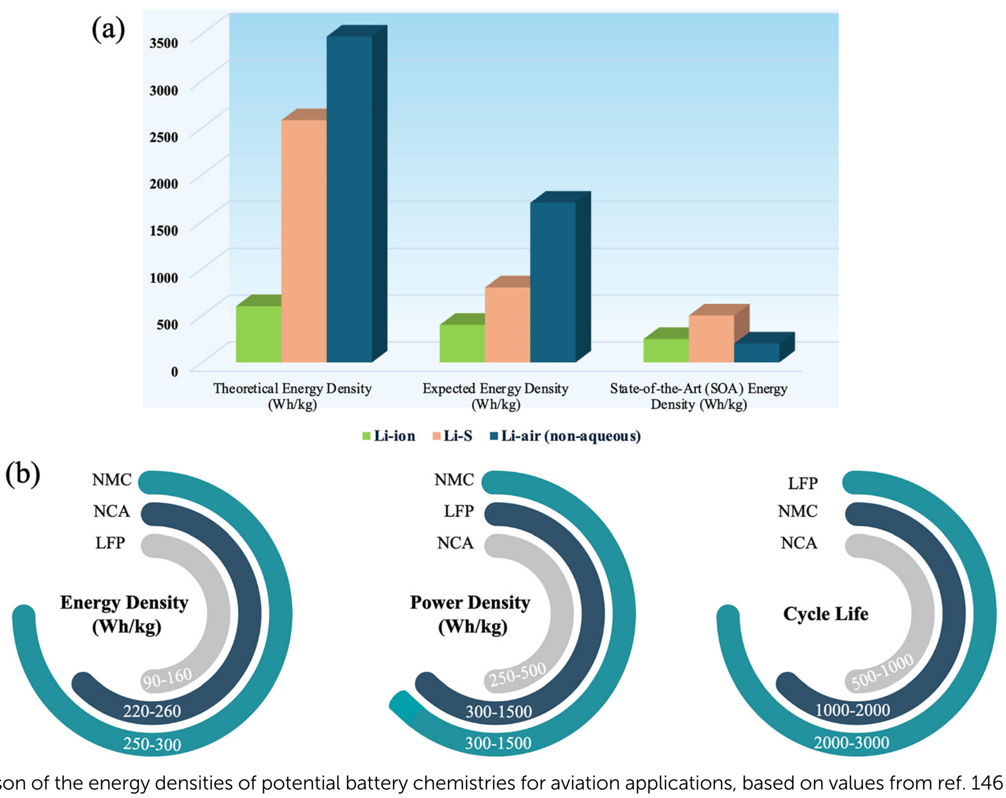


Fig. 7 (a) Comparison of the energy densities of potential battery chemistries for aviation applications, based on values from ref. 146–150. (b) Analysis of various lithium battery chemistries for aviation.

cells revealed that TR is initiated around 195 °C and peaks at 375 °C, with mass loss of up to 33 grams per cell.[139] This emphasizes the need for cell-to-cell propagation mitigation. Innovative module designs like NASA's X-57 billet architecture have demonstrated the ability to absorb energy and isolate failing cells to prevent TR spread. Moreover, under aviation-relevant conditions of low ambient pressure and temperature, TR severity is attenuated due to reduced oxygen levels and enhanced heat dissipation, effectively increasing the response window for containment.[140]

To improve thermal systems and operating safety, intensive research is continued in superior cooling approaches, such as phase-change materials and liquid cooling devices.[141] In addition, the development of intrinsically safer materials, such as flame-retardant electrolytes and thermally stable ceramic separators, has shown promise in suppressing the initiation and spread of TR.[142,143] Researchers have been actively designing battery management systems (BMSs) with real-time monitoring functionalities, allowing them to track early failure risks and dendrite growth to control the wear process.[144] Emerging prognostic algorithms now incorporate aging models, state-of-charge, and self-heating rates to predict TR onset during variable flight phases, especially during take-off and landing when current draw is high.[145]

LIBs continue to be the dominant battery chemistry for electric aviation development, with nickel–manganese–cobalt (NMC), nickel–cobalt–aluminum (NCA), and lithium–iron–phosphate (LFP) batteries being the most widely used types.[151] Both NMC and NCA possess high energy densities and, therefore, are suitable for use over a long distance, but are a monumental safety problem from a thermal instability perspective. Low-energy-density LFP batteries exhibit excellent safety and cycle life performances and are hence suited for applications where reliability is superior to the range.[151] Although commercial electric planes are still unreal, LIBs are making significant strides in regional and hybrid electric planes. Pipistrel and Bye Aerospace, for example, designed all-electric planes with a 100–200 km flight range for regional flights and training.[152,153] The Ampaire Electric EEL hybrid plane has shown 50–70% fuel savings on short-range flights, indicating the promise of battery-assisted propulsion in cutting aviation emissions.[154] Additionally, eVTOL planes, envisioned by Joby, Lilium, and Volocopter, are leading the charge toward urban air mobility and are heavily dependent on sophisticated LIB designs.[155] Nevertheless, battery operation at high altitudes still poses a challenge, as low temperatures and lower air pressures impair efficiency and lifetime.[156] These challenges are overcome by using temperature-management strategies, pressure-resistant housings, and various battery systems to optimize the performance under dynamically changing flight conditions. The use of fiber optic sensors for *in situ* temperature monitoring and early warning against TR events is also gaining traction, offering additional safety layers during cruise or high-altitude operations.[142] Although LIBs will dominate in the initial stage of electric-flight aviation, long-range electric flights will probably require advanced chemistries like solid-state batteries (SSBs) with higher energy densities, higher safety, and longer life over the cycle (Fig. 7b).[157] However, scalability, cost, and integration challenges must be solved before SSBs can substitute LIBs in commercial aviation. Ongoing investment in high-energy-density chemistries, circular economies, and low-cost production methods will dictate whether battery flights can break the short-haul dependency within the next few decades.

4.2. Advanced Li-ion chemistries

The aviation sector requires lightweight energy-storage systems, high specific energy, long cycle life, and safety. The existing battery technologies cannot satisfy these demanding requirements, particularly for electric and hybrid-electric aircraft applications. Table 5 summarizes the leading battery chemistries according to the maximum achieved energy density, cycle life, and technology readiness level. It serves as a benchmark for assessing the progress and limitations of the current systems.

4.2.1. Silicon-based anodes. Silicon is a novel anode material for future LIBs, offering a high theoretical capacity that is nearly 10 times higher than that of the traditional graphite anodes. However, its practical application is hindered by its extensive volume expansion during lithiation and delithiation, which causes mechanical degradation, cycling instability, and fast capacity loss.[165] In response to these problems, recent advances have focused on nano-structuring silicon anodes and using composite materials to improve the structural stability and cycling performance. Silicon–carbon composites and silicon–graphite hybrid anodes are being studied as a near-term option, which could increase the energy density by 20–40% over that of existing LIBs and reduce volume expansion problems.[166] Additionally, new silicon nanowire architectures and optimized binder solutions have been shown to possess better charge retention and mechanical robustness, and commercial developments have already achieved energy densities of over 500 Wh kg^{-1} in some cases, significantly expanding the range of electric aviation solutions.[167] In the air-transport sector, where low weight and high energy density are required, silicon anodes present a promising potential for pushing the battery performance to new levels, with ongoing research focused on

Table 5 Performance characteristics and readiness levels of battery chemistries for aviation

Battery chemistry	Specific energy (Wh kg^{-1})	Cycle life	Readiness level	Ref.
LIBs	330	1000–2000	Commercially deployed	158
Li–polymer	200	300–500	High readiness	159
LFP	205	2000–6000	Widely implemented	160
Solid-state	400	8000–10 000	Experimental stage	161
Nickel–metal-hydride	140	300–1000	Mature	162
Lead–acid	50	200–500	Legacy technology	163
Zinc–air	1105	200–500	Emerging	164

optimizing the material composition, electrolyte stability, and cycle life.

4.2.2. High-nickel cathodes. Enhancing the nickel content of NMC cathodes is a potential direction to raise the energy density of lithium-ion batteries, whose current specific energies are approximately 250–300 Wh kg^{-1}.[168] However, greater energy densities are required to support the high energy-to-weight requirements of electric and hybrid-electric aircrafts so they can be economically justifiable in aviation uses. Continued study is required to design more sophisticated compositions with energy densities greater than 500 Wh kg^{-1}.[169] Yet, thermal-instability–induced problems and accelerated capacity ageing are significant challenges to their wide-ranging application. Evading such drawbacks involves innovative surface modifications and doping techniques, which are prospective contenders for enhancing the structural stability, suppressing capacity ageing, and ensuring safety under harsh operating conditions.[170] The improved volumetric and gravimetric capacities of nickel-rich cathodes also enhance their viability for application in aviation, where energy is maximally stored, and system weight is minimized.[171] More significant growth in electrolyte optimization, cathode engineering, and thermal-management techniques will be crucial to fully leverage the potential of high-nickel cathodes for the next-generation aviation energy-storage systems.[172]

4.3. Solid-state batteries

Solid-state batteries (SSBs) are emerging as a disruptive technology to the traditional lithium-ion systems, working to overcome their significant limitations, including electrolyte instability, flammability risks, limited cycle life, and narrow voltage windows.[173] By using solid ion-conducting materials instead of liquid electrolytes, these batteries provide enhanced thermal and electrochemical stability, removing safety risks and improving energy densities.[174] One of the most characteristic aspects of solid-state technology is the utilization of ceramic or polymer electrolytes in combination with lithium–metal anodes, which have a very high theoretical capacity of 3860 mAh g^{-1} and a low electrochemical potential (−3.04 V).[175–177] Such an arrangement significantly improves the energy-storage capacity, decreases charging times, and ensures safety from TR; hence, SSBs are a probable solution for electrified aviation. With the dense weight and safety considerations of aerospace use, accepting solid-state architectures is a step toward higher power efficiency and long-range electric flights.

However, despite the improved thermal stability of solid-state electrolytes, recent studies have revealed that SSBs are not completely immune to TR events, especially under the extreme thermal and mechanical conditions associated with aviation. High-speed thermal imaging and calorimetric studies on reconstituted all-solid-state battery packs demonstrated that TR propagation occurs five times faster and with nearly ten times higher heat flow compared to conventional LIBs, posing a major safety risk for aircraft battery modules.[178] This highlights the need for aviation-specific design modifications, particularly for weight-constrained platforms where thermal dissipation is limited and crash tolerance is essential.[179]

Observing the aviation possibilities of SSBs, NASA initiated the Solid-state Architecture Batteries for Enhanced Rechargeability and Safety for Electric Aircraft (SABERS) project in 2020, emphasizing revolutionary energy-storage advances. Early results from SABERS showed that a carbon–sulfur cathode architecture could demonstrate an energy density of 1100 Wh kg^{-1} at a 0.4C discharge rate and 804 Wh kg^{-1} at a 1C discharge rate, much more significant than that of the conventional lithium-ion systems.[172] In parallel, QuantumScape achieved substantial breakthroughs in lithium–metal SSB design, with a 10-layer proof-of-concept boasting energy densities of 390–500 Wh kg^{-1}, fast charging (0–80% within 15 min), and stability of more than 800 charge–discharge cycles. These breakthroughs are testimonies to the gigantic potential of SSBs in transforming aviation energy storage using high-performance, lightweight, and heat-tolerant power solutions. However, issues appear in terms of bulk production, integrity of the electrode–electrolyte interface, and achievement of high power densities needed for challenging flight missions such as takeoff and landing.[180]

Additional safety-focused innovations have emerged from SABERS, including lithium–metal solid-state batteries with sulfur–selenium cathodes that operate at elevated temperatures (150 °C) to minimize the need for heavy cooling systems while maximizing stack efficiency.[181] These batteries also incorporate lightweight bipolar designs for weight optimization. Despite these advances, solid-state cells remain sensitive to mechanical deformation and vibration, leading to potential short-circuit or ignition events if not properly engineered. Current approaches to mitigate TR include the use of pressure-tolerant casings, thermally stable separators, and high-temperature-resistant solid electrolytes. Furthermore, advanced onboard BMS and modular architectures are being developed to restrict cell-to-cell propagation under fault conditions.[182] Hence, the realization of aviation-grade SSBs will require systems-level safety strategies beyond the materials level.

4.4. Lithium–sulfur batteries

Lithium–sulfur (Li–S) batteries are candidates for the next-generation energy-storage technology owing to their high theoretical energy density of 2500–2600 Wh kg^{-1}, which is 4.5 times greater than that of traditional LIBs.[132,148,183] Li–S share a lithium–metal anode and sulfur cathode, with a potential outlook towards application in aviation, where minimizing weight and maximizing energy density are key factors. Sulfur is light, cheap, and plentiful at approximately 36 USD kWh^{-1}, making Li–S batteries a cleaner and more economically sustainable option than lithium-ion systems.[132,184,185] However, even with these benefits, Li–S technology is confronted with intrinsic issues, mainly due to the insulating nature of sulfur and lithium sulfides, which require conductive additives to facilitate electronic transport in the electrodes.[118,132] Applications of conductive phases, including polymer matrices and carbon structures, have been investigated to achieve high conductivity and facilitate reversible lithium-ion mobility during charge and discharge cycles.[186,187] The infamous shuttle effect, caused by lithium polysulfide intermediate dissolution in the electrolyte, causes severe capacity decay and low cycle stability. This problem has spurred research into sophisticated cathode architectures and electrolyte modifications to overcome the dissolution of polysulfides, ultimately increasing the battery longevity and efficiency.[132,148]

A key disadvantage of the Li–S technology is the significant volumetric swelling of sulfur (up to 80%) on discharge, which leads to electrode degradation, active-material loss, and electrical separation.[132,148] The following technologies have applied to eliminate these problems: loading sulfur on porous carbon frameworks and developing sulfur–graphene nanocomposites, offering mechanical strength and electrochemical-property enhancement.[184] Most significantly, the progress in graphene–oxide cathodes have enabled Li–S cells to attain a maximum of 500 cycles. At the same time, electrolytes based on ionic liquids have extended their lifespan, to cycle lives reaching more than 1500 cycles at discharge rates of up to 6C.[188] Recent breakthroughs have introduced Li–S batteries with energy densities greater than 500 Wh kg^{-1}, representing a twofold improvement over current LIB technologies, all while reporting 1350 cycles, a notable advancement toward aviation integration.[189]

Despite these advances, Li–S systems face critical safety challenges in aviation contexts, particularly related to TR. The very high specific energy that makes Li–S attractive for aircraft also means that any TR event can release a large amount of heat and gaseous byproducts, increasing the likelihood of catastrophic failures if not mitigate.[136] The densely packed modules required for weight-optimized aircraft designs further elevate the risk of cell-to-cell propagation, with experimental evidence showing that adjacent cells can rapidly ignite under abusive conditions.[190] Aviation environments exacerbate these risks: fluctuating temperatures and low-pressure conditions at altitude have been shown to accelerate volatility and reduce thermal stability.[191] To address these issues, advanced thermal management solutions such as passive heat-absorbing structures and high-conductance spreaders are being explored to dissipate or quench runaway heat before it spreads.[192] Containment systems capable of withstanding high temperatures and confining ejecta, smoke, and flames at the module level have also been validated in aviation-relevant tests, providing valuable time for emergency procedures.[193] Early-warning systems using embedded thermal and pressure sensors are emphasized as essential for detecting TR onset, while compliance with rigorous NASA and FAA safety protocols ensures that aviation-grade Li–S packs are engineered to minimize propagation risks.[140] Collectively, these approaches underscore that while Li–S batteries are promising for lightweight, long-range flight, their deployment in aviation hinges on balancing energy density with uncompromising safety requirements.

The commercial viability of the Li–S batteries has already been established through their application in the Airbus Zephyr. This solar-powered UAV achieved a record-breaking flight time of 14 days. In addition, in 2019, a collaboration between Bye Aerospace and Oxis Energy successfully demonstrated a 500 Wh kg^{-1} Li–S battery pack, realizing significant weight reduction of the battery, which is a primary consideration in electric aviation.[194]

4.5. Lithium–air batteries

Lithium–air (Li–air) batteries are among the most promising contenders for future energy-storage systems because they possess a very high theoretical specific energy of 11.14 kWh kg^{-1}, significantly higher than that of the conventional lithium-ion and Li–S batteries and slightly lower than the energy density of jet fuel.[195] In contrast to the more traditional battery chemistries, Li–air batteries employ atmospheric oxygen as the cathodic reactant, reducing the overall cell weight and helping their theoretically high energy density of approximately 3500 Wh kg^{-1} become achievable.[196] This makes them extremely attractive in the aviation industry, where energy storage needs to be maximized without substantial weight increases. However, notwithstanding their theoretical potential, Li–air batteries face significant technical challenges that rule out their practical utility in aerospace applications. Low volumetric energy density, low discharge rates, and lower power output constrain their ability to deliver the high energy levels necessary for takeoff, cruising, and long-term flight missions.[149,197] Furthermore, Li–air batteries are also sensitive to ambient conditions such as moisture and atmospheric oxygen concentration, producing operating instability and safety issues when operated in aircraft environments.[196]

Overall, achieving their full potential, NASA developed a working prototype of a five-cell Li–air battery composed of an anode made of lithium metal, a porous carbon cathode, and an ether electrolyte; yet, the outcome indicated severe limitations. The battery only achieved 200 Wh kg^{-1}, 5% of the theoretical limit, and had an impoverished cycle life with a lifespan of just 5 to 25 charge–discharge cycles.[198] Optimizations have projected energy densities of 700–800 Wh kg^{-1} with a continuing development in the design of electrolytes and cathode stabilization.[198] Girishkumar *et al.*,[150] estimated Li–air batteries with 1700 Wh kg^{-1} in the future, while Thielmannl *et al.*,[199] estimated commercialization by 2030. Airbus and EADS are also actively exploring Li–air technology for use in the future Voltair aircraft, with a projected market entry in 2035.[200] However, providing constant energy under changing flight conditions remains the main challenge. Existing designs are plagued by irreversible side reactions, electrolyte degradation, and instability of the cathode, which hinder their long-term efficiency. Moreover, maintaining stable energy performance under variable pressure and temperature conditions requires paradigm shifts in the air-intake system designs and sophisticated battery-management strategies.

4.6. Lithium–metal batteries

Lithium–metal batteries (LMBs) are emerging as a second promising technology following the traditional lithium-ion technology, with increased energy density and lightweight characteristics that are crucial in air travel. In contrast to lithium-ion battery graphite anodes, LMBs utilize metallic lithium anodes, which give them a considerably higher theoretical capacity and allow them to hold more incredible energy per unit of weight.[15,16] This technology is especially beneficial in hybrid-electric and electric aircraft, where weight savings directly benefit flight range and fuel efficiency. Additionally, solid-state LMBs involving the use of nonflammable solid electrolytes have been known to exhibit heightened safety by blocking electrolyte leaks and mitigating the threat of TR, which is of primary concern in aerospace energy storage.[201,202] These batteries also promise reduced charging times and longer lifespans, and they are suitable for next-generation sustainable air systems.

Despite these advantages, LMBs pose unique thermal runaway and safety challenges in aviation. Exothermic reactions between the lithium metal anode and electrolytes, intensified by aluminum current collectors, can generate severe heat during failure events, amplifying the likelihood of catastrophic TR.[203] In-flight low-pressure conditions further complicate this issue, as they reduce heat release but increase the emission of flammable and toxic gases, presenting critical hazards in the confined aircraft environment.[204] The stringent weight and volume restrictions of aerospace platforms also limit the scope for incorporating robust thermal management or containment systems, leaving batteries more vulnerable to propagation risks.[205] Furthermore, crashworthiness considerations highlight the danger of mechanical deformation in packs installed within cargo compartments or nacelles, where structural compromise can trigger TR and compromise safety.[206] To mitigate these risks, advanced lightweight thermal management systems, material innovations such as solid-state electrolytes, and sophisticated detection and control strategies are being explored to provide early warning and intervention during abnormal conditions.[207]

Even with their benefits, there are several challenges to making LMBs popular in aviation. One of the unforgiving limits is the lithium dendrite growth that leads to internal short-circuits and loss in capacity, with detrimental safety concerns.[208] Experimental efforts are currently being made to stabilize the anode–electrolyte interfaces to inhibit dendrite growth while minimizing the battery-cycle deterioration and inefficiency.[201] Additionally, LMBs are being hybridized with sulfur (Li–S) and oxygen (Li–O_2) cathodes as a step to increase the energy density further while resolving the cost and performance issues.[209] The materials have been improved using extremely advanced coatings, electrolyte additives, and solid-state methods that improve the durability alongside manufacturability.[210] Simultaneously, machine learning–based battery-state monitoring is being researched to facilitate prediction-based maintenance and performance improvement in aviation use cases.[211]

4.7. Beyond lithium batteries

The drawbacks of LIBs, such as low energy density, high price, and safety issues, have encouraged the investigation of alternative battery chemistries in aviation applications. Metal–air batteries, especially aluminum–air (Al–air) and zinc–air (Zn–air) batteries, have been noted for their high terminal voltage and specific energy, and are suitable potential alternatives to the next-generation energy-storage systems in aviation.[149,197] Al–air batteries boast a definite merit in terms of theoretical energy densities and abundant material-supply regions. However, their practicality is hindered by the high water consumption involved in manufacturing and corrosion risks. Aluminum alloys have been proposed to be the key to managing these disadvantages, but their practical use in aircraft applications is yet to be proven. In the same way, zinc–air batteries have also attracted attention as a competing technology to Li–air systems, owing to their excellent achievable energy densities, especially under dual-battery modes. Still, with low specific power, compromised cycle life ($\sim$100 cycles), and cost of operation, they become a formidable entry barrier to integration with aviation.[132,212] Research is being conducted to improve the cyclability and efficiency of these metal–air batteries by developing catalysts and engineering electrolytes, which will become essential for real-world applications in air travel in the future.[213]

In addition to metal–air batteries, alternative metal-ion chemistries of sodium-ion (Na-ion) and potassium-ion (K-ion) batteries are also under research, as Na and K are very much in abundant supply and are less costly compared to lithium.[214,215] These new battery chemistries can likely overcome the lithium supply-chain limitations with an environmentally sustainable mass transport electrification solution. However, they still suffer from low volumetric energy density, small power capacity, and instability at the interfaces.[215] Development with solid-state electrolytes is already actively being sought to ensure stability and safety, and there is an urgent need to allow applications within the aviation sector.[216] Moreover, the shift away from lithium-based batteries has been prompted by economic and environmental factors, as lithium extraction has geopolitical, ethical, and ecological issues.[217,218] Thus, research on nickel-based, aluminum-based, and zinc–air batteries that keep advancing high-energy-density storage technologies exclusive to aviation is progressing. Although short-term commercialization remains uncertain, continued development in sodium-ion and metal–air chemistries can offer sustainable long-term remedies for electrified aviation.[215,218] A quick review of the current literature in terms of the future projections (by 2035–2040) at high technology readiness levels (TRLs) for energy densities and cycle lives of various battery chemistries is summarized in Table 6 below.

4.8. Structural batteries

Structural batteries (SBs) are also attracting considerable interest in aviation as they play the dual role of load-carrying structures and energy-storage devices, thus solving some of the most pressing problems of weight, energy density, and sustainability in future aircraft.[157,232–234] In contrast to traditional batteries that add weight to the plane, SBs use carbon-fiber composites that can act as electrodes and reinforcements

Table 6 Projected energy densities and cycle lives of advanced battery chemistries for use in aviation by 2040 at the highest technology readiness level (TRL)

Battery type	Target specific energy (Wh kg^{-1})	Expected lifespan (cycles)	Ref.
Li–S	400–600	500–1000	219–222
Li–Air	500–800	200–500	223 and 224
LMBs	400–600	500–1000	225 and 226
Solid-state Li	400–600	1000–2000	180 and 227
Zinc–air	300–400	200–00	228 and 229
Na-ion	200–300	1000–2000	230 and 231

simultaneously, with polymer electrolytes ensuring ionic conductivity.[235] This has been investigated in some of the aviation ideas, such as the more electric aircraft (MEA), hybrid electric aircraft (HEA), and all-electric aircraft (AEA), where the battery weight needs to be minimized to make electrification and fuel efficiency, making SBs a promising alternative for future airframe-integrated energy systems.[236] Over the last few years, advances in composite manufacturing have made it possible to manufacture multifunctional materials, which, while not yet mature, hold promising potential for efficient and lightweight energy storage.[237] Even though numerous issues remain to be resolved, for example, positive-structured electrode requirements, power-management integration, and large-scale manufacturability and scalability,[238] one of the most significant challenges is the high curing temperature of composites above the thermal stability of the battery materials embedded, resulting in compatibility and long-term electrochemical activity issues.[234] Researchers are working hard to develop novel polymer electrolyte formulations and the best carbon-fiber geometries to overcome these limitations and enhance the integration of aviation batteries into load-bearing components.[234]

Research on the structural application of batteries to aircraft structures has resulted in a phenomenal weight reduction in traditional structures. A comparison of aircraft frames demonstrated that replacing traditional materials with SB materials having an energy density of 125 Wh kg^{-1} results in a 5.1% weight reduction compared to aluminum structures, and a 1.5% reduction compared to conventional composite airframes.[239] More detailed analysis reveals that using SBs in Airbus A220-100 cabin floors would result in an overall mass reduction of 260 kg, for energy densities of 144 Wh kg^{-1}.[240] A conceptual study on the next-generation Airbus A320 replacement set a target of 100 Wh kg^{-1} for onboard electrical power systems, 200 Wh kg^{-1} for hybrid-electric propulsion, and 400 Wh kg^{-1} for AEA, showing the key role of SBs in aircraft electrification.[241] While their energy density was poorer than that of LIBs, their dual-use property compensated for weight penalties and rendered them useful for aircraft energy storage.[242] However, another recent paper suggested an early aircraft design approach that integrated SBs into major load-carrying structures, achieving a maximum of 26% weight reduction under optimal conditions.[243] However, certification and airworthiness remain a significant obstacle to the widespread use of such batteries, necessitating the development of new safety standards for multifunctional battery-integrated airframe structures.[236] Existing structural battery chemistries are also restricted by performance in terms of the thermal stability, ionic conductivity, and charge retention, and research is underway to improve their mechanical integrity with superior electrochemical performance.[244,245] Recent experimental results suggest that maintaining high electrochemical performance—such as stable capacity retention and low internal resistance can help preserve the structural integrity of carbon fiber electrodes. Still, the mechanical strength reduces with increasing lithium content, reflecting a compromise that must be resolved in future designs.[246,247] Thermal-management techniques are also required to achieve power efficiency and avoid performance degradation during different flight conditions.[248,249] With new developments in material science, composite engineering, and solid-state electrolytes, SSBs are set to take a giant step toward transforming aviation electrification, as a clean, light, and efficient storage technology that addresses the needs of the next-generation aircraft.

Scaling advanced battery technologies like solid-state, Li–S, and Li–air for aviation faces significant manufacturing and supply chain challenges. Current processes, such as hot pressing and electrolyte infiltration, are limited to prototype scales due to stringent environmental controls and low yields, complicating industrial integration.[250,251] Existing gigafactories, designed for conventional LIBs, are unsuitable for the new materials, requiring costly retooling and skill development.[252] Safety issues like dendrite growth and material loss further compromise reliability. Additionally, reliance on critical raw materials exposes production to price volatility and geopolitical risks, while recycling methods are still in early stages. Underdeveloped infrastructure for processing reactive materials and uncertainty in policy and certification elevate costs, delay adoption, and limit the deployment of these advanced batteries in commercial aviation.[253]

5. Hybrid electric propulsion (HEP)

HEP is an intermediate technology that bridges the gap between traditional combustion power and all-electric flights. It integrates internal combustion engines (ICE) or gas turbines with electric motors and batteries or fuel cells for versatile energy supply and more efficient flight throughout different flight phases. Compared to all-electric arrangements that require extensive redesign of the power plant, HEP systems involve reduced structural change but increased flight range; however, this is accompanied by substantial emissions and fuel-economy penalties.[254] In a hybrid set-up, the ICE is run at nearly its optimum operation point, with electric motors helping during energy-intensive flight periods such as take-off and climb. Hybridization is also used for engine-off operation under certain conditions, improving fuel efficiency and noise reduction. A power converter provides an efficient energy distribution, while direct-drive electric motors reduce the

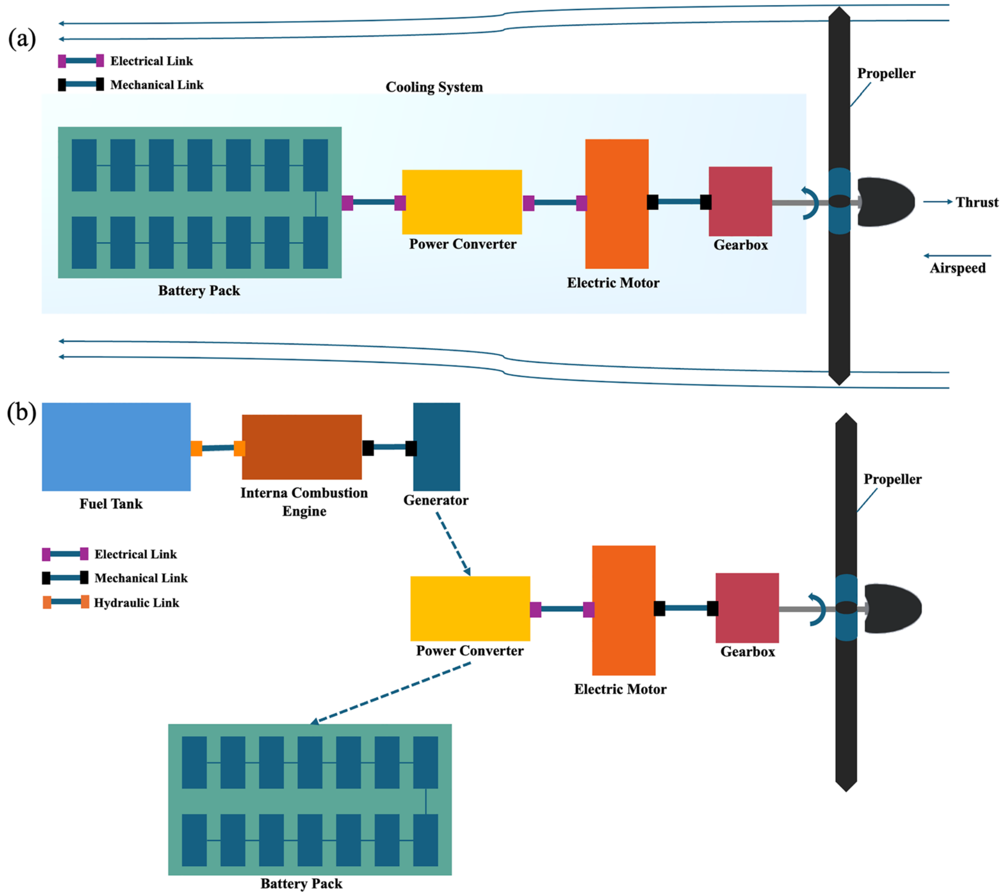


Fig. 8 (a) All-electric propulsion system with battery-powered electric motor. (b) HSEP configuration with engine-driven generator and battery support.

propeller speed reduction unit (PSRU) requirement and improve the mechanical efficiency.[254] These systems also support reduced noise footprints during take-off and landing, offering environmental advantages for operations near populated areas.[255]

Four large HEP architectures exist and are categorized based on mechanical and electrical power source integration:[256]

5.1. Hybrid-series electric propulsion (HSEP)

HSEP systems are emerging as a powerful solution for advancing low-emission aviation, particularly for regional and short-haul aircraft. In this innovative configuration, the ICE is functionally decoupled from the propeller, and instead, drives a generator that produces electricity to power a high-torque electric motor. This design allows the ICE to operate continuously at its optimal efficiency point, resulting in superior fuel economy and significantly reduced emissions compared to that of conventional systems.[255] The mechanical decoupling also offers substantial design flexibility, enabling the strategic placement of the ICE and compatibility with distributed propulsion (DP) architectures.[257] Furthermore, this design eliminates the need for a gearbox, which simplifies the mechanical complexity and reduces maintenance requirements. Series hybrids excel in DP applications and deliver quieter operations during takeoff and climb. Demonstrator platforms like NASA's X-57 Maxwell and Airbus's EcoPulse have concretely demonstrated the functional viability and performance benefits of HSEP configurations in real flight conditions, showcasing notable improvements in propulsion-system efficiency, energy management, and acoustic performance.[258] This configuration is schematically represented in Fig. 8a and b, where a fuel-burning engine powers a generator that supplies electricity to a motor driving the propeller.

Series hybrid systems have some limitations, mainly due to energy losses from converting power between mechanical and electrical forms, which reduce the overall efficiency.[259] Typically, these systems include three key parts: a compact fuel-efficient ICE, an electrical generator, and a variable-speed electric motor. All of these must be sized to handle peak power needs, which can increase the system's weight and complexity. This requires the use of lightweight materials and advanced design strategies.[260] Proper and optimized thermal management is also important, as it needs advanced cooling solutions to ensure reliability during high loads. Despite these challenges, studies show that series hybrid setups can greatly reduce the fuel consumption and emissions, making them appealing for meeting regulatory and environmental standards.[257] Continued improvements

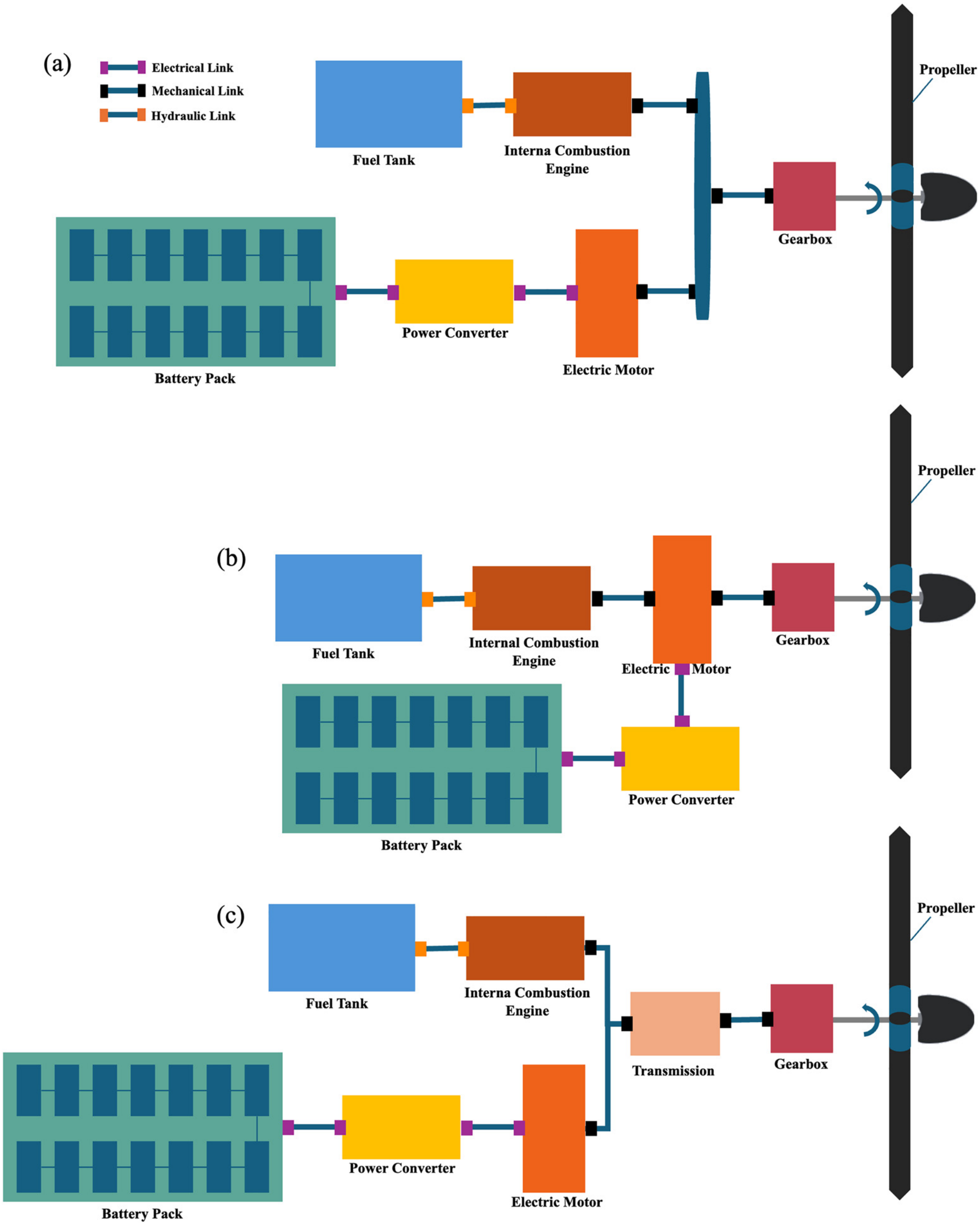


Fig. 9 (a) Basic HPEP system layout combining combustion and electric drives. (b) Single shaft, and (c) double-shaft series–parallel hybrid configurations with electrical and mechanical power splits.

in high-efficiency power electronics, electric motor technology, and specific optimization for hybrid flight cycles are crucial for increasing the power density beyond 1 kW kg^{-1} and for enabling wider use in future commercial aviation.[260]

5.2. Hybrid-parallel electric propulsion (HPEP)

HPEP systems can significantly improve aircraft efficiency and reduce emissions, making aviation more sustainable. In this setup, an ICE works alongside an electric motor (EM) to help drive the propeller. Both sources can work together or separately to provide thrust. Unlike series hybrid systems that convert power multiple times, the parallel configuration allows for a direct mechanical drive. This reduces the energy loss during conversion and enhances overall efficiency.[261] The ICE can both propel the aircraft and recharge the battery, optimizing how energy is used throughout the flight.[262] Studies show that HPEP systems can save approximately 10% of energy and cut CO_2 emissions by 4%, compared to traditional propulsion systems. Additionally, this setup offers flexibility, allowing for smaller ICE and EM sizes as they do not need to handle peak power demands alone. This leads to lighter designs and improved flight endurance. Real-world demonstrators, such as Cessna 337 aircraft, confirm the benefits of significant fuel savings and a longer operational range,[262] as illustrated in the system architectures shown in Fig. 9a–c.

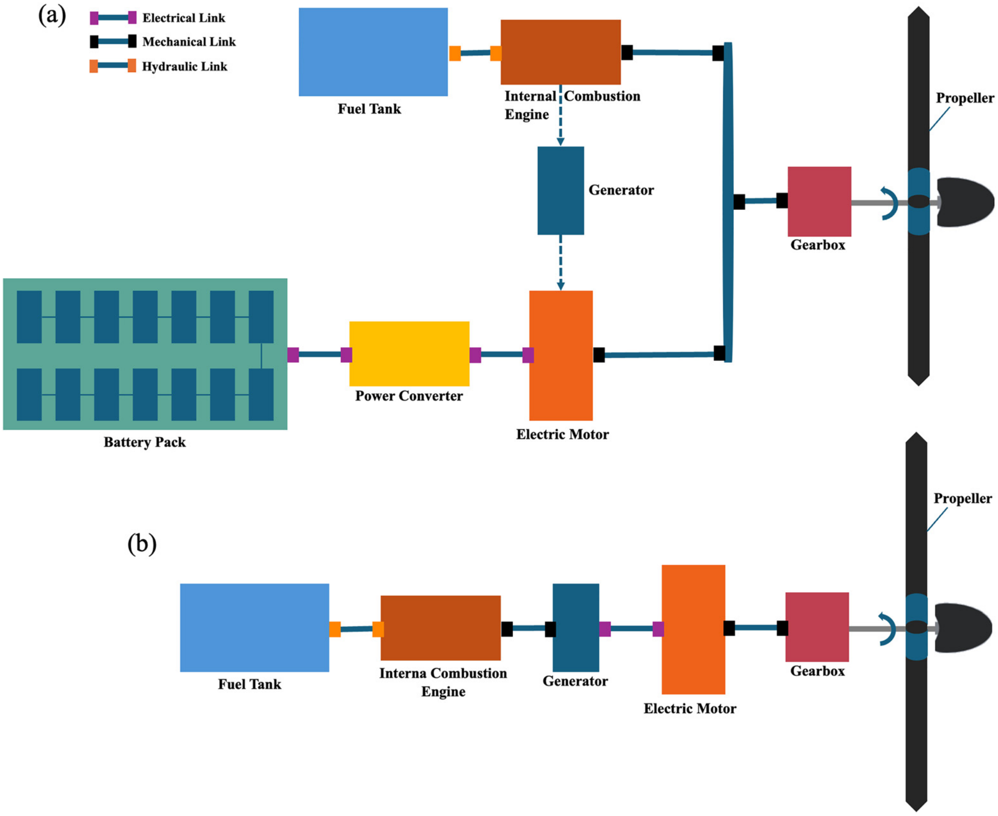


Fig. 10 (a) HSPEP system layout. (b) Turboelectric propulsion configuration using generator-driven electric motor.

Despite these advantages, HPEP systems also pose challenges. The main issues are mechanical connections, energy management, and cooling needs. To keep the ICE and EM working together smoothly, complicated designs are necessary.[263] Advanced control systems and power management are crucial to balance the workload between the ICE and EM, which helps improve efficiency and extend battery life.[258] Even though HPEP has fewer components than series configurations, using both charging and propulsion at the same time can create thermal stress, making well-engineered and robust cooling strategies essential. Studies have focused on lightweight drivetrain designs and better electric machine integration to maintain a high performance without adding extra weight.[263] Architecturally, there are two setups: single-shaft configuration, where the ICE and the EM are on the same shaft, which creates a simpler system while making control a bit more challenging. In contrast, the double-shaft configuration separates the ICE and EM onto different shafts, allowing for more precise control of power. This separation enhances the efficiency during various flight phases, such as climbing and cruising.[257] Selecting the right configuration plays a crucial role in determining the system's complexity, control, and overall performance for different mission types.

5.3. Hybrid series–parallel electric propulsion (HSPEP)

HSPEP systems combine the benefits of both series and parallel hybrid designs. This setup uses a planetary gearbox to share power between an ICE and EM. Depending on the flight phase, it can draw energy from one or both sources. This flexibility allows ICE and EM to operate near their optimal efficiency points, thus improving the overall energy performance, particularly during variable-load conditions. This configuration is ideal for missions that require high-speed cruising while keeping low emissions during taxiing or climbing. It delivers energy in a controlled and energy-efficient manner without needing oversized components. During low-power phases like taxiing, takeoff, or descent, the EM can supply most of the thrust, while both ICE and EM work together during high-demand cruising. However, because both units are mechanically connected, they create passive drag and internal resistance even when one source is inactive, reducing the net overall efficiency during longer flights,[264] as shown in Fig. 10a.

Demonstrations underscore the practical implementation potential of the HSPEP systems. A HEP prototype for the Cessna 337 achieved a maximum take-off power of 134 kW, marking an important step for real-world applications.[262] Other single-seat aircraft demonstrations revealed that these systems could save fuel and reduce CO_2 emissions through hybrid designs that split power.[255] On the modeling front, a test of a 100 kW HSPEP powertrain used numerical simulations and showed an error of less than 5%, confirming the accuracy of design simulations. Hardware-in-the-loop (HIL) testing platforms have facilitated controller calibration and system response tuning across mission profiles.[265] Studies suggests that HSPEP systems can save up to 10% in energy and reduce CO_2 emissions by 4% compared to traditional engines. This is particularly true when using mission-specific modes like "max recharge" and "max efficiency" to optimize performance during different flight stages.[262]

Incorporating planetary gear systems adds weight and mechanical complexity to designs, which requires the creation of lighter actuators and better materials for gearboxes.[258] Managing heat is a key challenge in HSPEP systems as both ICE and EM generate a lot of heat. Coupled thermal–electric optimization is essential to preserve the system longevity and safety, especially during high-load operations.[266,267] Adding renewable energy sources can improve the energy efficiency, but it also complicates the management of energy distribution and control.[266] Still, adaptive energy-management strategies and well-optimized power-splitting controls can help increase endurance without needing much more battery weight. As research continues, HSPEP systems are expected to play an important role in reducing the environmental impacts of aviation, especially in regional and UAV applications where flexible propulsion strategies offer measurable performance and sustainability gains.

5.4. Turboelectric hybrid propulsion (THP)

THP systems are an advanced way to reduce carbon emissions in aviation without using onboard batteries. In these systems, a gas turbine or ICE generates electricity, which then powers an electrically driven high-efficiency EM to create thrust using fans or propellers (Fig. 10b). This setup separates the mechanical and propulsive parts, allowing the ICE to work efficiently during different flight stages. It also offers flexible placement of components within the aircraft, supporting designs like DP and boundary layer ingestion (BLI) for better aerodynamics.[268] There are two types of turboelectric systems: complete and partial. Complete systems rely entirely on electric thrust, while partial systems combine electric power with traditional turbofans. The NASA STARC-ABL project is an example of the partial system, as it uses a gas turbine for providing the main thrust and electrically assisted fans for support.[269] Integrating SOFCs and superconducting motors potentially powered by green hydrogen, can increase the thermal and electrical efficiency, allowing for zero-emission operations. Recent studies have shown that SOFC–gas-turbine systems can achieve over 75% efficiency during cruising, highlighting their potential for long-range electric aviation.[270]

Improvements in efficiency have been made by integrating airframes and propulsion systems. Tail-mounted BLI systems in turboelectric aircraft have cut the fuel consumption for the payload range by approximately 10.4%.[271] Distributed ducted fan systems combined with high-temperature fuel cells have lowered specific fuel consumption by as much as 46%. However, this improvement comes with a weight increase of 160%, highlighting the challenge of balancing energy density with mass.[272] Superconducting motors provide high power density and reduced losses, but they need strong cryogenic systems and thermal shielding. This means that the weight of the

Table 7 Comparative performance metrics of propulsion and energy storage systems for aviation[277–279]

Technology	Specific energy (Wh kg^{-1})	Specific power (W kg^{-1})	Estimated cost	Safety considerations
SAFs	~11 000–12 000 (≈Jet-A)	Very high (thermal type)	High (premium over jet fuel)	Flammable; compatible with existing infrastructure
Hydrogen combustion	~33 000 (LH_2)	High	Medium–high	Cryogenic risks; NO_x emissions require mitigation
Hydrogen fuel cells (PEM/SOFC)	1000–2000 (system level)	Moderate	High	Needs pure hydrogen; sensitive to thermal management
LIBs	330	250–1000	$100–150 per kWh	Fire risk; TR if not managed
SSBs	400–500	100–500	High ($200–400 per kWh est.)	Safer than Li-ion; solid electrolyte suppresses dendrites
LMBs	~500	Moderate	Higher than Li-ion	Dendrite risk; needs stable SEI/interface
Li–S	450–550	Low-moderate	Potentially low (sulfur abundant)	Polysulfide shuttle and low cycle life
Li–air	Up to ~3400 (theoretical)	Low-moderate	Very high/experimental	Highly reactive; electrolyte stability issues
Na-ion	75–200	Up to 1000	Low ($40–77 per kWh)	More stable; lower energy density than Li-ion
Zn–Air	Practical ~440	~100	Low	Rechargeability and electrolyte issues
HEPs	System dependent	Moderate-high	High (dual system cost)	Complex integration; requires cooling & fail-safes

powertrain and electromagnetic interference are still significant challenges. Although the theory is promising, real-world demonstrations of turboelectric systems are limited due to integration complexity, weight issues, and technology readiness.[273]

Significant progress is being made in bridging the gaps in electric aviation. Delft University and Bauhaus Luftfahrt have found that turboelectric aircraft can cut fuel weight by as much as 28%. However, this advantage might be offset by a 14% increase in the maximum take-off weight for a typical 400-nautical-mile mission.[274] Studies further show that advanced designs and improvements in aerodynamics can lead to better performance, but only if the weight of components is kept low.[104,275] Current challenges include underdeveloped superconducting materials, battery systems, cryogenic cable management, and inconsistent certification standards.[276] Despite these challenges, turboelectric systems are an essential long-term option. Their future success depends on efficient cryogenic electronics, compact SOFCs, scalable thermal management solutions, and overall optimization for electric aviation.

These various hybrid propulsion configurations signify progressive advancements toward fully electric aviation. Each architecture plays a distinct role in aviation decarbonization, from partial reliance on combustion in parallel and series systems to the sophisticated thermal-electrical synergy in turboelectric propulsion. The performance suitability of these systems depends on aircraft class, mission profiles, and the maturity of enabling technologies. To enable a side-by-side comparison of the propulsion and energy storage systems discussed, Table 7 provides a concise overview of key performance metrics. This summary aids in technology selection based on mission requirements, aircraft class, and the maturity of each system.

5.5. System-level integration challenges

5.5.1. Thermal management

5.5.2.1. SAFs. The integration of SAFs into conventional and next-generation aircraft is relatively straightforward due to their compatibility with existing fuel infrastructures and thermal management strategies used for Jet A-1 fuel.[280] However, challenges arise, such as changes in fuel lubricity and pump performance due to lower aromatic content in some SAFs. Engine and airframe manufacturers are assessing compatibility across approved SAF blends, and advanced materials like aerogels are being explored for better thermal efficiency.[281] Innovations such as microtube-based heat exchangers from collaborations like honeywell and reaction engines can achieve up to 30% weight savings and improve heat rejection. SAFs also present opportunities in hybrid-electric propulsion, potentially serving as auxiliary heat sinks.[282] Optimizing thermal integration of SAFs in hybrid-electric systems will be key as the industry shifts toward multi-fuel strategies for sustainable aviation.

5.5.2.2. Hydrogen fuel cells. Hydrogen fuel-cell propulsion presents unique thermal integration challenges, from cryogenic storage to waste heat rejection, requiring innovative solutions. Recent work by Filipe *et al.* highlights the benefits of hydrogen's cryogenic storage temperature (20 K) as both an energy source and thermal sink, leading to 10–23% reductions in weight, energy consumption, and drag in regional aircraft without vapor compression systems.[283] Kösters *et al.* demonstrated a lightweight thermal management approach using hydrogen reactant flow for cooling PEM fuel-cell stacks, maintaining thermal thresholds effectively.[284] Additionally, Quaium *et al.* showed that a two-phase coolant system leveraging ram-air heat rejection reduced system mass by 43% compared to one-phase liquid cooling.[285] The UK' FlyZero initiative emphasizes the advantages of high-temperature PEM fuel cells (HT-PEMFCs, operating above 160 °C), achieving specific heat rejection rates above 20 kW kg^{-1} *versus* 5 kW kg^{-1} for low-temperature models.[286] These insights suggest that utilizing hydrogen as both fuel and coolant can lead to efficient, lightweight thermal architectures for next-generation fuel-cell aircraft.

5.5.2.3. Battery technology. Thermal management in battery-powered electric aircraft is crucial for safety and performance, particularly under aviation-specific stressors like high discharge rates and low temperatures. TR is divided into three stages: initial overheating, heat accumulation with gas release, and combustion.[287] Mitigation strategies include robust designs, thermal isolation using fire-resistant barriers, and advanced venting strategies for low-pressure environments.[288] During takeoff and climb, heat dissipation needs are high, with discharge rates of 3–5C. Traditional cooling systems often fail to meet aviation demands, but immersion cooling in dielectric fluids offers significantly higher heat removal capabilities. Nanofluid systems can reduce cell temperatures by 50%,[289] while hybrid methods using phase-change materials (PCMs) manage both baseline and peak heat loads.[290] High altitudes complicate thermal management, as lower pressures can increase burning rates and cause venting failures.[291] Advanced electrolytes can enhance stability in cold conditions, and machine-learning adaptive cooling systems are being explored to optimize cooling dynamically.[292]

5.5.2.4. Hybrid electric propulsion. Thermal management for hybrid-electric aircraft requires a multi-layered approach to address interactions between batteries, electric machines, fuel cells, combustion engines, and environmental control systems (ECS). Studies on hybrid platforms like STARC-ABL and Eco-Pulse highlight the importance of integrated liquid cooling loops, utilizing fluids like PGW30 or PSF-5 for thermal stability. Advanced architectures, such as dual-loop systems, efficiently manage heat from various components.[293,294] Innovative cooling methods, like oscillating heat pipes and PCM-assisted systems, offer efficient thermal rejection with minimal weight penalties. Research into nanofluid coolants and adaptive ECS-TMS coupling has shown promise in reducing system sizes while maintaining acceptable fuel burn (1.4%).[295] Increasing allowable junction temperatures (380–400 K) can enhance performance during cruise and eliminate drag penalties. Overall, multi-loop modular architectures combined with multidisciplinary design optimization and AI-driven thermal control are vital for the safe and efficient deployment of hybrid-electric propulsion in commercial aviation.[296,297]

5.5.2. Power electronics and voltage matching. Efficient power electronics play a crucial role in voltage, current, and power management for electrified aviation, especially in hybrid-electric and hydrogen fuel-cell systems. Unlike conventional SAF systems, electric and fuel-cell aircraft rely on robust DC–DC and DC–AC converters to stabilize high-voltage batteries and propulsion units. Aviation-grade converters must withstand thermal and dielectric stresses while meeting stringent electromagnetic compatibility (EMC) standards, making wide-bandgap semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN), appealing for use in inverters.[298] Multi-port DC–DC converters are crucial for modular electric propulsion, enabling the balancing of loads across various components.[299] For hydrogen-electric aircraft, lightweight, cryogenic-compatible converters are vital for linking PEM fuel cells to high-efficiency inverters while minimizing heat generation. High-voltage DC bus systems ($\geq$540 V) are proposed to reduce wiring weight and resistive losses in range-sensitive platforms.[300,301]

Beyond efficiency, voltage matching across diverse energy sources is a significant challenge. In hybrid aircraft, batteries on AC motor phases can boost voltage, but require complex switching circuits.[302] For more-electric aircraft, integrating $\pm$270 V and 28 V DC buses demands advanced topologies like the decoupled triple active bridge converter.[303] Ongoing developments include digitally controlled converters for precise management,[304] bi-directional and multi-port converters with wide-bandgap device, and modular architectures for reliability.[305] Future innovations, including superconducting storage systems and lightweight converter components, highlight the importance of advancing propulsion integration in sustainable aviation.

5.5.3. Control strategies for multimodal systems. The integration of control strategies for multimodal propulsion systems poses a complex challenge in coordinating energy sources for dynamic missions. Hybrid-electric propulsion systems (HEPS) require coordination of power dispatch, component sizing, and fault handling during flight phases. Nakka and Alexander-Ramos highlighted the control complexities in balancing propulsion components for performance during climb, cruise, and descent.[306] Recent advancements in reinforcement learning (RL) and adaptive energy management show promise in hydrogen fuel cell-battery UAVs, alongside Waddington *et al.* in managing LH_2 fuel cell subsystems.[307,308] To address unexpected variations, adaptive neural networks for fault-tolerant control have been explored. In contrast, model predictive control (MPC) with lifetime-aware limits optimizes battery and fuel cell usage.[309]

Effective control strategies must unify diverse energy sources within aircraft propulsion architectures. Advanced energy management systems (EMS) allocate power from thermal and electric sources for mission efficiency.[310] Optimal control formulations, including convex optimization, support real-time decision-making while adapting to aircraft mass changes.[311] Multi-level MPC adapted from automotive applications provides oversight of energy distribution, adhering to aviation operational rules.[312] NASA's Turbine Electrified Energy Management (TEEM) architecture exemplifies scalable turbine-battery integration, and onboard DC microgrids use Lyapunov-based and nonlinear droop controllers to ensure fault tolerance.[313] These layered control mechanisms enhance operation across SAF, hydrogen, battery, and hybrid-electric propulsion systems in next-generation aircraft.

6. Flight demonstrators of sustainable propulsion technologies

6.1. SAF and hydrogen propulsion

Recent progress in SAFs has made them an important option for reducing carbon emissions in aviation. Boeing has taken a leading role in this effort with its ecoDemonstrator program, launched in 2012. This program has tested over 250 technologies related to sustainability. Boeing has also assessed how SAF works with different engines and flight conditions. In April 2024, Boeing made its biggest SAF purchase, buying 9.4 million gallons to support its operations in the U.S. This move shows Boeing's commitment to reducing carbon emissions in the near term.[314] Airbus has also tested SAF, using 100% SAF in its long-haul flights on the A350 aircraft with Rolls-Royce Trent XWB engines. This confirms the technical feasibility of using SAF for commercial flights.[315]

Hydrogen propulsion is a promising approach for achieving zero-emission flights. Boeing made history in 2008 by flying a manned aircraft, the Diamond HK36 Super Dimona, using a hydrogen fuel cell and LIBs. In 2009, the Antares DLR-H2 became the first aircraft to fly solely on hydrogen fuel cells. By 2016, the HY4 was the first four-seat passenger aircraft powered by hydrogen fuel cells.[316] In January 2023, ZeroAvia tested its Dornier 228 with a 600 kW hydrogen-electric powertrain; it plans to build a demonstrator for 2026 with KLM.[317] Airbus's ZEROe program is researching both hydrogen combustion and fuel-cell propulsion. In 2023, Airbus tested a powerful 1.2 MW hydrogen fuel-cell system.[318] Other projects like the Blue Condor and Universal Hydrogen's Dash 8 retrofit also showed that hydrogen worked for small and medium applications. Hydrogen is attractive because it has a high energy density of approximately 120 MJ kg^{-1}. However, challenges such as cryogenic storage, tank integration, and developing infrastructure remain significant hurdles.[319]

Together, SAF and hydrogen-powered aircraft underscore the fact that the aviation industry is addressing climate change through multiple approaches. Hybrid planes such as Heart Aerospace's Heart X1/ES-30 aim to fly 200 km on electricity alone and up to 400 km using a combination of SAF or hydrogen fuel. These developments are gaining traction in commercial, regional, and experimental aviation. They provide

Table 8 Summary of SAF and hydrogen-powered aircraft demonstrators with key specifications

Aircraft/program	Developer/ organization	Propulsion type	Key features/notes	Status/timeline	Ref.
 ecoDemonstrator Program	Boeing	SAF & hybrid-electric	Tests over 250 green technologies; SAF integration across platforms	Active since 2012	314
 A350 SAF Long-Haul Test	Airbus	100% SAF combustion	Validated long-haul flight using Rolls-Royce Trent XWB with 100% SAF	First tested in 2021	320
 Dornier 228 (ZA600)	ZeroAvia	Hydrogen-electric (fuel cell)	19-seater aircraft; 600 kW fuel-cell system	First flight in Jan 2023	317
 ZA2000 Demonstrator	ZeroAvia & KLM	Hydrogen-electric (fuel cell)	Designed for regional turboprops; demo with KLM	Flight planned for 2026	317
 ZEROe Fuel Cell Demo	Airbus	Hydrogen fuel cell	1.2 MW stack tested for commercial aircraft integration	Power-on completed in 2023	318
 ZEROe Concepts	Airbus	Hydrogen combustion/fuel cell	Various aircraft concepts (blended wing, turboprop, turbofan)	Ongoing development; service by 2035	318

Table 8 (*continued*)

Aircraft/program	Developer/ organization	Propulsion type	Key features/notes	Status/timeline	Ref.
 Blue Condor	Airbus	Hydrogen combustion	Glider platform to evaluate contrail and emission impact	First hydrogen flight in Nov 2023	321
 HY4	H2FLY & DLR	Hydrogen-electric (fuel cell)	Four-seater aircraft; demonstrated Europe's first piloted hydrogen flight	Since 2016; continuous testing	322
 Universal Dash 8	Universal Hydrogen	Hydrogen combustion + fuel cell	Regional retrofit; modular hydrogen pods	Partial test flight completed in 2023	323
 Heart X1 / ES-30	Heart Aerospace	Hybrid-electric + SAF/H_2	Regional aircraft targeting 200 km electric + 400 km hybrid range	First flight expected in mid-2025	324

critical data for new regulations, technology, and operations needed for air travel to become climate neutral. A summary of the key demonstrator aircraft powered by SAF and hydrogen, along with their propulsion types and specifications, is provided in Table 8.

6.2. Hybrid-electric propulsion

This section discusses the testing of HEP systems through real flight demonstrations. Research groups, universities, and aerospace companies build prototypes to evaluate designs, improve power management, and solve integration issues. To assess the scalability of hybrid-electric systems, demonstrators are categorized according to the MTOW and mission type as small-scale (typically UAVs), medium-scale (light-crewed aircraft), and large-scale (regional and commercial aircraft). This helps compare performance and identify technical challenges. The following section begins by focusing on small-scale UAVs, which have laid the foundation for HEP testing through early-stage demonstrators.

6.2.1. Small-scale demonstrators. In particular, UAVs are essential for testing new HEP systems. Their small size, low cost, and flexibility make them suitable for exploring different propulsion setups and energy-management methods. In 2005, researchers at the University of California-Davis designed a 13.6 kg UAV with a 4.65 m wingspan and 220 Wh battery for Intelligence, Surveillance, and Reconnaissance (ISR) missions. Simulations showed that their hybrid design, using a neural network to optimize energy use, could reduce the energy consumption by 54%, compared to a gasoline-powered UAV.[325,326] Later, the Air Force Institute of Technology (AFIT) improved this design and found that a clutch-start parallel system with a charge-sustaining strategy could reduce the empty weight. They built a prototype using a 969 W Honda GX35 engine and 1.2 kW Fuji motor in a UAV, but a complete flight test was not conducted.[327,328]

The Queensland University of Technology (QUT) advanced the field by building a test rig with a 10 cc ICE and 600 W brushless motor. Their control strategy achieved 6% reduction in fuel use with just 5% increase in weight.[326,329] In Europe, Schömann and his team at the Technical University of Munich developed scalable HEP system models for UAVs. They created a quick sizing method that showed the feasibility of aircraft in the 10–70 kg payload range. This included a 35 kg UAV that could carry a 16 kg payload.[330,331] Friedrich and Robertson (2015) applied ideas from manned aircraft to a 20 kg UAV, using a 900 W ICE and 400 W motor in parallel, which saved 47% fuel compared to ICE-only designs.[255] Studies have also showed that integrating supercapacitors with LIBs can enhance power delivery during peak thrust phases and significantly extend the flight time.[332] Likewise, SOFCs paired with thermionic and thermoelectric generators have been conceptually demonstrated to produce 553.7 W of electrical output at 49.3% efficiency, representing a promising direction for long-endurance hybrid UAV applications.[333]

There has also been significant commercial progress. Quaternium's HYBRiX.20, launched in 2017, was one of the first hybrid fuel-electric quadrotors to fly for over 2 h with a 6 kg payload using a series-hybrid system.[334,335] Harris Aerial's Carrier H4 Hybrid HL, expected in 2023, will have a 4.3 kW onboard generator and will be able to carry 18 kg for 3 h when fueled with 15 L of gasoline.[336] Other series-hybrid UAVs, like Skyfront's Perimeter 8 and Foxtech's GAIA 160, offer similar payloads with slightly less endurance. By contrast, Yeair! introduced a parallel hybrid system using four rotors, combining 600 W electric motors with 1 kW ICEs for a total output of 6.4 kW, allowing a 1 h flight with a 5 kg payload.[334] These developments are invaluable for testing hybrid strategies and setting performance standards for future larger aircraft.

6.2.2. Medium-scale demonstrators. HEPs in medium-scale aircraft represent an advanced step towards sustainable aviation. These aircraft, which are typically used in general aviation, go beyond small UAVs to include piloted operations. These platforms link lightweight autonomous systems with larger regional aircraft. Their capability to accommodate pilots and passengers allows for useful data collection in real-world situations, including operational loads, flight times, and certification challenges. Medium-scale prototypes are vital for testing propulsion systems, improving power distribution, and evaluating the possibility of retrofitting older aircraft. Recent numerical models have confirmed the performance of hybrid electric power systems under different operating conditions, with errors under 5%. This shows that the 100 kW-class hybrid systems suit this aircraft type.[264]

In 2009, flight design introduced a hybrid powertrain with an 86 kW ICE and 30 kW EM. This setup provided extra thrust during takeoff and powered the EcoEagle, an aircraft built for the 2011 NASA green-flight challenge.[337] In parallel, the University of Cambridge and Flylight Airsports Ltd transformed a lightweight glider, Alatus, into a hybrid aircraft with an 11.2 kW EM and 76 cc ICE.[338] Although it could not recharge its battery mid-flight, the project led to the development of SOUL, which was completed in 2014. Using a specific charging algorithm, this newer model allowed battery regeneration while flying. Airbus, Siemens, and Diamond Aircraft developed the DA36 E-STAR, the first manned series hybrid-electric aircraft, which featured a 70 kW EM and 30 kW rotary engine. The improved version, E-STAR 2, integrated the powertrain better, reducing its weight by approximately 100 kg and enhancing its range.[339] HEP has also facilitated n-flight recharging and power-sharing, reducing fuel use and improving energy efficiency.[340]

Further research focused on improving the scalability and propulsion efficiency. The HYPSTAIR initiative, which lasted from 2013 to 2017, developed a 200 kW hybrid system for Pipistrel's Panthera aircraft. This system was designed for regional flights carrying up to 70 passengers.[341] In 2019, Ampaire retrofitted a Cessna 337, called the EEL, with a 180 kW EM to create a parallel hybrid system. However, this setup decoupled regenerative capabilities.[342] Ripple's retrofits showed 54 kg fuel savings for planes like DA20 and Cessna 172, but this came with a trade-off of reducing the payload by up to 27 kg.[343] Further studies by Boggero and Glassock looked at specific mission needs. For example, a 30% hybrid approach for the Piper PA-38 saved 46 kg in weight and cut fuel use by 10 kg.[344] Another study showed a hybridization ratio of 0.67 in a skydiving aircraft, providing 224 kW of power per engine for short, high-power flights.[345] Finger *et al.* compared different propulsion systems and found that parallel systems used weight more efficiently than series hybrids. However, safety regulations requiring 100 km diversion after a failure increased the MTOW by 50%.[346,347] Challenges remain with thermal regulation and structural optimization, where adding hybrid components can increase the weight and complicate thermal management, as shown in various studies on HEP systems.[259]

Urban air mobility (UAM) is accelerating innovation in hybrid-electric vertical flights. In 2018, Workhorse's SureFly became the first hybrid VTOL demonstrator. It used a 150 kW ICE to power eight distributed EMs, with plans for future upgrades to a 223 kW turbine engine.[348] New designs like Bell's Nexus, a ducted-fan VTOL aircraft, and Honeywell's hybrid turbogenerator set new benchmarks in multimodal transport systems.[349] Rolls-Royce developed a flexible hybrid-electric system that could switch between series and parallel operation, allowing for larger commercial applications.[350] These medium-scale aircraft showed that hybrid propulsion systems were ready for use in traditional and VTOL aviation. They also encouraged partnerships between industry and academia to turn hybrid-electric ideas into practical solutions, reflecting the industry's commitment to reducing carbon emissions in regional flights.[340]

6.3.3. Large-scale demonstrators. Large-scale demonstrators represent a significant step forward in sustainable aviation, aiming to target regional and intercontinental routes, potentially replacing traditional turboprop and jet-engine planes. These aircraft can carry from 30 to over 100 passengers, with reduced emissions and fuel usage. However, significant challenges still exist—low payload capacity and heavy weight of batteries and electric systems. For instance, a study by Pornet *et al.* showed 16% reduction in fuel consumption for a 900 nautical-mile mission using a parallel hybrid system. It failed to reach the long-range goal of 3300 nautical miles without increasing the wing size.[351] Similarly, Zamboni *et al.* found that, while parallel configurations provided modest fuel savings with the current technology, series configurations had more benefits as the electric components improved.[352]

Several collaborative projects have emerged to explore the commercial potential of large hybrid aircraft. In 2013, Boeing supported Zunum Aero in creating the ZA10, a 12-seat regional hybrid-electric aircraft, with planned delivery in 2022.[353] In 2017, Airbus, Rolls-Royce, and Siemens teamed up to launch the E-Fan X, which modified a BAe 146 airliner by replacing one of its four turbofans with a 2 MW EM powered by a 2.5 MW generator and 2-ton battery.[354] At an academic level, Delft University of Technology used the ATR 72-600 as a reference aircraft. Their research showed that it could achieve 28% reduction in fuel weight, but with a 14% increase in MTOW.[355] Bauhaus Luftfahrt studied a 180-seater hybrid aircraft and found that, even with advanced battery technology (1.5 kW kg^{-1}), hybrid aircraft were mainly suitable for short-to-medium range flights owing to limitations in energy density and system weight. Georgia Tech also developed the NXG-50 concept, which projected a 15% reduction in energy consumption over the lifecycle for regional jets.[351,356,357]

Turboelectric distributed propulsion (TeDP) systems are key in large-scale research projects. In collaboration with ESAero and Boeing, NASA has developed various designs, including the ECO-150 concept and blended-wing N3-X. These fans take in air from the plane's boundary layer and are powered by cryogenically cooled EMs.[358,359] The STARC-ABL concept further combines the aerodynamics of the SUGAR Freeze platform with a propulsion system from N3-X.[268] In Europe, Rolls-Royce and Airbus have worked on the DEAP and E-Thrust programs, which utilize superconducting motors, ultimately leading to the EcoPulse™ demonstrator, developed with Daher and Safran.[360] In 2019, United Technologies introduced Project 804, a hybrid-electric demonstrator powered by a 2 MW class motor and geared turbofan producing 107 kN of thrust.[361]

In recent advancements, the Airbus EcoPulse™, a demonstrator with a design based on the Daher TBM 900, completed over 100 test hours by late 2024. This aircraft had six wing-mounted electric propellers, each with 50 kW, powered by a 100 kW APU and battery. It significantly improved the aerodynamics and noise reduction.[362] In parallel, Heart Aerospace introduced its full-scale Heart X1 demonstrator for the ES-30 hybrid aircraft. This aircraft aimed for a range of 200 km on electric power and 400 km using hybrid power, with its first flight expected by mid-2025.[324] NASA and Boeing are working on the X-66A, a new single-aisle aircraft with a special wing design called transonic truss-braced wing (TTBW). This design aims to improve fuel efficiency by up to 30%, with its first flight planned for 2028.[363] Supporting these advancements, Hui *et al.* reported that hybrid-electric designs could reduce fuel use by 10% and energy consumption by 4.7%, compared to traditional aircraft. This highlights their potential for achieving sustainability goals.[364] Meanwhile, Thonemann *et al.* found that hybrid systems based on LIBs provided short-term environmental benefits. In contrast, hydrogen fuel cell hybrids might meet long-term climate goals for regional and long-range flights.[365] These studies also identified challenges such as battery energy density, thermal control, and certification rules as barriers to broader adoption, emphasizing the need for technological breakthroughs and supportive regulations.[258,365] An overview of hybrid-electric propulsion aircraft demonstrators, including their propulsion configurations, payload capacities, and power systems, is summarized in Table 9.

Fig. 11 indicates that the existing hybrid-electric propulsion systems are technology-based and restricted to a narrow performance envelope. Most demonstrator aircraft currently feature a range below 350 nautical miles and have payload capacities of only four passengers, far from conventional commercial aircraft capability. This is because of the battery energy density and weight and power-management limits of the current electric systems. Although several parallel, series, and turboelectric hybrid configurations are being researched and show potential, these are still in the conceptual or early-

Table 9 Summary of hybrid-electric aircraft demonstrators with key specifications

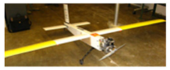
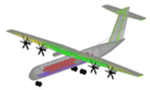
Demonstrator scale	Aircraft/project	Organization/institute	Hybrid configuration	MTOW	Payload/Seats	ICE/EM power	Flight time	Ref.
Small	 AFIT UAV	Air-Force Institute of Technology	Parallel	16 kg	1.2 kg	969 W/1.2 kW	Unknown	328
	 HYBRiX.20	Quaternium	Series	20 kg	6 kg	—	2 h	335
	 Airborg	Topflight Technologies	Series	50 kg	10 kg	—	1 h	366
	 Yeair! Quadrotor	Yeair!	Parallel	>10 kg	5 kg	1 kW ICE+ 600 W EM (× 4)	1 h	367
Medium	 SOUL	University of Cambridge	Parallel	210 kg	—	8 kW ICE/12 kW EM	—	255
	 DA36 E-Star	Airbus, Diamond, Siemens	Series	770 kg	2 seats	30 kW ICE/70 kW EM	—	368
	 Ampaire EEL	Ampaire	Parallel	2100 kg	—	156 kW ICE/180 kW EM	—	342
	 SureFly VTOL	Workhorse Group	Series	680 kg	—	150 kW ICE	—	369

Table 9 (*continued*)

Demonstrator scale	Aircraft/project	Organization/institute	Hybrid configuration	MTOW	Payload/Seats	ICE/EM power	Flight time	Ref.
	 eVTOL Concept	Rolls-royce	Series/parallel	Unknown	—	500 kW EM planned	—	370
	 Hybrid ATR-72 Concept	Delft University of Technology	Parallel	22 t	68 seats	2.2 MW ICE/1.2 MW EM	—	371
	 E-Fan X	Airbus, Rolls-Royce, Siemens	Series	Unknown	~100 seats	3 × 31 kN ICE/2 MW EM	—	354
Large	 ZA10	Zunum Aero	Series	5 t	12 seats	1 MW ICE	—	353
	 ECO-150	ESAero, NASA	TeDP (Series)	63 t	100 seats	Turbofan/18 MW EM	—	358
	 N3-X	NASA	TeDP (Series)	223 t	300 seats	60 MW ICE/56 MW EM	—	268

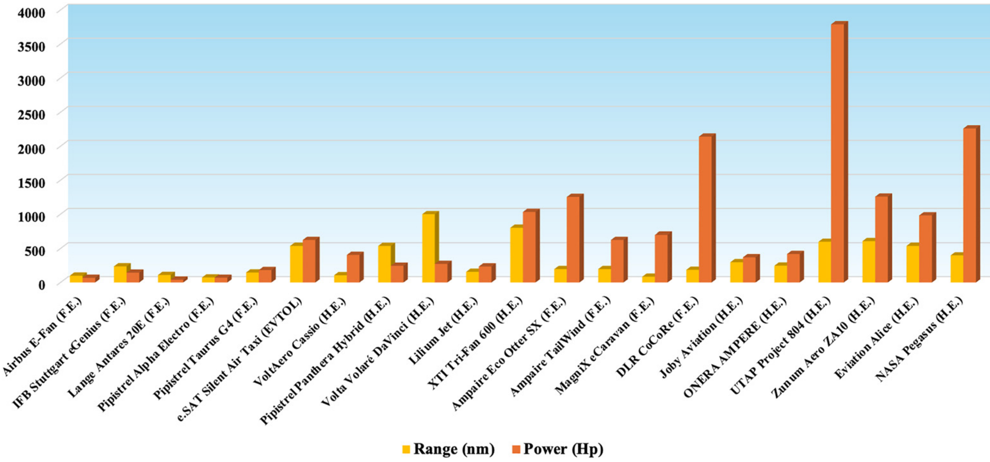


Fig. 11 Comparative analysis of various proposed hybrid-electric propulsion demonstrators.

demonstrator phases because of such limitations. Therefore, breakthroughs will be required in battery chemistry, power-distribution architecture, and thermal-management techniques. The future will require relentless investment and combined research and development of industry, academia, and regulation to drive hybrid-electric aircraft into increased range, larger capacity, and commercialization.

7. Safety, certification, and reliability

7.1. SAFs

The main benefit of SAFs is that they can blend with Jet A or Jet A-1 fuels without needing significant changes to the aircraft engines or fuel systems. Certifications for using SAFs in aviation follow the ASTM D7566 guidelines, which outline approved production methods like HEFA-SPK, FT-SPK, and ATJ-SPK. When blended in specific ratios, SAFs meet ASTM standards for commercial aviation use.[372] SAFs provide combustion efficiency and thermal stability like traditional jet fuels. However, their lower aromatic content can affect older engines; therefore, long-term compatibility testing is required.[373] To ensure safety and reliability, manufacturers and aviation authorities perform thorough evaluations, including testing emissions, fuel systems, and combustion chambers.[374]

Recent studies have highlighted that SAF certifications must meet safety and technical standards to ensure safety throughout aviation. Evolving SAF standards aim to improve safety while allowing more flexibility in the blending ratios and fuel properties, to facilitate broader adoption.[40] Fully formulated synthetic fuels like FT-SPK/A, must meet all Jet A-1 specifications before global commercial acceptance.[41] In addition, experts are analyzing the dependability of aviation energy systems that use SAFs. They use advanced modelling tools like the aviation power system reliability probability network model (APS-RPNM) to assess these power-system interdependencies.[375] While SAFs have clear environmental and operational benefits, challenges still exist. These include aligning certification processes across different regulations and ensuring consistent performance in various operational conditions. Finally, combining SAFs with new technologies, such as structural batteries or hybrid-electric engines, requires new safety standards and dynamic certification strategies. This is essential to maintain the aviation sector's high safety and performance consistency standards.[20,376] While SAFs leverage existing infrastructure with minimal modification, hydrogen and fuel-cell systems introduce fundamentally different challenges related to storage and chemical volatility.

7.2. Hydrogen fuel cells

Hydrogen-powered aviation systems, which use hydrogen combustion and fuel cells, face specific safety and certification challenges. A significant concern is safe hydrogen storage, especially in its high-pressure gas or liquid form. Cryogenic hydrogen must be stored below −253 °C, requiring advanced insulation and substantial containers to prevent leaks. High-pressure storage (350 to 700 bar) poses risks related to structural failure from changing loads and material fatigue. Any leaks can create explosive mixtures with air, and ignition can occur from sources like static electricity or hot surfaces.[11] Systems need detection and safety measures such as hydrogen sensors, good ventilation, and compartmentalization to reduce the risk of explosions. Airbus's Blue Condor and ZeroAvia's Dornier 228 demonstrator planes have incorporated these strategies to manage hydrogen risks.[317] However, rules for certifying hydrogen systems are still in development. Current aviation-fuel regulations (*e.g.*, EASA CS-25, FAR Part 25) offer a foundation for testing, but specific criteria for hydrogen, such as frequent leak checks and cold soak tests, are still being created and must be aligned across global agencies.[40]

Fuel cells, particularly PEMFCs, are becoming popular owing to their efficiency and zero emissions. However, their operational safety relies heavily on robust thermal management, gas-flow control, and water management. Problems like membrane rupture, anode flooding, or thermal runway can reduce power or release flammable gases. Therefore, aviation designs must be fault-tolerant and have real-time controls for current density, humidity, and pressure.[377] Certification standards for fuel-cell systems are still developing, so they must adapt traditional safety rules like DO-160 or CS-E to address hydrogen-electric systems during flights and emergencies,[375] redundancy in power systems, and automated isolation protocols for individual fuel cells to meet safety requirements. For instance, ZeroAvia's ZA600 and Airbus's 1.2 MW fuel cell demonstrator use modular designs to avoid single points of failure.[317] Reliability models like the APS-RPNM are applied to assess system dependencies and improve certification readiness.[376] In the future, coordinated regulations, thorough failure analysis, and global testing standards will be crucial for the widespread use of hydrogen and fuel-cell technologies in aviation. Beyond gaseous or liquid fuels, battery systems form the core of all-electric propulsion, demanding rigorous safety protocols because of thermal and chemical instabilities.

7.3. Battery systems

Safety and reliability are crucial in aviation energy systems, particularly with LIBs in electric aircraft. These batteries can catch fire or explode because of TR from internal short circuits, overcharging, or physical damage.[378] The risks increase under aviation conditions like low pressure and high altitudes, which highlights the need for thorough testing and validation of battery packs.[379] To reduce these risks, aircraft battery systems include multiple safety features: thermal containment, pressure relief, and passive flame arrestors. Additionally, using numerous battery modules that work independently is a critical fail-safe mechanism in case of localized failure.[380] The concept of "design for safety" has become essential; it requires addressing potential risks early in the battery-system design process.[381]

Adopting advanced BMS is crucial to support hardware solutions. These systems use real-time monitoring, cutting-edge algorithms, and, increasingly, machine learning and internet-of-things technologies to monitor the battery-cell behavior, predict failures, and extend battery life.[382–384] This ability to anticipate issues improves the reliability and allows maintenance based on actual conditions, which is particularly useful for high-utilization aviation fleets. Companies must comply with standards like RTCA DO-311A, EUROCAE ED-40, and UN 38.3 to get certified. These standards require various tests for mechanical, electrical, and thermal abuse, such as overcharging, short-circuiting, crushing, and exposure to extreme temperatures, for environmental factors like vibration, altitude, and humidity.[385] However, the rules can be complicated, especially with the development of new battery technologies like solid-state and silicon-anode systems. Certification processes can be lengthy and costly, slowing down the rollout of new technologies.[386] The aviation industry now advocates for more flexible, harmonized, and internationally consistent rules to make approvals easier and encourage innovation. Additionally, with a growing focus on environmental responsibility, future certifications must consider sustainable sourcing, recycling, and end-life management. This requires cooperation between the industry, regulators, and environmental organizations.[387]

A critical trade-off in aviation battery systems is the balance between achieving high performance and maintaining stringent safety standards, which is particularly relevant for battery-powered eVTOL platforms. Advanced chemistries such as high-nickel cathodes and lithium–metal anodes provide the energy density required to extend flight range, yet their higher reactivity increases the likelihood of thermal runaway under abusive conditions.[388] Similarly, fast-charging protocols designed to meet short turnaround times in urban air mobility can accelerate lithium plating and dendrite growth, compromising cycle life and reducing safety margins.[389] At the pack level, weight-saving strategies such as limiting active cooling or reducing protective housings improve gravimetric efficiency but diminish tolerance to thermal and mechanical abuse, especially under low-pressure and variable-temperature aviation environments where TR propagation behaves differently from ground systems.[390] These mechanistic interplays highlight that performance gains often narrow safety buffers, reinforcing the importance of advanced BMS, lightweight thermal-management systems, and aviation-specific certification frameworks that mandate redundancy and fail-safe operation. Such integrated approaches are essential to ensure that high-performance batteries can be deployed safely and reliably in eVTOL and other electric aviation applications.[391] While batteries and fuel cells offer emission-free propulsion, integrating multiple energy sources in hybrid-electric systems poses a unique challenge of dynamic coordination and fault isolation.

7.4. Hybrid electric propulsion

HEP systems combine ICE and EM to lower emissions and noise while keeping operations flexible. However, these systems are complex in controlling architecture, power flow, torque sharing, and real-time thermal management between the ICE and EM. Different hybrid configurations (series, parallel, and series–parallel) must smoothly switch between propulsion modes, especially during critical phases like takeoff or emergency descents. Energy management systems that use hardware-in-the-loop testing are crucial to model these systems and identify issues like mode mismatches or energy shortages before they affect safety.[259,392] Advanced fault tolerance is also essential. For example, H-type architectures can continue to provide propulsion even if a part of the system fails, allowing for fault isolation without shutting down the entire system.[392]

Certification and assessing the safety of hybrid systems is an evolving challenge. Current regulations (*e.g.*, CS-23 and DO-160) focus on traditional engines and do not fully cover the interactions between electrical and mechanical parts. New standards include dual-domain verification protocols to address overheating, motor short circuits, engine failures, and issues between fuel and electric systems.[393,394] Documenting hybrid systems, including safety standards, analyzing possible shortcomings, and powertrain reactions to faults, requires more resources than that used in traditional engines.[393] Using advanced wide-bandgap semiconductors like gallium nitride in

Table 10 Comparative overview of safety and certification parameters across propulsion systems based on ref. 395 and 396

Safety parameter	SAFs	Hydrogen & fuel cells	Batteries	HEP
Thermal hazard	Low	Moderate (owing to cryogenic storage and leak risks)	High (risk of TR)	Medium (complex thermal interactions between ICE and EM components)
Regulatory standard	ASTM D7566 (mature and widely adopted)	Emerging standards (*e.g.*, EASA CS-25 extensions, FAA hydrogen roadmap)	RTCA DO-311A, UN 38.3 (established for aviation batteries)	Developing (*e.g.*, EASA SC E-19, FAA special conditions for electric/hybrid systems)
Requires redundancy	Moderate (compatible with existing systems)	High (necessitates leak detection, ventilation, and modular fuel-cell designs)	Very high (requires multiple independent modules and robust BMSs)	Complex (demands dual-domain fault isolation and redundancy across mechanical and electrical systems)
Integration complexity	Low (drop-in compatibility with existing infrastructure)	High (challenges with cryogenic storage, material compatibility, and safety systems)	High (necessitates advanced thermal management and structural integration)	Very high (requires sophisticated coordination between ICE and EM, along with complex control systems)
Real-time monitoring	Low (standard fuel-monitoring systems suffice)	High (requires hydrogen sensors, fuel-cell controllers, and safety interlocks)	Very high (advanced BMSs with real-time diagnostics, often incorporating machine learning and internet-of-things technologies)	High (energy management systems with hardware-in-the-loop testing for dynamic coordination and fault detection)

power electronics increases the component durability and response speed, making systems more robust.[259] Redundancy strategies such as split inverters, multiple battery packs, and interconnected electrical buses help ensure that no single failure can jeopardize flight continuity. As hybrid-electric aircraft move from demonstration to certified use, cooperation between aviation regulators and industry will be crucial for these complex system's safe and timely introduction. A comparative overview of safety challenges, certification maturity, and integration requirements across propulsion systems is provided in Table 10 to highlight cross-technology considerations critical for aviation deployment.

8. Environmental and lifecycle analysis

8.1. SAF production

Life cycle assessment (LCA) is a critical approach to assessing the sustainability of SAFs, particularly in support of net-zero aviation ambitions. According to the ISO 14040 and 14044 guidelines, a good LCA should have a cradle-to-grave approach that captures all phases, from raw material supply, feedstock conversion, and fuel production to downstream distribution, use, and end-of-life treatment.[397] Although global warming potential (GWP) is the most frequently used environmental indicator, a full LCA must also consider other impact categories such as fossil resource depletion, acidification, eutrophication, formation of particulate matter, ozone layer depletion, and induced land-use change (ILUC).[398] Especially for synthetic fuels from CO_2, the sustainability impact heavily depends on assumptions regarding carbon accounting, specifically the source of CO_2 (industrial emissions or direct air capture) and the renewability of hydrogen and electricity inputs. As noted by the LCA, such fuels must encompass the reaction phase, *e.g.*, chemical conversion of CO_2 into hydrocarbons through FT synthesis or other catalytic conversion. This phase involves significant energy inputs and affects both upstream emissions and overall carbon intensity. Therefore, multi-metric LCAs are particularly important in preventing burden shifting and in evaluating the net benefit of CO_2 utilization in aviation fuel production.[399]

Under ICAO's CORSIA framework, an SAF must show at least 10% reduction in life-cycle greenhouse gas (GHG) emissions compared to traditional jet fuels, with a baseline of 89 g CO_2e per MJ. Additionally, SAFs must meet 14 sustainability criteria covering carbon storage, water use, soil health, pollution, biodiversity, and social impacts.[400,401] The LCA includes core LCA of emissions from the entire process, including feedstock production, processing, transport, and combustion. It also considers ILUC, which can significantly affect the total GHG emissions. Many waste-based feedstocks, such as used cooking oil and municipal solid waste, are considered zero ILUC. Furthermore, various land use strategies may effectively mitigate the impacts of ILUC. These strategies include the integration of SAF feedstock crops on degraded or marginal lands, the adoption of intercropping or cover cropping practices, and the repurposing of abandoned farmland. Innovations in geospatial monitoring and land classification, particularly through the application of satellite data and artificial intelligence tools, now facilitate more precise attribution of land-use emissions. This advancement contributes to the refinement of ILUC factors utilized in regulatory assessments. Nevertheless, ILUC is not only a technical challenge but also a conceptual limitation. Reported values vary widely, and the framework assumes that future land-use choices will continue without regard for climate objectives, which may not reflect future realities. This limits its reliability as a stand-alone policy tool. While ILUC remains useful for benchmarking, multi-metric LCAs combined with integrated land-climate governance provides a more credible and comprehensive framework for evaluating SAF sustainability.[402] Collectively, these practices provide significant climate benefits while minimizing ecological trade-offs. This improves their environmental benefits and makes them more appealing under international guidelines.[7]

At the end of the lifecycle, the disposal and recycling of SAF byproducts impact environmental performance. Biorefinery

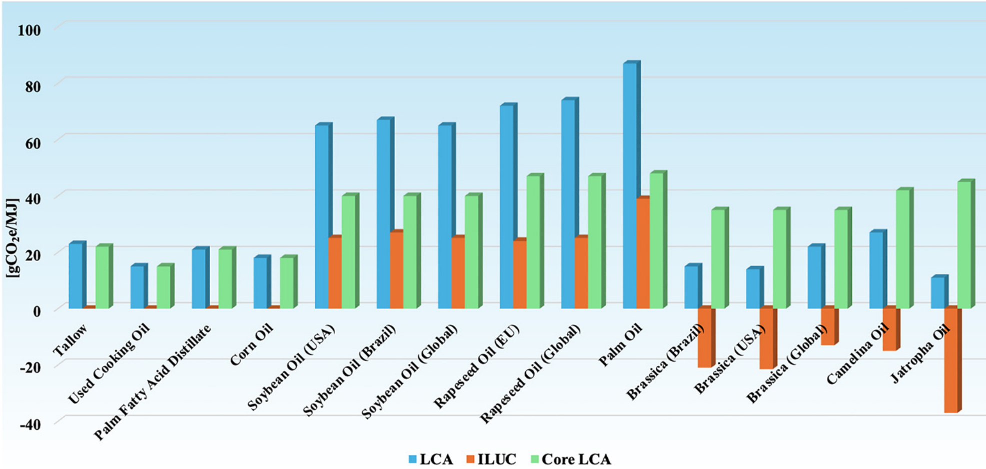


Fig. 12 Lifecycle emissions, ILUC, and Core LCA values for HEFA feedstocks based on ICAO default values and independent research.

residuals, like lignin-rich solids and fermentation residues, must be managed through valorization, energy recovery, or safe disposal to prevent burden shifting.[403] Infrastructure for collection, blending, and storage adds downstream emissions, and during the use phase, final combustion still produces CO_2, though with a lower net balance due to its biogenic origin.[404] Incorporating circular practices such as reusing process water, recovering co-products (like fertilizers and chemicals), and implementing end-of-life fuel management is essential for minimizing waste and ensuring sustainable SAF pathways throughout the entire cradle-to-grave cycle.[403]

A comparison of different pathways for producing SAF shows that processing miscanthus using FT-SPK conversion in the U.S. produces the lowest lifecycle emissions at −22.5 g CO_2e per MJ, because of the low ILUC factor.[400] ATJ fuels from isobutanol and ethanol also have low emissions of −10.7 g CO_2e per MJ and −6.8 g CO_2e per MJ, respectively. Among the pathways using HEFA, jatropha oil has a low emission value of 10.4 g CO_2e per MJ owing to its minimal usage. In contrast, palm and soybean oil have much higher emissions of over 60–80 g CO_2e per MJ owing to their significant ILUC impacts. These results underscore the importance of feedstock, farming methods, and conversion process in determining environmental impact, as shown in Fig. 12. Understanding core LCA and ILUC effects provides critical insight into which SAF pathways offer true climate benefits and which may involve unintended trade-offs within existing agricultural systems.[400,401] Collectively, this comprehensive LCA framework enables more accurate benchmarking of SAF pathways under varying feedstock, process, and energy input conditions.

8.2. Hydrogen and fuel-cell use

Hydrogen is a promising low-carbon energy source; however, its overall benefits depend on how it is produced. Therefore, a detailed LCA of hydrogen production routes is essential to determine environmental sustainability. Studies show that conventional steam methane reforming (SMR) has the highest global warming potential, of 0.098 kg CO_2eq per tkm. In comparison, hydrogen from renewable sources offer lower emissions: wind energy produces 0.025 kg CO_2eq per tkm, hydro energy generates 0.023 kg CO_2eq per tkm, and solar energy results in 0.042 kg CO_2eq per tkm. However, there are trade-offs associated with each production method. For instance, solar hydrogen production has a higher ionizing radiation potential, measuring 0.0192 kBq Co–60 eq per tkm, because of the solar-panel manufacturing process.[405] Additionally, the effects on terrestrial acidification and freshwater eutrophication vary. There are also differences in ecotoxicity and human cancer risk across different production methods. As shown in Fig. 13a and b, such variations also extend to terrestrial acidification and freshwater eutrophication, while Fig. 13c highlights the ecotoxicity and human carcinogenic toxicity differences across the different production methods. In addition to GWP, other environmental categories of impact include particulate-matter emissions, photochemical ozone formation, and land-use occupation (LUO), which make sustainability comparisons even more challenging. The solar-based pathway has the highest LUO (6.2×10^{-4} m^2 a per tkm) and freshwater eutrophication effect (0.000022 kgPeq per tkm^{-1}), whereas SMR shows the greatest particulate-matter and ozone contribution.[405] Studies have shown that hydrogen burning and SOFC technology can reduce total lifecycle air-traffic emissions by up to 59.5% under optimal conditions.[406,407] Yet, these systems bring economic trade-offs, operational costs may rise by 10.8%, and the cost per ton of CO_2 avoided increases proportionally, highlighting the need for comprehensive techno-economic analyses and harmonized ILUC models.[408]

From a material extraction perspective, hydrogen technologies present upstream environmental burdens. The platinum-group metals, which are critical for PEMFC catalysts, require energy-intensive mining and refining processes that result in significant GHG emissions and ecotoxicity.[409] Additionally, carbon-fiber reinforced composites utilized in high-pressure hydrogen tanks are produced from petroleum precursors that

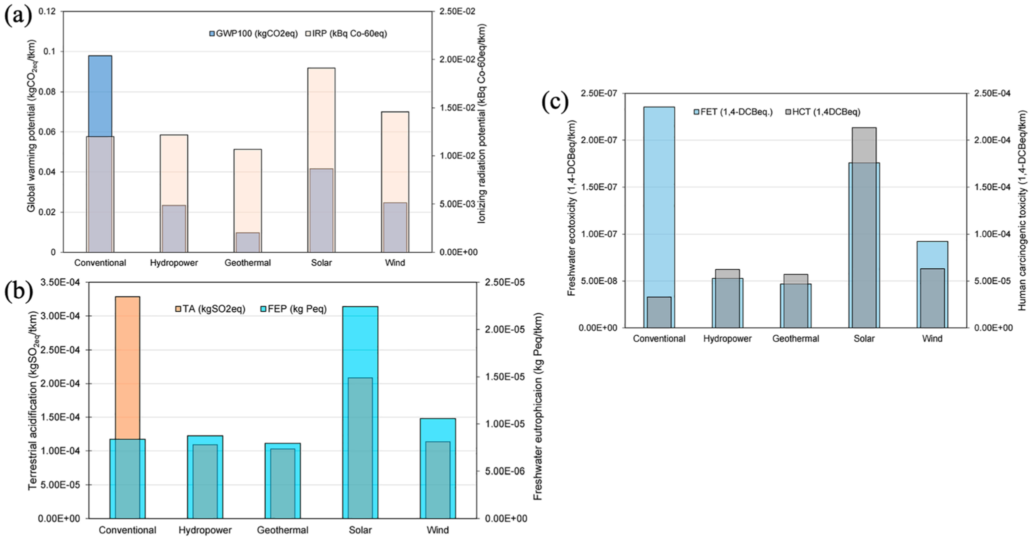


Fig. 13 (a) and (b) Life-cycle global warming potential and ionizing radiation potential for different hydrogen production routes. (c) Freshwater ecotoxicity and human carcinogenic toxicity impacts according to the hydrogen-production method. Adapted with permission from ref. 405. Copyright 2021, Elsevier.

possess high embodied energy. These upstream processes must be considered in LCAs to fully capture the material footprint associated with hydrogen aviation systems.

To further support the hydrogen production studies, more recent cradle-to-gate LCAs of hydrogen fuel-cell systems, *i.e.*, PEMFCs, SOFCs, and alkaline fuel cells (AFCs), shed fascinating insights into their environmental performance. PEMFCs have the highest GWP of 1200 kg CO_2 eq. per MWh owing to platinum catalyst loading and SMR-derived hydrogen. Higher efficiency SOFCs come next at 950 kg CO_2 eq. per MWh, with the most preferred being AFCs at 600 kg CO_2 eq. per MWh, particularly if complemented by electrolytic hydrogen from renewables.[410,411] Both the upstream hydrogen source and production process are responsible for these variations. Ironically, PEMFCs have approximately 200 kg CO_2 eq. per MWh from production alone, while SOFCs and AFCs have 150 kg and 100 kg, respectively.[410,411] In addition to GWP, LCAs highlight the significant environmental benefit of wind-powered PEM electrolysis as the cleanest source of hydrogen.[407]

In the use phase, although hydrogen combustion eliminates CO_2 emissions, it produces water vapor at high altitudes, which can form contrails and cirrus clouds with additional radiative forcing effects. These non-CO_2 impacts must be included in aviation LCAs to avoid underestimating hydrogen's climate impact.[412] Fuel-cell aircraft emissions are lower than those of conventional and alternative fuels (*e.g.*, jet and methanol).[413,414] Sustainability, however, also relies on resource-demanding factors such as platinum and carbon-fiber tanks requiring efficient recycling and end-of-life disposal.[407,415] Currently, recycling of PGMs from fuel-cell stacks is technologically feasible but energy-intensive, with recovery rates below 70% in most pilot processes, while large-scale recycling of carbon-fiber composites is still underdeveloped, leading to landfilling or incineration in many cases. Developing circular pathways for catalyst recovery, tank material reuse, and integration of low-impact substitutes is essential to ensure a cradle-to-grave sustainable transition.[416]

To make fuel cells scalable for aviation, inherent issues like infrastructure, harmonization of regulations, and cost competitiveness must be resolved. New technologies like airport-based hydrogen production, SOFC thermal optimization, and catalyst reuse will be instrumental in making long-range, zero-emission aviation possible.[417,418]

8.3. Battery supply chain

In addition to these scale-up barriers, environmental impact of aircraft battery supply chains ranges from raw-material extraction to end-of-life treatment of LIBs, which constitute the backbone of electric propulsion technology. Lithium, cobalt, and nickel are key materials that are harmful to the environment if exploited irresponsibly. For example, lithium production consumes enormous amounts of water, which may deplete local water supply and interfere with sensitive ecosystems.[378] Similarly, cobalt mining, especially in the Democratic Republic of Congo, has been linked to habitat destruction and human-rights abuses (Das *et al.*, 2024). Nickel mining contributes to the emission of GHGs and groundwater and soil pollution, such as through acid-mine drainage.[383] Geographically, as much as 68% of global emissions of battery production are found in merely three countries: China (45%), Indonesia (13%), and Australia (10%) reflecting the uneven distribution of environmental costs globally.[419] Such worries have increased the interest in sodium-ion batteries that employ more abundant and less harmful raw materials.[384] Beyond raw-material extraction, the manufacturing phase of batteries also contributes significantly to lifecycle impacts. The production of cathode and anode active materials, polymer binders, electrolytes, and separators is highly energy-intensive, often requiring

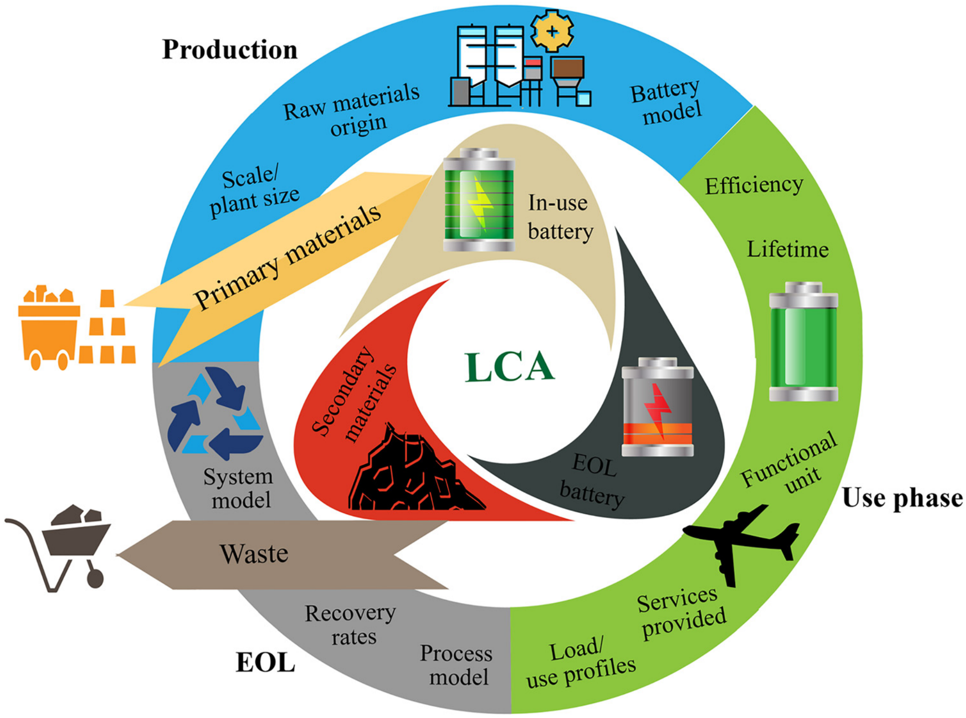


Fig. 14 Battery lifecycle from raw-material extraction to second-life use and recycling.

clean-room conditions and dry-room facilities powered by fossil-based electricity in major gigafactory regions. These processes add substantially to the embodied carbon footprint of aviation battery packs, with recent LCAs attributing up to 40% of a cell's total emissions to the manufacturing stage alone.[403,420]

LCA models must account for the environmental effect of battery technologies. The cradle-to-grave analysis considers the effects from extraction to disposal, noting that as much as 31% of emissions occur before refining.[421] Cradle-to-cradle models focus on recycling and reuse, which can minimize environmental effects by more than 58%.[421] Recycling operations, most of all, can directly reduce emissions by as much as 61% below levels of original extraction,[419] and hydrometallurgical and pyrometallurgical operations have return rates of 51% and 17%, respectively. The source of power utilized during recycling is also essential, and variations in emissions of up to eight times are based on the utilization of renewable or fossil-fueled power.[421] The second-life battery uses, like airport stationary storage or combination with renewables, have further environmental advantages in keeping waste generation at bay and enhancing material efficiency (Fig. 14).[422] During the use phase, aircraft battery packs require active cooling, protective casings, and frequent monitoring to prevent TR, all of which increase the system-level weight and energy penalty. Aviation conditions such as rapid pressurization–depressurization cycles and extreme temperature fluctuations also shorten cycle life, necessitating earlier replacements compared to automotive batteries. These replacements increase material throughput and add indirectly to the lifecycle footprint.[423]

Even with such advancements, inefficiencies in the existing recycling infrastructure remain a drawback, recycling only a few percent of valuable materials.[424] In addition, the cobalt content in batteries has been the most significant driver of environmental impact, followed by the ore grade and refining location.[425] Where recycling is absent, end-of-life batteries pose risks of toxic metal leaching into soil and groundwater if disposed of in landfills, underlining the importance of safe disposal infrastructure for aviation-scale packs. Long-term projections indicate that, assuming the aviation industry will shift to LFP batteries, the cumulative savings in emissions can reach up to 1.5 $GtCO_2eq$ by 2050.[419] Therefore, lifecycle management with recycling, alternative chemistry, and low-impact sourcing are key drivers. As reaffirmed in several reports, the aviation sector needs to develop a circular battery economy to ensure decarbonization in the long term.[387,424,426]

8.4. Hybrid electric systems

Hybrid-electric power systems have the critical potential to lower the lifecycle emissions from aviation, with estimates from cradle-to-grave analysis indicating a 49–57% reduction in the carbon intensity of an RPK under conservative assumptions and an 82–88% reduction when powered from renewable energy sources and supplemented by long-lifespan battery technology.[1] At the raw-material stage, hybrid systems require both battery minerals (lithium, cobalt, nickel) and rare-earth elements such as neodymium and dysprosium for motors and permanent magnets, all of which are associated with high mining energy demands, water use, and toxicity risks. These material dependencies contribute significantly to upstream

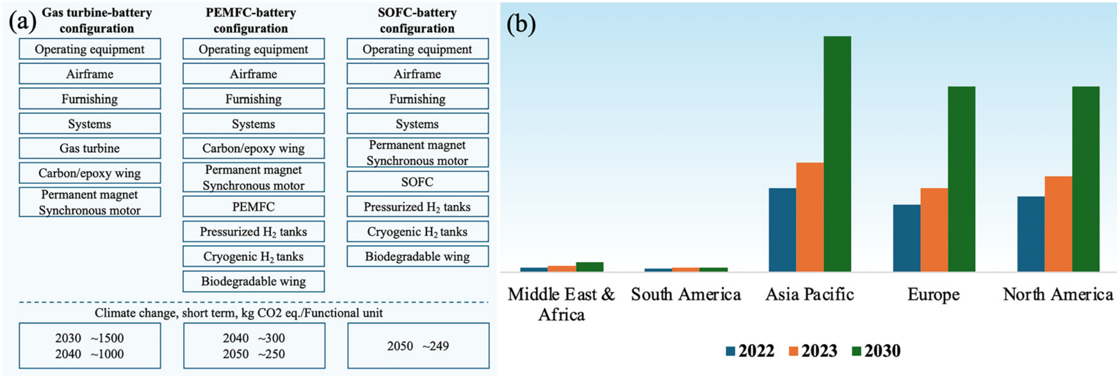


Fig. 15 Carbon-emission comparisons of HEA configurations: gas-turbine battery, PEMFC battery, and SOFC battery systems. Adapted from ref. 429 originally elaborated based on ref. 365. (b) Regional forecast of the global battery recycling market growth from 2022 to 2030. Redesigned from ref. 429 originally elaborated based on ref. 437.

lifecycle burdens.[427] Among the architectural alternatives, series, parallel, and series–parallel hybrids, the discrete-parallel architecture, which was analyzed using the ADEBO and ReCiPe metrics, achieved a 15.1% cost reduction at 0.3 hybridization and as high as 7% greater savings by utilizing renewable energy.[256] The HECATE electrical network setup (800 V KHVDC, 540 V HVDC, 28 V LVDC), a representative of the system solutions at the infrastructure level, can facilitate 30% reduction in GHG emissions by 2035 and net-zero aviation goals by 2050.[1]

HEAs exhibit multiple trade-offs among dual energy sources, integration challenges, and battery-lifecycle penalties. Manufacturing hybrid-electric aircraft requires additional steps compared to conventional aircraft, as electric motors, converters, and power electronics (often based on SiC and GaN semiconductors) must be integrated alongside traditional gas turbines. This dual drivetrain architecture increases production energy demand and adds complexity in certification, further raising the embodied emissions of the manufacturing stage.[428] A four-seater HEA with an electric range of 45 min has an emission of $\sim$160 g CO_2 eq. per km, which is lower than the 170 g CO_2 eq. per km from a conventional aircraft, with electric propulsion responsible for 1.467 kg CO_2 eq. per L compared to 2.0 kg CO_2 eq. per L from kerosene.[429] 250 Wh kg^{-1} and 0.4 BMF capacity batteries deliver 430 km range but must be replaced every 600 cycles per year upon extensive cycling, contributing to 20% of the factory emissions per year.[430] On an average, Li–S batteries release 80.8 kg CO_2 eq., whereas Li–air batteries release as low as 19.1 kg CO_2 eq.[106] Whole battery packs for commercial aircraft can release between 3.18×10^5 and 3.81×10^5 kg CO_2 eq., based on the type of battery configuration and aircraft size.[431]

The hybrid battery recycling issues addressed in Section 7.3 also apply to hybrids owing to their integration complexity and over-cycling acute material consumption. Existing systems recycle 5% of batteries, but new biometallurgical technologies using *Aspergillus niger* and battery modularity design portend possible gains.[432–435] Beyond batteries, end-of-life considerations extend to power electronics, motors, and structural housings designed to accommodate hybrid packs. Recycling rare-earth magnets and composite-integrated motor housings remains technologically immature, and recovery rates are still below 20% globally. Addressing these downstream challenges will be essential to close the loop and ensure a sustainable hybrid-electric aviation ecosystem.[436] Lifecycle-emission drivers are infrastructure needs and dual-certification regulatory requirements for dual charging and fueling. However, prototypes such as EcoPulse, Ampaire Electric EEL, and the flight-tested E-Fan X confirm HEA feasibility. These platforms yield peak-load shaving during takeoff, maximize fuel efficiency, and minimize acoustic pollution, offering scalable hybridization within the clean aviation regime.[1] These system-level comparisons and market trends are shown in Fig. 15a and b, covering emissions from hybrid configurations and battery recycling forecasts.

9. Conclusion and prospects

As efforts to decarbonize aviation are intensifying, it is becoming increasingly evident that no single technology will deliver a one-size-fits-all solution. The sector's future will hinge on a portfolio of complementary strategies tailored to aircraft type, range, and operational context. SAFs, hydrogen fuel cells, battery-electric systems, and hybrid-electric architectures each offer distinct strengths and limitations. Infrastructure readiness, system-integration complexity, energy-source availability, and regulatory alignment will shape their implementation trajectories.

SAFs represent a near-term drop-in solution for existing fleet-emission reduction; however, extensive implementation is limited by production cost, feedstock availability, and life-cycle carbon variability. Though HEFA is leading the current SAF production, long-term scalability will hinge on shifting to low-cost alternatives like ATJ and HFS-SIP. Technical priorities include enhancing oxidation stability, optimizing feedstock blending for local flexibility, and optimizing fuel conversion. Higher environmental efficiency will also demand the valorization of byproducts and optimization of realistic emission models. Strong policy support through carbon pricing, blending targets, and incentives is essential, given the high cost of production and resource competition. Waste feedstocks and nonfood feedstocks prioritized relative to ecological limits, alongside open government and lifecycle regimes, will be needed to unleash SAFs full climate potential. If cost parity and feedstock sustainability can be ensured, SAFs are likely to remain the preferred solution for medium- and long-haul decarbonization, especially within the existing global aviation infrastructure.

Hydrogen fuel cells are a leading technology with advanced efficiency and zero emissions in air, and they are a long-term foundation for zero-carbon flights. With electrical efficiencies of 70% or more, they already outperform conventional combustion engines and are increasingly well-matched to regional and long-haul aircraft. Advances in cryogenic liquid-hydrogen storage and metal-hydride technologies are improving the volumetric efficiency, safety, and thermal management. Life-cycle studies indicate that hydrogen fuel aircraft can decrease kerosene-based GHG emissions by 50–99%, and thus, they are suitable for achieving climate targets. Their viability, however, relies on installing scalable refueling facilities at airports, cryogenic system certification, and modifying aircraft to work around hydrogen's volumetric constraints. Worldwide standardization of safety standards and large-scale green hydrogen production will be key to addressing these barriers. Through concert policy, industrial cooperation, and technological innovation, hydrogen fuel cells will most likely be the cornerstone of aviation's energy revolution.

Battery technologies allow short-range aviation electrification, particularly for commuter aircraft and urban air mobility. Although lithium-ion systems currently lead, their lower energy density and thermal tolerance have prompted the search for better-performing chemistries. Solid-state and Li–S with 400–600 Wh kg^{-1} energy densities promise safety and lifecycle performance improvements. Technologies like lithium–air and nanostructured batteries aim to extend the performance further, including the 'Bat1k' concept that targets 1000 Wh kg^{-1}. However, weight limitations, thermal management, recyclability, and regulatory hurdles remain to be addressed. Aviation-grade battery installation also depends on extremely robust BMSs and globally harmonized safety standards. In addition, upstream and end-of-life environmental effects must be estimated through a complete lifecycle analysis. Meanwhile, technologies like MEA designs and hybrid-electric configurations can provide bridging solutions with advancing battery technology.

Hybrid-electric power is an actionable transition from traditional combustion to all-electric flights, with near-term advantages in emission reduction, fuel efficiency, and mission flexibility. Series, parallel, and turboelectric powerplants maximize power delivery across flight segments, aiming to achieve up to 45% fuel savings by 2045. Series designs in some applications have high near-term potential for implementation, particularly in regional segments. As battery energy density and fuel-cell efficiency improve, hybrid powerplants will achieve more attractive power-to-weight ratios and greater ranges. Improved design tools like range-equation modelling facilitate optimized system arrangements tailored to different mission profiles. Flight test demonstrators such as Airbus EcoPulse, Rolls-Royce E-Fan X, and Ampaire Electric EEL have proven in-field demonstrations of such configurations on various scales. Life-cycle analyses confirm that although some environmental burdens would be shifted to production and infrastructure, the overall sustainability would be enhanced. Economic analyses also show long-term cost savings in operation, even as integration complexity emerges. The industry must advance certification schemes, develop enabling infrastructure, and prioritize systems-engineering methodologies that support modular, scalable hybrid platforms to gain all these benefits.

Overall, sustainable aviation will be based on a strategically converging sequence of various propulsion and energy systems. Instead of relying on a one-size-fits-all strategy, the industry will have to utilize a multi-solution strategy involving aircraft type, range, geography, and energy infrastructure. Lifecycle performance, coordination of global rules, and convergence of standards will be the targets for this transformation. As SAFs, hydrogen fuel cells, batteries, and hybrid-electric configurations advance, the next decade will be critical for the transition from demonstrators to certified market-fit platforms. With focused investment, material innovation, dual system-based safety certification harmonization, and robust industry-policy alignment, the aviation industry can transition from proof-of-concept to rollout, making carbon-free flights a scalable reality.

Author contributions

Ningaraju Gejjiganahalli Ningappa: conceptualization, writing – original draft, writing – review & editing. Karthik Vishweswariah, Sabbir Ahmed, Mohamed Djihad Bouguern, and Anil Kumar M R: writing – review & editing. Karim Zaghib: conceptualization, supervision, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

No data was used for the research described in the article.

Acknowledgements

The research was funded by Concordia University. The authors thank the Government of Quebec (MEIE) for its financial support.

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