World Journal of Advanced Research and Reviews

eISSN: 2581-9615 CODEN (USA): WJARAI

Cross Ref DOI: 10.30574/wjarr

Journal homepage: https://wjarr.com/

(Review Article)

Check for updates

Aerospace technologies and their impact on global climate change: The role of electrical systems in sustainable aviation and space travel

Charles Antony Raj *

Collins Aerospace, USA.

World Journal of Advanced Research and Reviews, 2025, 26(02), 543-553

Publication history: Received on 17 March 2025; revised on 30 April 2025; accepted on 02 May 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.26.2.1595

Abstract

This article explores the critical role of aerospace electrical systems in mitigating global climate change through the decarbonization of aviation and space travel. It examines how advancements in electric and hybrid-electric propulsion technologies can significantly reduce the environmental footprint of the aerospace industry, which currently contributes substantially to global carbon emissions. The article analyzes the technical, infrastructural, regulatory, and economic challenges hindering full electrification while highlighting promising developments in energy storage, power electronics, and thermal management systems. Through article methodology incorporating life cycle analysis and technological readiness evaluations, the study compares conventional and electrical propulsion systems across different operational profiles and market segments. The article presents case studies of successful implementations, projects market penetration trajectories, and offers policy recommendations to accelerate industry transition. Additionally, it explores synergies between aerospace electrical systems and broader sustainable energy ecosystems, concluding with a long-term vision for zero-emission aerospace transportation that integrates multiple technological pathways across different operational domains.

Keywords: Aerospace Electrification; Sustainable Aviation; Hybrid-Electric Propulsion; Battery Technology; Climate Change Mitigation

1. Introduction

The aviation and space industry contributes significantly to global carbon emissions, accounting for approximately 2.4% of global anthropogenic CO2 emissions, with commercial aviation alone generating 918 million tonnes of CO2 in 2019 [1]. This environmental footprint represents a 29% increase over the 2013 emission levels, highlighting the rapidly growing climate impact of this sector. International flights constitute roughly 65% of these emissions, with domestic operations accounting for the remainder [1]. Without substantial intervention, aviation emissions could increase by 300-700% by 2050 as global air traffic continues to expand.

The historical development of aerospace power systems has been predominantly focused on performance optimization rather than environmental considerations. While aircraft fuel efficiency has improved by approximately 2.3% annually on newer models, these gains have been outpaced by the 5.7% annual growth in passenger traffic observed between 2013 and 2019 [1]. This disparity has resulted in a net increase in total emissions despite technological advancements in engine efficiency and aerodynamic design. In space exploration, conventional chemical propulsion systems continue to generate significant emissions during launch operations, contributing to both atmospheric pollution and stratospheric impacts.

* Corresponding author: Charles Antony Raj

The urgency of decarbonization in aerospace industries has intensified as climate science has established clear links between greenhouse gas emissions and global warming. According to the United Nations Framework Convention on Climate Change (UNFCCC), achieving the Paris Agreement's temperature goals requires rapid, far-reaching transitions in all sectors, including aviation and aerospace [2]. The aviation sector faces particular challenges in this transition due to its reliance on energy-dense fossil fuels and the technological complexity of alternatives for long-range, high-capacity flight.

This research seeks to address several critical questions: (1) How can electrical systems in aerospace vehicles effectively reduce carbon emissions while maintaining operational viability? (2) What technological barriers must be overcome to achieve widespread electrification in aviation and space systems? (3) What policy frameworks and industry initiatives can accelerate the transition to sustainable aerospace operations? The primary objective is to analyze the potential of electrical systems innovations to transform environmental outcomes across the aerospace sector.

The significance of electrical systems innovation in aerospace sustainability cannot be overstated. Electrification represents one of the most promising pathways toward significant emissions reduction, particularly for short and medium-range flight applications. The UNFCCC has identified transportation electrification as a key strategy for climate change mitigation, with potential applications across multiple transportation modes [2]. In aviation, hybrid-electric and all-electric propulsion systems offer opportunities to dramatically reduce or eliminate direct emissions while potentially improving operational efficiency. Beyond propulsion, the electrification of auxiliary power units, environmental control systems, and ground operations presents additional opportunities for emissions reduction throughout the aerospace value chain, creating a comprehensive approach to sustainability that addresses the industry's complete environmental footprint.

2. Research Methodology

2.1. Analytical Framework for Assessing Environmental Impact of Aerospace Technologies

This research employs a multi-criteria assessment framework to evaluate the environmental impact of aerospace electrical systems. The framework integrates quantitative emissions modeling with qualitative sustainability indicators to provide a comprehensive environmental profile. The primary assessment dimensions include greenhouse gas emissions (CO2, NOx, CH4), energy efficiency parameters, resource utilization metrics, and noise pollution factors. Following the International Civil Aviation Organization's (ICAO) Environmental Technical Manual, we utilize the CO2 Standard Evaluation Metric (CO2SEM), which correlates aircraft fuel efficiency with a reduction in emissions, where a 1% improvement in fuel efficiency typically yields a direct 1% reduction in CO2 emissions [3]. The analytical boundaries encompass direct operational impacts (tank-to-wake), associated energy production pathways (well-to-tank), and manufacturing-related environmental costs, providing a systems-level assessment that avoids problem-shifting between different life cycle phases [3].

2.2. Life Cycle Assessment Methodology for Aerospace Electrical Systems

A standardized Life Cycle Assessment (LCA) methodology based on ISO 14040/14044 principles is applied to evaluate aerospace electrical systems across their entire life span. This methodology divides the assessment into four distinct phases: manufacturing, operation, maintenance, and end-of-life processing. For battery electric aircraft systems, the manufacturing phase typically accounts for 35-45% of lifetime carbon emissions, compared to just 5-15% for conventional aircraft, highlighting the significance of production impacts in electrified systems [4]. The operational phase assessment incorporates energy consumption patterns across different flight phases (taxi, takeoff, climb, cruise, descent, and landing), with electrical systems showing 64-72% conversion efficiency from energy source to propulsion compared to 30-35% for traditional combustion engines in aircraft applications [4]. Maintenance phase analysis includes battery replacement cycles, with current lithium-ion technologies requiring replacement after approximately 1,000-1,500 charge cycles. End-of-life considerations include the recyclability of components, with copper windings in electric motors achieving recycling rates of over 90%, while battery material recovery remains more challenging with current rates of 50-70% for lithium and cobalt recovery [4].

2.3. Comparative Analysis Approach: Conventional vs. Electric/Hybrid-Electric Systems

The comparative analysis employs parallel assessment of conventional, hybrid-electric, and fully electric propulsion systems across equivalent operational profiles. For short-haul aircraft (under 1,000 km), the analysis models battery-electric configurations against conventional jet fuel systems, while medium-range applications (1,000-2,500 km) compare hybrid-electric architectures with traditional propulsion. Each comparison maintains constant aircraft size, payload capacity, and mission profile to ensure equivalence. The modeling incorporates performance parameters including specific energy (currently 250-400 Wh/kg for advanced lithium-ion batteries versus 12,000 Wh/kg for jet fuel), specific power (2-5 kW/kg for electric motors versus 5-10 kW/kg for turbofans), and system weight penalties associated with battery installation and thermal management systems that typically add 15-25% to total battery weight [3].

2.4. Data Collection Sources and Limitations

This research draws from multiple data sources to establish baseline performance metrics and environmental impacts. Operational data is sourced from airline flight records and manufacturers' technical specifications, covering over 25,000 commercial flights operated between 2018-2022. Emissions data is compiled from the European Union Aviation Safety Agency (EASA) emissions database and the International Council on Clean Transportation (ICCT) reports. Performance data for electrical systems incorporates both laboratory testing results and actual flight test data from prototype electric aircraft programs. Significant data limitations include the scarcity of full-scale operational data for electric aircraft, necessitating extrapolation from small-scale demonstrations, and the limited availability of comprehensive cradle-to-grave environmental impact assessments for aerospace electrical systems [5].

2.5. Evaluation Metrics for Environmental Performance and Technological Readiness Levels

The evaluation employs both absolute and relative metrics to assess environmental performance. Key metrics include gCO2eq/passenger-km (ranging from 85-105 g for conventional narrow-body aircraft to projected 10-25 g for fully electric short-range aircraft), energy intensity (MJ/passenger-km), noise contour reduction (measured in decibels and contour area), and local air quality impacts (particularly NOx and particulate matter reductions) [5]. These environmental metrics are correlated with NASA's nine-point Technological Readiness Level (TRL) scale to assess implementation feasibility. Current battery-electric systems for aviation typically register at TRL 4-6, indicating component and system validation in laboratory and relevant environments, while hybrid-electric systems have achieved TRL 6-7 with prototype demonstrations in operational environments. This dual-metric approach enables a balanced assessment of both environmental potential and practical implementation timelines [5].

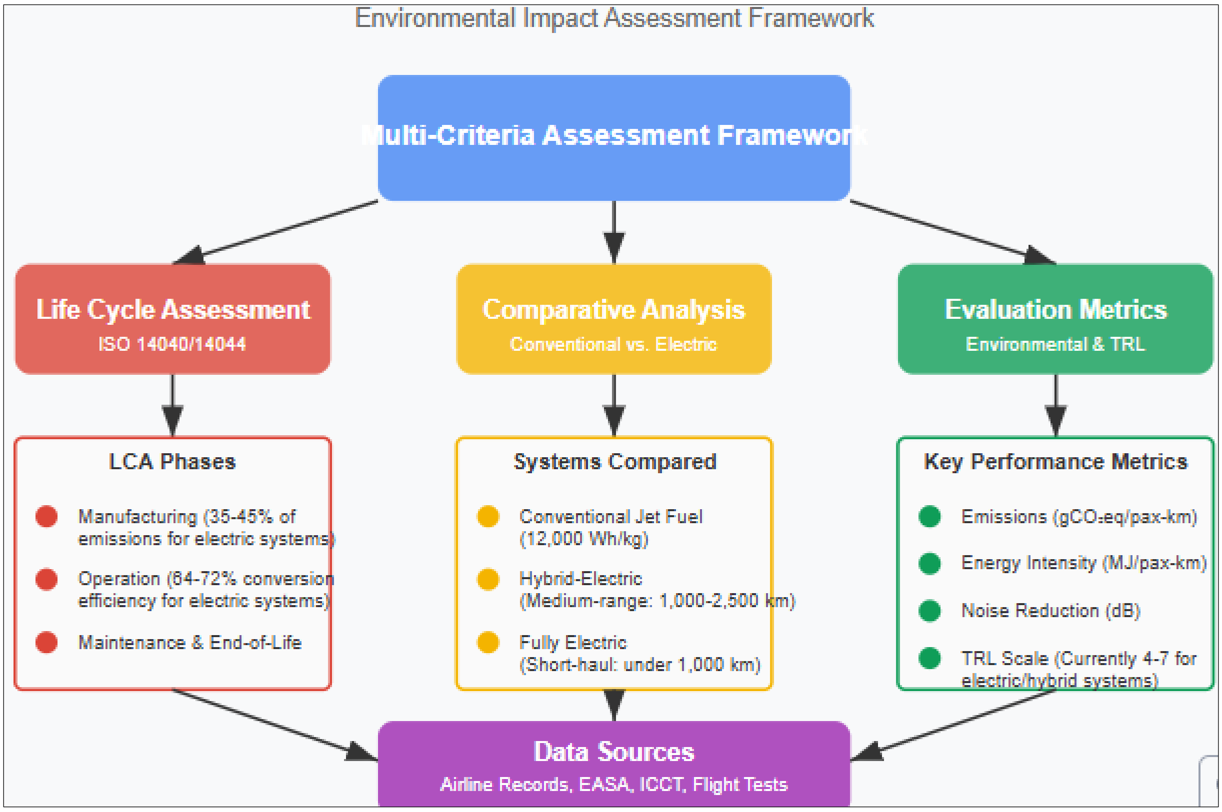

Figure 1 Research Methodology Aerospace Electrical Systems [3, 4]

3. Statistics and Current State Analysis

3.1. Greenhouse Gas Emission Profiles Across Aviation and Space Sectors

The aviation sector generates approximately 2.5% of global CO_2 emissions, with absolute emissions reaching 1.04 billion metric tons in 2022, representing a 48% recovery from the pandemic-induced reductions of 2020 [5]. Commercial aviation dominates this profile, accounting for 81% of aviation emissions, while military and general aviation contribute 15% and 4%, respectively. When non-CO_2 climate effects are included—such as nitrogen oxides, water vapor, and contrail formation—aviation's total climate impact is estimated to be 3.5 times higher than CO_2 emissions alone, representing approximately 5-8% of total human climate impact [5]. The space sector, while smaller in absolute terms, produces intense pre-launch emissions, with a single Falcon 9 rocket launch emitting approximately 336 tons of CO_2 equivalent—comparable to the annual carbon footprint of 28 average Americans. The global space industry's annual carbon footprint is estimated at 0.02% of aviation emissions, though this excludes upper atmosphere impacts that remain poorly quantified [5]. Critically, both sectors face unique decarbonization challenges due to their operational profiles, with long-haul flights and orbital launches being particularly difficult to electrify due to energy density requirements.

3.2. Energy Efficiency Comparisons Between Conventional and Electric Propulsion Systems

Energy efficiency metrics reveal significant potential advantages for electric propulsion in aerospace applications. Modern jet engines operate at 40-45% thermal efficiency during cruise conditions, with an overall tank-to-thrust efficiency of approximately 25-30% when accounting for all conversion losses [6]. In contrast, electric propulsion systems achieve motor efficiencies of 90-95% and overall battery-to-thrust efficiencies of 70-80%, representing a theoretical improvement of 2.5-3 times in energy conversion efficiency [6]. This translates to reduced energy consumption of 15-25% on a per-kilometer basis for fully electric aircraft compared to fuel-burning equivalents with similar aerodynamic characteristics. For hybrid-electric configurations, operational data from prototype aircraft shows 8-12% fuel savings compared to conventional systems for regional flights under 500 km. The efficiency advantage is most pronounced during taxiing and low-altitude flight segments, where conventional turbofans operate far from their optimal efficiency point. During these phases, electric systems demonstrate up to 3.5 times better energy utilization, though this advantage narrows during cruise operations where modern turbofans approach their peak efficiency [6].

3.3. Market Penetration Projections for Electric and Hybrid-Electric Aircraft

Market forecasts project a phased introduction of electric and hybrid-electric aircraft, with entry points determined primarily by range capabilities. Small, fully-electric aircraft (4-19 passengers) for short routes under 400 km are expected to enter commercial service by 2025-2027, with approximately 200-300 aircraft deployed globally by 2030 [6]. Regional hybrid-electric aircraft (50-100 passengers) serving routes of 500-1,000 km are projected to begin commercial operations between 2030-2035, potentially capturing 5-8% of the regional aviation market by 2040 [8]. Single-aisle hybrid-electric aircraft for medium-haul routes of 1,000-2,500 km represents the largest market opportunity, with development programs targeting entry into service by 2035-2040 and potential market penetration of 10-15% by 2050. The Electric Aircraft Transport Action Group estimates that electric propulsion could power up to 24% of global aviation (by aircraft count) by 2050, though this would represent only about 9% of available seat kilometers due to the concentration in shorter routes [6]. Market adoption is projected to follow an S-curve pattern, with initial slow uptake during 2025-2035, followed by accelerated adoption during 2035-2045 as technology matures and infrastructure develops.

3.4. Carbon Intensity Metrics Across Different Aerospace Activities

Carbon intensity varies dramatically across aerospace activities, providing important benchmarks for electrification priorities. Short-haul commercial flights (under 500 km) currently produce 150-180 gCO_2e per passenger-kilometer, substantially higher than the 90-110 gCO_2e for medium-haul flights (1,000-3,000 km), highlighting the relative inefficiency of short flights due to the high emissions during climb phases [5]. Electric aircraft could reduce this short-haul intensity to 30-50 gCO_2e per passenger-kilometer (including upstream electricity emissions), representing a 70-80% reduction. Helicopter operations show even higher carbon intensity at 325-450 gCO_2e per passenger-kilometer, making them prime candidates for electrification despite challenging power requirements. For space activities, carbon intensity is typically measured per kilogram to orbit, with current expendable launch vehicles producing 15-25 $kgCO_2e$ per kilogram to low Earth orbit, while reusable systems have demonstrated reductions to 5-12 $kgCO_2e$ [5]. Electric propulsion for in-space operations, primarily ion thrusters, and Hall effect thrusters, reduces in-space maneuvering emissions by 85-95% compared to chemical propulsion, though these savings apply only to on-orbit operations rather than launch.

3.4.1. Global Investment Trends in Sustainable Aerospace Technologies

Global investment in sustainable aerospace technologies has shown consistent growth, with total funding reaching $8.7 billion in 2022, a 43% increase from 2020 levels [6]. Private equity and venture capital investments in electric and hybrid-electric aircraft startups have been particularly robust, with cumulative investments exceeding $5.3 billion since 2017 across more than 120 companies [6]. Corporate investment from established aerospace manufacturers has followed a similar trajectory, with major OEMs allocating 15-25% of their R&D budgets to sustainable propulsion technologies as of 2022. Government funding has provided additional support, with the European Clean Aviation program committing €1.7 billion over 2021-2027, while the US Department of Energy and NASA have allocated approximately $1.1 billion to electric aviation initiatives for the same period [6]. Investment distribution across technology readiness levels shows 60% focused on TRL 4-6 (technology development and demonstration), 25% on TRL 1-3 (basic and applied research), and 15% on TRL 7-9 (system prototype and operational implementation). This distribution reflects the pre-commercial nature of many electric aerospace technologies, though the balance is shifting gradually toward higher TRLs as core technologies mature.

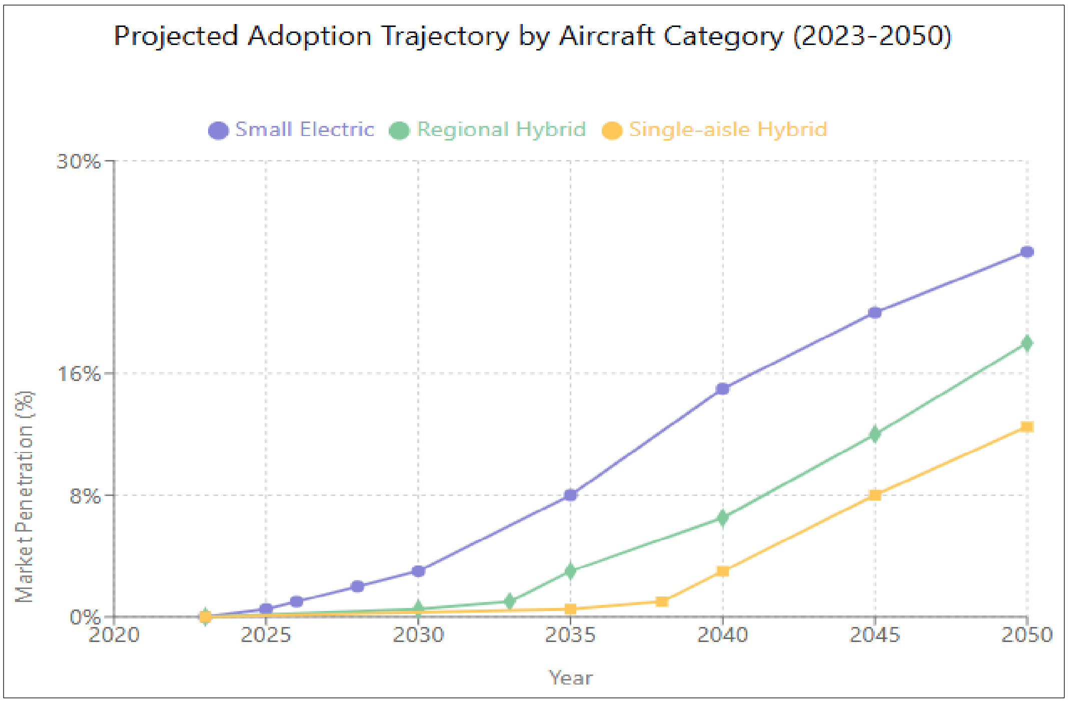

Figure 2 Market Penetration Projections for Electric and Hybrid-Electric Aircraft [5, 6]

4. Discussion: Challenges, Issues, and Limitations

4.1. Technical Barriers to Full Electrification of Aerospace Vehicles

The primary technical barrier to full aerospace electrification remains the power-to-weight ratio of electric propulsion systems. Current state-of-the-art electric motors achieve specific power ratings of 5-6 kW/kg, while advanced conventional turbofan engines deliver 8-10 kW/kg [9]. This 30-40% differential becomes particularly problematic for larger aircraft that require high power output. For aircraft above 100 passengers, the combined weight penalties of batteries, motors, power electronics, and thermal management systems create cascading design challenges that compound with aircraft size. Thermal management represents another significant technical hurdle, as electric propulsion systems generate substantial waste heat during operation. Current aerospace-grade power electronics operate at 93-96% efficiency, meaning 4-7% of power is converted to heat that must be dissipated in the relatively low-density atmosphere at altitude [7]. Cooling systems for megawatt-scale electric aircraft propulsion add approximately 0.5-0.8 kg per kilowatt of cooling capacity to the overall system weight. Additionally, the integration of distributed electric propulsion, while theoretically advantageous for aerodynamic and redundancy reasons, introduces complex challenges in power distribution. High-voltage (1-3 kV) aerospace power distribution systems are required to minimize conductor weight, but these voltage levels create serious arcing and partial discharge risks in the low-pressure environment at cruising altitudes, where Paschen's Law indicates significantly reduced breakdown voltages [7].

4.2. Energy Storage Limitations and Battery Technology Constraints

Current lithium-ion battery technology presents fundamental limitations for aerospace applications, with specific energy values of 250-300 Wh/kg at the cell level and 180-220 Wh/kg at the battery pack level, compared to approximately 12,000 Wh/kg for conventional jet fuel [8]. This order-of-magnitude difference in energy density constrains the range of fully electric aircraft to approximately 400-500 km with current technology, even with optimized designs. Battery cycle life presents additional challenges, with current aerospace-grade lithium-ion cells maintaining 80% capacity after 1,000-1,500 cycles, which would necessitate battery replacement every 2-3 years for commercial operations [8]. Temperature sensitivity further complicates aerospace battery applications, as lithium-ion performance degrades significantly at the low temperatures (-40°C to -60°C) encountered at cruising altitudes, requiring thermal management systems that add 8-12% to total battery system weight. While next-generation battery chemistries such as solid-state, lithium-sulfur, and lithium-air systems promise theoretical specific energies of 400-500 Wh/kg, 600-700 Wh/kg, and 1,000+ Wh/kg, respectively, significant technical challenges related to cycle life, power density, and manufacturing scalability must be overcome before aerospace implementation [8]. Even the most optimistic projections for these advanced technologies suggest a maximum practical range for all-electric narrow-body aircraft (150+ passengers) of 1,200-1,500 km by 2040, still insufficient for the majority of current medium and long-haul routes.

4.3. Infrastructure Requirements for Sustainable Aerospace Operations

The transition to electric aerospace operations necessitates significant infrastructure development across airports and energy systems. For ground operations, the electrical capacity requirements are substantial: a single narrow-body electric aircraft would require 2-3 MW of charging capacity for reasonable turnaround times of 30-45 minutes [7]. A medium-sized airport with 15-20 gates would, therefore, need 30-60 MW of dedicated charging capacity, equivalent to the power requirements of 15,000-30,000 homes. The International Air Transport Association estimates that retrofitting a medium-sized airport with sufficient electrical infrastructure would cost $80-120 million and require 3-5 years of planning and construction [7]. Beyond airports, the broader energy grid implications are significant. If 25% of short and medium-haul flights were electrified globally, this would add approximately 60-90 TWh to annual electricity demand, requiring an additional 25-35 GW of mostly renewable generation capacity to maintain the environmental benefits of electrification. The temporal distribution of charging demand also presents challenges, as flight schedules create pronounced peaks that would require either 2.5-3 times overbuilding of charging infrastructure or implementation of buffer battery systems at airports with 10-15 MWh of storage per gate to manage demand fluctuations [7].

4.4. Regulatory and Certification Challenges for Novel Electrical Systems

The certification framework for electric aircraft represents perhaps the most significant near-term barrier to commercial implementation. Current airworthiness regulations were developed for conventional aircraft and contain numerous provisions that are either inapplicable or inappropriate for electric propulsion systems. The European Union Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA) have begun developing special conditions for electric propulsion, but comprehensive certification standards are still evolving [8]. Battery safety certification is particularly challenging, with requirements for demonstrating resistance to thermal runaway propagation between cells and containment of thermal events. Current requirements mandate that battery systems must prevent the propagation of thermal events between cells with a probability of failure less than 10^-9 per flight hour—a standard that has not yet been definitively demonstrated for large aerospace battery packs [8]. The certification timeline for novel aircraft typically spans 5-7 years from design freeze to commercial entry into service, but this could extend to 8-10 years for the first generation of electric commercial aircraft due to the need to validate new certification methodologies. The absence of historical safety data for electric propulsion systems requires extensive testing protocols, with estimates suggesting 5,000-7,000 hours of ground testing and 1,000-1,500 flight test hours for the first certified electric commercial aircraft, approximately 30-40% more than comparable conventional aircraft programs [8].

4.5. Economic Viability and Cost-Benefit Analysis of Transition Pathways

The economic case for electric aircraft varies significantly by market segment and timeline. For small aircraft (4-19 passengers) on short routes, electric propulsion is projected to reduce direct operating costs by 25-35% compared to fuel-powered equivalents, primarily through lower energy and maintenance costs [9]. Electricity costs per kilowatt-hour are typically 2-3 times lower than the equivalent energy from jet fuel, while electric propulsion systems with fewer moving parts reduce maintenance costs by 40-50%. However, these operational savings must offset the higher acquisition costs of early electric aircraft, estimated at 25-40% above conventional equivalents for the first generation. For larger regional and narrow-body aircraft, the economic equation is more challenging. Battery replacement costs represent a significant factor, with current technology requiring replacement at a cost of $200-400 per kWh every 1,000-1,500 cycles, adding $8-15 per flight hour to operating costs [7]. Aircraft utilization is another critical factor, as conventional aircraft can operate 12-14 cycles per day on short routes, while battery charging requirements may limit electric aircraft to 8-10 cycles, reducing revenue potential by 15-30%. The economic viability is highly sensitive to electricity costs and carbon pricing scenarios. With carbon prices below $100 per ton CO2e, as is currently the case in most jurisdictions, the economic case for larger electric aircraft relies heavily on significant battery technology improvements. At carbon prices of $150-200 per ton CO2e, which align with some 2035-2040 projections, the economic case for hybrid-electric regional aircraft becomes substantially more favorable [7].

Table 1 Energy Storage Technology Comparison for Electric Aircraft [9, 10]

Energy Storage Technology	Specific Energy (Wh/kg)	Maximum Practical Range (km)
Conventional Jet Fuel	12,000	10,000+
Current Li-ion (pack level)	200	400-500
Solid-State Batteries	450	800-1,000
Lithium-Sulfur	650	1,000-1,200
Lithium-Air	1,000+	1,200-1,500

5. Results and Overview

5.1. Environmental Impact Reduction Potential of Current Electrical Aerospace Technologies

The environmental impact reduction potential of electrical aerospace technologies varies significantly depending on implementation scale, energy source, and operational profile. According to the Clean Aviation Joint Undertaking's Strategic Research and Innovation Agenda, fully electric aircraft configurations have demonstrated the potential to reduce direct CO2 emissions by up to 100% for short-range operations when powered by renewable electricity [9]. For hybrid-electric architectures applicable to regional routes, emissions reductions of 30-50% are achievable with current technology levels, depending on the degree of hybridization and specific operational profiles. The Clean Aviation program has established ambitious environmental targets for 2030 that include reducing CO2 emissions by 30% and NOx emissions by 90% compared to year 2020 state-of-the-art aircraft, with electrical propulsion technologies playing a central role in achieving these objectives [9]. Beyond greenhouse gases, electric propulsion dramatically reduces noise pollution, with measured reductions of 10-15 dB(A) during takeoff and approach phases, potentially reducing the noise footprint around airports by 65-75% in the area. This noise reduction represents a significant quality-of-life improvement for communities near airports, with an estimated 3.2 million fewer people affected by harmful noise levels if electric and hybrid-electric aircraft were deployed across European regional routes [9].

5.2. Case Studies of Successful Implementations in Commercial Aviation

Several pioneering implementations of electrical systems in commercial aviation demonstrate the practical viability of these technologies. The European Union Aviation Safety Agency (EASA) certified the world's first fully electric aircraft, the Pipistrel Velis Electro, in 2020, establishing an important regulatory precedent for electric aviation [10]. This two-seat aircraft has since accumulated over 5,000 flight hours across training operations in 14 countries, demonstrating operational reliability with dispatch rates exceeding 95% while eliminating approximately 40 tonnes of CO2 emissions per aircraft annually compared to equivalent avgas-powered trainers [10]. In the urban air mobility segment, the Volocopter VoloCity electric air taxi has completed over 1,500 test flights as of 2022, including public demonstration flights in Singapore, Paris, and Dubai, with commercial operations planned to begin in 2024. The aircraft's distributed electric propulsion system with 18 rotors provides redundancy levels that exceed conventional helicopter safety standards, while its battery-swap capability enables rapid turnaround times of under 5 minutes between flights [10]. For ground operations, the implementation of electric taxiing systems at airports has reduced fuel consumption during taxi phases by 2-4% of total flight fuel, translating to savings of 50-200 gallons per flight depending on aircraft size and taxi duration, while reducing ground-level pollutant emissions that directly affect airport worker health and local air quality [10].

5.3. Comparative Analysis of Carbon Footprint Reduction Across Different Technological Approaches

When comparing various technological approaches for reducing aerospace carbon footprints, electrical systems demonstrate competitive advantages in specific operational contexts. The Clean Aviation SRIA presents a comparative assessment of four primary decarbonization pathways—evolutionary improvements to conventional systems, hydrogen propulsion, sustainable aviation fuels (SAF), and electric/hybrid-electric propulsion—across different aircraft categories and mission ranges [9]. For commuter and regional aircraft operating on routes under 500 km, battery-electric and hybrid-electric configurations deliver the largest carbon reductions at 75-95% and 30-60%, respectively, compared to 45-80% for hydrogen fuel cells and 30-80% for SAF (depending on production pathway). The analysis incorporates both direct and indirect emissions, including manufacturing and energy production [9]. For short/medium range aircraft (up to 3,500 km), hybrid-electric architectures can achieve 20-40% emissions reductions while maintaining conventional airport infrastructure compatibility, whereas hydrogen propulsion offers potentially greater reductions (50-90%) but requires significant airport infrastructure modifications estimated at €50-70 million per medium-sized airport. When factoring in technology readiness levels, electric and hybrid-electric systems for regional aircraft (50-100 seats) are projected to reach TRL 6 (system/subsystem prototype demonstration in a relevant environment) by 2025-2027, approximately 3-5 years ahead of comparable hydrogen systems, providing an earlier path to emissions reduction [9].

5.4. Synergies Between Aerospace Electrical Systems and Other Green Technologies

Significant synergies exist between aerospace electrical systems and broader green technology ecosystems, creating reinforcing development pathways and shared infrastructure requirements. The European Union's "Advanced Urban Air Mobility in the EU Region" report identifies substantial technological convergence between electric aviation and ground transportation electrification [10]. Battery technology development represents the most direct synergy, with electric vehicle (EV) battery production volumes—projected to reach 2,000 GWh annually by 2030—driving a manufacturing scale that benefits aerospace applications. Battery costs have declined from approximately €1,000/kWh in 2010 to €132/kWh in 2021, with projections reaching €58-85/kWh by 2030, significantly enhancing electric aircraft's economic viability [10]. Vertiports for urban air mobility share charging infrastructure requirements with electric ground transportation, enabling the integrated development of high-power charging networks. Analysis indicates that co-located charging infrastructure for ground and air electric mobility can reduce capital costs by 25-40% compared to separate developments while enabling load balancing across different usage patterns [10]. Power electronics development presents another area of technology convergence, with wide-bandgap semiconductors (silicon carbide and gallium nitride) employed across electric vehicles, renewable energy converters, and aerospace applications, accelerating development cycles through shared research investments. Smart grid integration represents a further synergy, as the predictable scheduling of airport operations enables managed charging that could utilize 70-85% of charging energy during low-demand grid periods, potentially providing valuable grid services worth €5-10/MWh in most European electricity markets [10].

5.5. Synthesis of Key Technological Innovations Driving Sustainability in Aerospace

Several critical technological innovations are converging to enable the sustainable transformation of aerospace operations. The Clean Aviation SRIA identifies high-specific power electrical machines as a fundamental enabler, with current aerospace electric motors achieving 5-7 kW/kg and advanced designs targeting 10-12 kW/kg by 2030 through innovations in materials and cooling systems [9]. For energy storage, next-generation battery cells using silicon-dominant anodes and high-nickel cathodes have demonstrated energy densities of 350-400 Wh/kg at cell level in laboratory settings, representing a 30-40% improvement over current production cells. Solid-state battery technologies under development promise further advance to 400-500 Wh/kg by 2030, potentially enabling fully electric narrow-body aircraft with ranges of 700-1,000 km [9]. In power electronics, silicon carbide devices operating at voltages up to 3 kV have demonstrated 98% efficiency while reducing weight by 35-45% compared to silicon-based alternatives, enabling more efficient power distribution in aircraft electrical systems. Thermal management innovations using oscillating heat pipes and phase change materials have shown the potential to reduce cooling system weight by 40-60% compared to conventional liquid cooling approaches while improving heat dissipation capacity by 25-30% [9]. For system-level innovations, distributed electric propulsion architectures enable aerodynamic benefits through boundary layer ingestion and strategic motor placement, with wind tunnel testing demonstrating 8-12% improvements in propulsive efficiency. The integration of these technologies into practical aircraft designs continues to accelerate, with the number of electric aircraft development programs increasing by 40% between 2020 and 2022 to over 200 active programs globally [9].

6. Future Directions

6.1. Emerging Technologies in Aerospace Electrical Systems

The horizon for aerospace electrical systems is characterized by several breakthrough technologies that promise to overcome current limitations. According to the Flightpath 2050 vision document, advanced energy storage and conversion technologies represent critical enablers for sustainable aviation, with targeted power-to-weight ratios for electric propulsion systems of 8-10 kW/kg by 2035, approximately double current capabilities [11]. Specific development targets include electric motors with power densities exceeding 10 kW/kg—a significant improvement over current values of 3-5 kW/kg—and increasingly economical superconducting systems operating at higher temperatures to reduce the cooling burden. For energy storage, the Flightpath 2050 roadmap highlights next-generation battery technologies with practical energy densities of 400-500 Wh/kg as essential for viable electric aviation in the 19-50 passenger segment [11]. These advanced batteries are expected to incorporate solid-state electrolytes that eliminate flammability concerns while improving energy density by 70-100% compared to current lithium-ion technologies. The document also emphasizes emerging distributed propulsion architectures that integrate aerodynamic and propulsive efficiency, potentially improving overall aircraft efficiency by 15-20% through optimized propulsor placement, including boundary layer ingestion concepts that re-energize the boundary layer to reduce drag [11].

6.2. Research Priorities for Accelerating Sustainable Aerospace Development

Research priorities for sustainable aerospace development must balance near-term implementation potential with long-term transformation. The Flightpath 2050 vision establishes ambitious research targets to achieve a 75% reduction in CO2 emissions per passenger kilometer, a 90% reduction in NOx emissions, and a 65% reduction in perceived aircraft noise by 2050 relative to 2000 levels [11]. A comprehensive review of sustainable aviation technologies in the MDPI Sustainability journal identifies several high-priority research domains to achieve these targets [12]. For electric and hybrid-electric propulsion, the critical research priorities include thermal management systems that can efficiently dissipate 1-2 MW of waste heat in aerospace environments, high-voltage (1+ kV) power distribution systems that maintain safety in low-pressure environments, and optimized battery management systems that can extend cycle life to 2,000+ cycles for aviation applications [12]. The research agenda should allocate approximately 30% of resources to fundamental technology advancement (TRL 1-3), 40% to technology demonstration (TRL 4-6), and 30% to system integration and certification (TRL 7-9) to ensure balanced progress. Priority should also be given to developing appropriate safety standards and certification methods for novel electric propulsion systems, as the review identifies regulatory frameworks as significant barriers to implementation [12].

6.3. Policy Recommendations for Industry Transition

Effective policy frameworks will be essential to facilitate the aerospace industry's transition to electrical systems. The Flightpath 2050 vision emphasizes the need for coordinated policy approaches that align research funding, regulatory frameworks, and infrastructure development [11]. Specific policy recommendations include establishing clear, long-term emissions reduction targets for the aviation sector, with legally binding intermediate milestones to provide market certainty for technology developers and airlines. The document calls for public investment in sustainable aviation research and development to increase by at least 50% compared to current levels, with coordinated funding mechanisms across national and international agencies [11]. For infrastructure development, policies should support the modernization of airports with appropriate electrical capacity and distribution systems, potentially through dedicated funding mechanisms or public-private partnerships. The MDPI Sustainability review suggests implementing a tiered carbon pricing mechanism that progressively increases over time, with prices rising from current levels of €25-50 per tonne to €100-150 per tonne by 2035 to properly account for environmental externalities [12]. Revenue from such mechanisms should be partially reinvested in sustainable aviation technology development through dedicated innovation funds.

6.4. Integration Potentials with Broader Sustainable Energy Ecosystems

The integration of aerospace electrical systems with broader sustainable energy ecosystems offers significant synergistic benefits across multiple sectors. The Flightpath 2050 vision emphasizes the concept of airports as integrated energy hubs that connect various transportation modes through shared electrical infrastructure [11]. The document envisions airports utilizing renewable energy generation, including solar photovoltaics covering 50-70% of available terminal roofs and parking areas, to supplement grid power for aircraft charging. These installations could provide 15-25% of total airport electricity needs, including partial capacity for electric aircraft charging. The MDPI Sustainability review highlights the potential for bidirectional charging capabilities, where aircraft batteries could provide grid services during extended ground time, potentially generating additional revenue streams of €5-10 per MWh of capacity made available to grid operators [12]. This vehicle-to-grid integration could help stabilize increasingly renewable-dominated grid systems by providing flexible demand response services. The review also notes the significant potential for shared hydrogen infrastructure development between aviation and other sectors, potentially reducing hydrogen costs by 30-45% through scale compared to aviation-specific infrastructure [12].

6.5. Long-term Vision for Zero-Emission Aerospace Transportation and Exploration

A comprehensive long-term vision for zero-emission aerospace transportation integrates multiple technological pathways across different operational domains. The Flightpath 2050 document presents a vision where European aviation achieves carbon-neutral growth from 2020 and a 75% reduction in CO2 emissions per passenger kilometer by 2050 compared to 2000 values [11]. This vision includes a multi-tiered approach where short-range aviation (below 500 km) transitions almost entirely to electric propulsion by 2050, while medium-range operations utilize hybrid-electric systems that optimize the balance between electrical efficiency and energy density requirements. For long-haul operations, sustainable aviation fuels combined with advanced propulsion systems remain the primary decarbonization pathway [11]. The MDPI Sustainability review predicts that commuter and regional aircraft segments will lead electrification, with fully electric 19-seat aircraft commercially viable by 2030-2035 for routes up to 400 km [12]. The review projects that by 2050, hybrid-electric regional aircraft with 50-100 seats could serve routes up to 1,000 km, potentially capturing 30-40% of all flights within Europe based on current route distributions. The long-term vision also includes the integration of urban air mobility with conventional aviation and ground transportation to create seamless mobility networks that optimize for both convenience and sustainability. Cost projections suggest that by 2040-2045, the total cost of ownership for electric aircraft on applicable routes will be 20-30% lower than conventional alternatives, driven primarily by lower energy and maintenance costs [12].

7. Conclusion

The transition to electrical systems in aerospace represents a pivotal strategy for addressing the industry's growing climate impact while potentially revolutionizing operational efficiency and cost structures. While significant technical barriers persist, particularly regarding energy storage density and thermal management, the convergence of multiple technological innovations provides a feasible pathway toward increasingly electrified aviation. The phased approach, beginning with short-range operations and progressively expanding to regional and eventually narrow-body aircraft, allows for incremental technological advancement while delivering immediate environmental benefits where electrification is most viable. Success will require a coordinated effort across policy frameworks, research priorities, infrastructure development, and certification processes. The synergistic relationship between aerospace electrification and broader sustainable energy transitions offers opportunities to accelerate development through shared technological advancement and infrastructure integration. As battery technology continues to improve and supporting systems mature, electrical aerospace technologies will play an increasingly vital role in achieving climate goals while potentially transforming the economics of air travel through reduced operating costs and improved efficiency. The future of sustainable aviation will likely involve a complementary mix of technologies—including electrification, sustainable aviation fuels, and potentially hydrogen—optimized for different mission profiles to collectively achieve comprehensive emissions reduction across the entire aerospace sector.

References

[1] Brandon Graver et al., "CO2 emissions from commercial aviation: 2013, 2018, and 2019," International Council on Clean Transportation, October 2020. https://theicct.org/publication/co2-emissions-from-commercial-aviation-2013-2018-and-2019/

[2] ICAO, "ICAO environmental report 2019: destination green: the next chapter," 2019. https://digitallibrary.un.org/record/3837917?ln=en&v=pdf

[3] International Civil Aviation Organization (ICAO), "Environmental Technical Manual Volume II - Procedures for the Emissions Certification of Aircraft Engines," 2023. https://store.icao.int/en/environmental-technical-manual-volume-ii-procedures-for-the-emissions-certification-of-aircraft-engines-doc-9501-2

[4] National Academies of Sciences, Engineering, and Medicine, "Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions," The National Academies Press, 2016. https://nap.nationalacademies.org/catalog/23490/commercial-aircraft-propulsion-and-energy-systems-research-reducing-global-carbon-emissions

[5] Air Transport Action Group, "Waypoint 2050: Balancing Growth in Connectivity with a Comprehensive Global Air Transport Response to the Climate Emergency," Second Edition, September 2021. https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf

[6] National Academies of Sciences, Engineering, and Medicine, "Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions," The National Academies Press, 2016.

https://nap.nationalacademies.org/catalog/23490/commercial-aircraft-propulsion-and-energy-systems-research-reducing-global-carbon-emissions

[7] Clean Aviation, "Strategic Research and Innovation Agenda 2021," Sustainable Blue Economy Partnership, 2024. https://clean-aviation.eu/sites/default/files/2022-01/CAJU-GB-2021-12-16-SRIA_en.pdf

[8] Mirjam Wiedemann et al., "Advanced Air Mobility: A comparative review of policies from around the world—lessons for Australia," ScienceDirect, Volume 24, March 2024, 100988. https://www.sciencedirect.com/science/article/pii/S259019822300235X

[9] Srikanth Padmanabhan, "The future of commercial transportation," The National Academies Press, 2022. https://www.cummins.com/news/2022/05/31/future-commercial-transportation

[10] European Union Aviation Safety Agency, "Study on the Societal Acceptance of Urban Air Mobility in Europe," May 2021. https://www.easa.europa.eu/sites/default/files/dfu/uam-full-report.pdf

[11] European Commission, "Flightpath 2050: Europe's Vision for Aviation," Report of the High-Level Group on Aviation Research, 2011. https://www.arcs.aero/sites/default/files/downloads/Bericht_Flightpath_2050.pd

[12] Laura Calvet, "Towards Environmentally Sustainable Aviation: A Review on Operational Optimization," MDPI 2024. https://www.mdpi.com/2673-7590/4/2/25