Battery Technology in Aviation: Current State and Future Prospects

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ABSTRACT

This comprehensive review explores the current state and future prospects of battery technology in aviation, addressing the challenges and potential solutions for electrifying aircraft. It evaluates various battery chemistries, including advanced lithium-ion, solid-state, lithium-sulfur, and lithium-air batteries, with a focus on their energy densities, safety profiles, and suitability for aviation. Key challenges such as energy density limitations, power requirements, safety concerns, and environmental factors are discussed in detail. The review also highlights emerging technologies and innovative approaches, including More Electric Aircraft (MEA) concepts, hybrid-electric propulsion systems, superconducting technologies, and structural batteries. Regulatory and certification challenges are emphasized, underscoring the need for harmonized standards and adaptive frameworks. The article concludes with a future outlook, detailing the potential impact of these technologies on aircraft design, operational efficiency, and sustainability in aviation.

Introduction

The projected increase in air travel demand, coupled with the significant environmental implications, presents a critical challenge for the aviation industry. The International Civil Aviation Organization (ICAO)'s ambitious goal of decarbonizing aviation by 2050 highlights the urgency for transformative measures[1]. Achieving sustainable aviation growth requires new technologies[2]. One of the many promising technologies to have come up in this field is the electrification of aircraft. Electric and hybrid-electric propulsion systems promise to redefine the future of flight. At the heart of this transformation lies the advancement of battery technology, which is pivotal to realizing electric and hybrid-electric propulsion systems.

This paper provides a comprehensive analysis of the current state of battery technology in aviation. Key themes include:-

- The current landscape of battery technologies suitable for aircraft propulsion
- Various battery chemistries and their potential applications in aviation
- Challenges and limitations in adapting battery technology for flight
- Emerging technologies and future prospects in electric aviation

By exploring these themes, this article aims to contribute to the understanding of battery capabilities, limitations, and future trajectories, offering insights for academia and industry working toward sustainable aviation.

1 Current State of Battery Technology in Aviation

Battery technology is central to the mission of making aviation sustainable. The current landscape of battery technology in aviation is marked by rapid advancements aimed at overcoming the unique challenges the aviation sector poses. As the industry moves toward electrification, the demand for high-performance batteries has intensified[5]. Today, of the various available battery chemistries, lithium-ion batteries remain the most promising and widely used technology for electric applications, although significant challenges have yet to be overcome[6]. Recent studies indicate that the Technology Readiness Level (TRL) for aviation applications still requires substantial improvements to ensure safety and reliability. The stringent safety requirements of the aviation industry also require a thorough understanding of the thermal runaway characteristics of Lithium-ion Batteries, especially under the low-pressure conditions experienced during flight[7, 8].

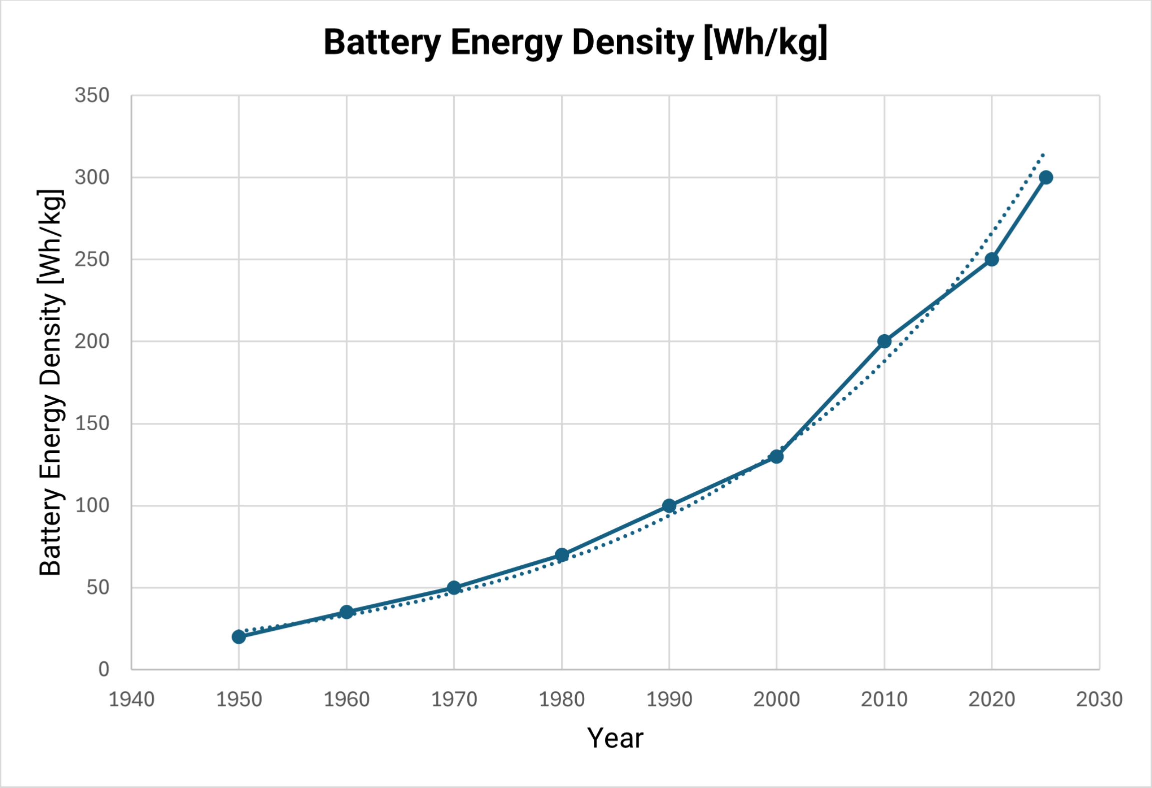

Figure 1. Energy density improvement in battery technology[3]

1.1 Lithium-ion Dominance

Lithium-ion batteries are the leading choice for electric and hybrid-electric aircraft research due to their relatively high energy density and established manufacturing processes. Pursuing higher energy densities is crucial for the viability of electric aircraft. Current Lithium-ion Batteries exhibit energy densities ranging from 90 to 260 Wh/kg, which is insufficient for larger aircraft, necessitating advancements to reach around 800 Wh/kg for practical applications to begin. The most common chemistries include: -

- Lithium Nickel Manganese Cobalt Oxide (NMC)
- Lithium Nickel CObalt Aluminium Oxide (NCA)
- Lithium Iron Phosphate (LFP)

Table 1 compares the key parameters in the different lithium ion chemistries.

Chemistry	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Life
NMC	250-300	300-1500	1000-2000
NCA	220-260	250-500	500-1000
LFP	90-160	300-1500	2000-3000

Table 1. Comparison of Lithium-ion Battery Chemistries for Aviation

While NMC batteries provide the highest energy density, they also face significant safety challenges. LFP batteries, while lower in energy density, excel in safety and cycle life, making them suitable for applications prioritizing reliability over range[9].

1.2 Energy Density: The Key Challenge

Energy density remains the primary challenge for electric powertrains in aircraft. Currently, the best commercially available lithium-ion batteries achieve specific energies of around 250-300 Wh/kg[10]. Although this represents significant advances in battery technology, it still falls way short of the energy density of conventional jet fuel (about 12000 Wh/kg)[11]. This disparity is

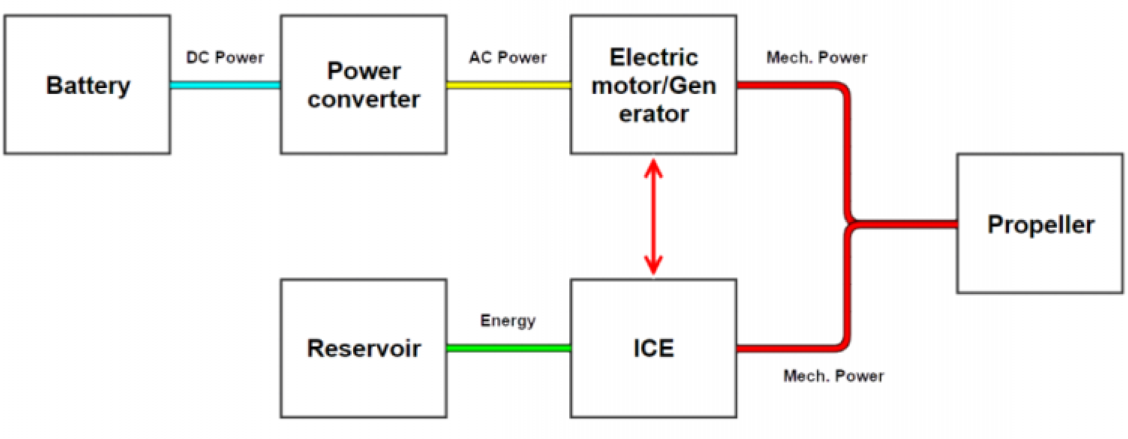

Figure 2. A typical hybrid-electric aircraft powertrain[4]

further compounded by the need for efficient propulsion systems and electric motors, as even marginal improvements in energy efficiency can significantly enhance range and flight duration.

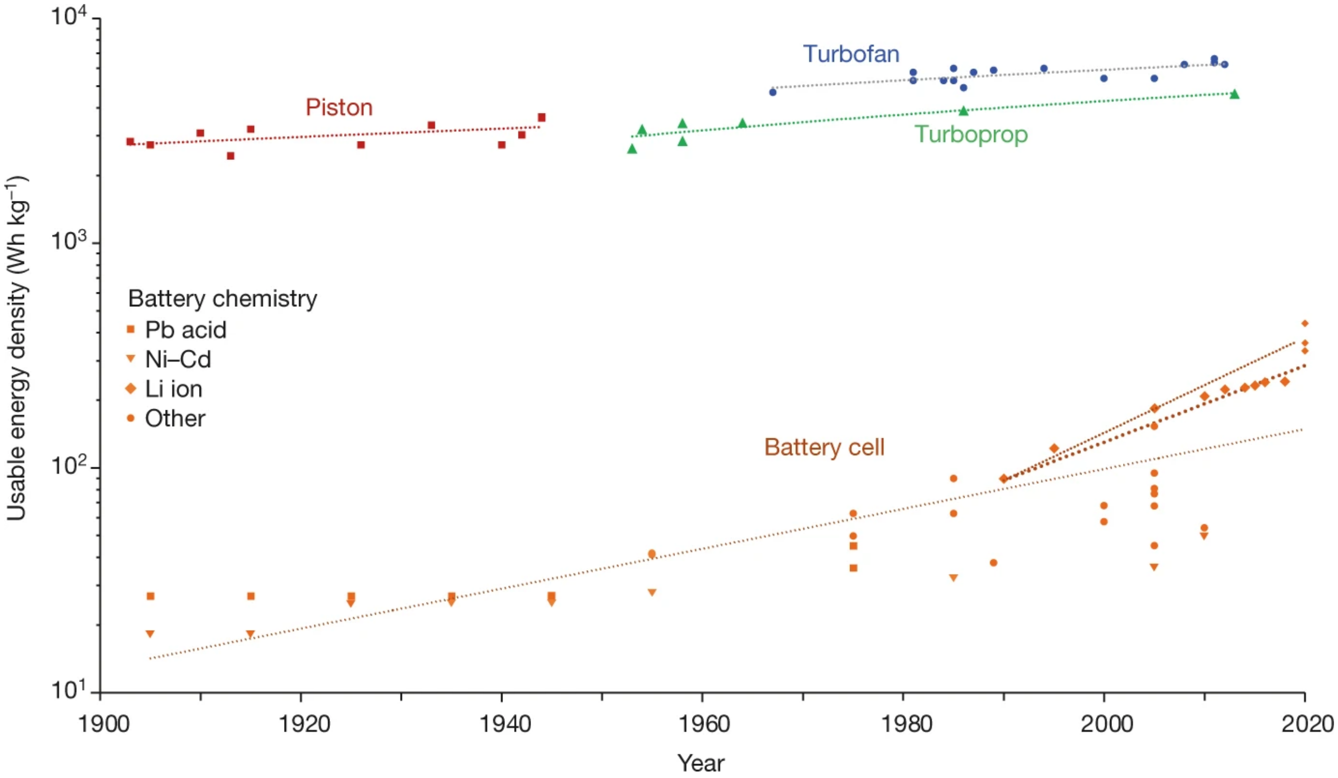

Figure 3. History of usable energy density in aviation[12]

Figure 3 shows the history of usable energy density in aviation. The figure highlights the main challenge faced in the electrification of aircraft. Usable energy density is defined as the energy in the fuel or battery multiplied by the efficiency of converting that energy into shaft power at cruise.[12]

1.3 Safety Considerations

Safety is paramount in aviation, and battery systems are no exception to the intense safety scrutiny. Current lithium-ion batteries face challenges related to thermal runaway and fire risks. Thermal runaway is a self-perpetuating process that causes a rapid increase in temperature in an area that can not dissipate heat. It tends to occur in batteries when they can not get rid of heat fast enough. These risks are highly significant in aviation, where battery failure can have catastrophic consequences. The potential for thermal events and the loss of critical power supply must be meticulously addressed through rigorous safety protocols and innovative design strategies[13]. The aviation industry is increasingly recognizing the need for certifiable aerospace-grade electrical components to mitigate these risks and ensure the safe operation of electric and hybrid aircraft[14]

A review of the literature available reveals that currently work is being done in the following fonts to address these safety concerns: -

- Improved Battery Management System (BMS) - Advanced BMS monitors individual cell temperatures, voltages, and other parameters in real time, allowing for early detection and prevention of potential issues.
- Enhanced Cooling Mechanisms - Novel cooling systems, including phase-change materials and advanced liquid cooling, are being developed to manage battery temperature more effectively during flight.
- Stable Chemistries - Research into more stable cathode materials and solid-state electrolytes aims to reduce the risk of thermal runaway at the chemical level.
- Containment and Suppression - In the event of a battery fire, new containment designs, and fire suppression systems are being developed to mitigate the impact on the aircraft.

1.4 Current Applications

While there are limitations to date on making electric/hybrid-electric aircraft a full-fledged reality, it is important to study the current applications that battery technology has already enabled in the field of aviation: -

- Small Electric Aircraft - Companies like Pipistrel and Bye Aerospace have developed all-electric aircraft for pilot training and short-range flights. These aircraft typically have ranges of 100-200 kilometers and flight times of 1-2 hours[15,16].
- Hybrid-Electric Systems - Larger aircraft are incorporating hybrid-electric systems to reduce fuel consumption. For instance, the Ampaire Electric EEL, a modified Cessna 337 Skymaster, uses a hybrid-electric propulsion system to achieve 50-70 % fuel savings on short routes[17].
- Electric Vertical Takeoff and Landing (eVTOL) Vehicles - Companies like Joby, Lilium, and Volocopter are developing eVTOL aircraft for urban air mobility. These vehicles rely heavily on advanced battery technology to achieve the power and energy requirements for vertical takeoff and landing[18].

1.5 Performance at Altitude

Another challenge for batteries is to maintain performance at high altitudes. Lower temperatures and reduced air pressure can significantly affect battery efficiency and lifespan[19]. Current research focuses on several areas to address this challenge: -

- Temperature Management - This area of research is focused on developing heating systems to maintain optimal battery temperature at high altitudes.
- Pressure-Resistant Designs - This area of research focuses on creating battery enclosures that can withstand pressure differences without compromising on safety or performance.
- Altitude-Specific Chemistries - Researching battery chemistries that are less sensitive to atmospheric pressure changes.
- Adaptive BMS - Developing management systems that adjust battery performance parameters based on altitude and environmental conditions.

The exploration of alternative battery technologies, such as solid-state batteries, is gaining traction due to their potential to offer higher energy densities and improved safety profiles.

2 Battery Chemistries and Their Potential for Aircraft Applications

While lithium-ion batteries currently dominate the discussions, there have been several promising alternatives too that could potentially overcome the limitations of the existing technology. These advancements could pave the way for a new generation of electric aircraft capable of meeting the operational demands of commercial aviation. Moreover, the integration of machine learning and artificial intelligence in battery research is emerging as a promising avenue to accelerate the discovery of new battery materials and optimize existing technologies[20,21]. This section will give a brief overview of these battery chemistries.

2.1 Advanced Lithium-ion Chemistries

2.1.1 Silicon-based Anodes

Silicon has emerged as a promising anode material due to its high theoretical capacity, potentially promising up to 10 times the capacity of traditional graphite anodes; however, challenges such as volume expansion and cycling stability remain[22].

The latest development in this field includes nano-structured silicon anodes that mitigate the volume expansion issues. Further, silicon-graphite composite anodes are being looked into as a potential near-term solution. There is a potential to increase energy density by 20-40% compared to current lithium-ion batteries[23].

2.1.2 High-Nickel Cathodes

Increasing the nickel content in NMC cathodes promises a significant boost to the energy density. These batteries can achieve specific energies of approximately 250-300 Wh/kg, which is still below the optimal range required for larger aircraft[24]. However, this comes with the challenges of increased thermal instability and faster capacity fade. Current research is focused on enhancing their performance through surface coatings that improve the stability and dopants that can enhance structural integrity. Some advanced formulations are targeting specific energies exceeding 500 Wh/kg[25]. Further, researchers are also looking into better optimizing electrolyte compositions for high-nickel systems.

2.2 Solid-State Batteries

Solid-state batteries replace the liquid electrolyte with a solid ion-conducting material, promising potential benefits in safety, energy density, and time to charge. They represent a significant leap forward in battery technology, offering higher energy densities (up to 500-800 Wh/kg) and improved safety profiles due to the absence of flammable liquid electrolytes[26]. They are of particular interest to the aviation industry because of their potential to improve safety due to the non-flammable electrolyte, higher energy density with a theoretically possible range extending up to 400-500 Wh/kg currently, and better performance at higher altitudes due to reduced sensitivity to pressure changes.

Although optimistic for the industry, challenges still persist for solid-state batteries. Interface stability between electrodes and solid electrolytes is yet to be obtained. Achieving high power density for take-off and landing phases remains another challenge. Besides, there are concerns about the manufacturability and cost of solid-state batteries at scale.

2.3 Lithium-Sulfur Batteries

Lithium-sulfur batteries offer a theoretical energy density of 2567 Wh/kg, which is significantly higher than that of other lithium battery chemistries. This chemistry has, therefore, been touted as the future for enabling longer-range electric aircraft. In addition, the abundance of sulfur makes this a lower cost compared to its counterparts.

However, as with other chemistries, this, too, has its challenges. The most significant challenge that lithium-sulfur batteries face is their poor cycle life due to the polysulfide shuttle effect. The polysulfide shuttle effect is caused by the dissolution of intermediate lithium polysulfide species in the electrolyte, leading to an irreversible loss of sulfur, resulting in rapid capacity fading. Other challenges include the electrically insulating property of Sulfur and the significant volume expansion of sulfur during the repeated charging/discharging processes, which disrupts the structural integrity of the electrodes. They are largely still experimental, but ongoing research is focused on overcoming the challenges to make them viable for aviation[27].

2.4 Lithium-Air Batteries

Lithium-air batteries have the highest energy density among any battery chemistry, estimated at around 3500 Wh/kg, primarily due to their use of oxygen from the atmosphere as a cathode reactant[28]. However, there are many challenges concerning this chemistry. First, they have very low practical energy density and power density. The rechargeability and cycle life are extremely poor. Also, this chemistry is sensitive to atmospheric conditions, which is particularly problematic for the aviation industry. Research is ongoing to address these issues, but significant breakthroughs are needed before lithium-air batteries can be considered for aviation applications.

2.5 Overall Outlook

While currently lithium-ion batteries are used almost exclusively in electric aircraft, achieving long-range electric flight and adapting electric flight into the mainstream would require a breakthrough in battery chemistry. Currently, solid-state and lithium-sulfur batteries look more promising and are likely headed towards a breakthrough that will offer the step-change needed in energy density for the broader adoption of electric aircraft.

Table 2 shows a comparison of the various battery technologies for aviation applications with their maximum energy density currently achieved, cycle life, and the Technology Readiness Level (TRL) of the chemistry.

Significant challenges remain in translating the theoretical values that aviation-grade battery systems could offer into practical reality. Factors such as cycle life, power density, and performance under aviation-specific conditions will be crucial to determine which chemistry ultimately is the right one for the aviation sector. The transition to electric and hybrid-electric

Battery Chemistry	**Maximum Energy Density achieved till date (Wh/kg)**	**Cycle Life**	**TRL**
Lithium-Ion (LIB)	330[29]	1000-2000	High
Lithium-Polymer (Li-Po)	200[30]	300-500	High
Lithium Iron Phosphate (LFP)	205[31]	2000-6000	High
Nickel-Metal Hydride (NiMH)	140[32]	300-1000	High
Lead-Acid	50[33]	200-500	High
Zinc-Air	1105[34]	200-500	Low
Solid-state	400[35]	8000-10000	Low

Table 2. Comparison of Battery Chemistries for Aviation Applications

aircraft will depend heavily on the successful development of these advanced battery chemistries. The aviation industry must continue to invest in research and development to overcome the existing challenges associated with these technologies and achieve the necessary TRLs for commercial deployment.

3 Challenges and Limitations in Adapting Battery Technologies for Flight

The adaptation of battery technologies for flight presents a multitude of challenges and limitations that must be addressed to facilitate the transition to electric aviation. This section further explores some of the key challenges that must be overcome before battery-powered flight becomes mainstream.

3.1 Energy Density vs. Weight

It is no surprise that this features as the first challenge. The most significant limitation of battery-powered flight has been the low energy density of batteries compared to conventional jet fuel. This disparity directly impacts the range and payload capacity of electric aircraft. Currently, in the market, Lithium-ion batteries provide an energy density in the range of 250-300 Wh/kg only[36]. This, when compared to the energy density of jet fuel, which provides about 12000 Wh/kg, highlights the substantial gap that needs to be covered before battery chemistries can reach the same potential as jet fuel[37]. Even the theoretical limit for lithium-ion battery chemistry is around 800 Wh/kg. This translates to only about 6% of the energy per unit weight compared to jet fuel. Emerging technologies, such as Lithium-Sulfur (Li-S) batteries, promise higher energy densities (up to 500 Wh/kg) but face challenges related to cycle life and the polysulfide shuttle effect, which complicates their practical application in aviation[38, 39]. Furthermore, the empty weight fraction (EWF) in aircraft design must be optimized to allow for the integration of battery systems without compromising structural integrity[5].

This limitation has widespread ramifications in the aircraft design as well as the weight distribution and balance. Current all-electric and hybrid-electric aircraft are limited to short-haul flights. The weight of the batteries reduces the available payload capacity. Because battery weight remains constant throughout the fuel, unlike liquid fuel, it presents unique challenges. Fuel burn during flight typically moves the Center of Gravity (CG) rearward, which is compensated for in aircraft design. However, the CG remains fixed with batteries, requiring new approaches to aircraft balance and control surface design. This also necessitates the strategic placement of battery packs for optimal weight distribution. At the same time, in order to mitigate weight issues, designers are exploring unconventional aircraft layouts such as Distributed Electric Propulsion (DEP) systems, Blended-Wing Body designs to integrate batteries into the aircraft structure, and Short Take-off and Landing (STOL) configurations to maximize efficiency.

3.2 Power Requirements and Discharge Rates

Aviation requires a high power output, especially during the takeoff and climb phases. Batteries must deliver high discharge rates without compromising safety[40]. This proves to be a challenge, along with the fact that there is a need to manage variable power needs throughout the flight envelope. The power-to-weight ratio (thurst-to-weight) for jet engines is typically 5-10 kW/kg, while for current lithium-ion batteries, it is about 1-2 kW/kg. This difference necessitates larger and heavier battery packs to meet the peak power requirements.

Take-off power may require discharge rates of 3-5 C from batteries. Such high discharge rates can lead to increased heat generation, accelerated degradation of battery components, and reduced overall energy efficiency. This increases the importance of thermal management, leading to greater research in the field. Liquid cooling, phase-change materials, and advanced air cooling designs are some of the avenues of research in this area.

- Efficiency Optimization - Batteries and power electronics need to maintain a high efficiency across a wide range of power outputs. The challenge lies in designing systems that are efficient at both peak and cruise power levels.

- Battery Degradation - The frequent cycling between high and low power states can accelerate battery aging. Therefore, there is a need for battery chemistries to handle variable discharge without significant degradation in capacity.

- Thermal Management - As previously mentioned, cooling systems must adapt to varying heat generation rates, which leads to the challenge of maintaining optimal battery temperature across all flight phases.

- Power Electronics - Inverters and motor controllers must efficiently handle wide power ranges. Here, there is a potential for advanced wide-band gap semiconductors to improve efficiency and power density.

To address these challenges, several innovative approaches are being explored. Ampaire's Electric EEL uses a hybrid system to supplement battery power during high-demand phases. This works by combining batteries with other power sources like fuel cells to optimize for both peak power and energy density. NASA's X-57 Maxwell demonstrator uses 14 electric motors along the wing. This approach is called Distributed Electric Propulsion (DEP), and it works by using multiple smaller electric motors instead of a few large ones. This allows for more efficient power distribution and redundancy. Other approaches being explored include AI-driven systems that predict and optimize power distribution based on flight phase and conditions and using supercapacitors in conjunction with batteries to handle short-duration high power demands. Besides, the development of fast-charging cells that maintain high specific energy is an active area of research, as current technologies struggle to balance these competing demands[41].

3.3 Safety and Reliability

Safety and reliability are of utmost importance in aviation. The inherent risks associated with lithium-ion batteries, which are currently the most prevalent technology in electric aviation, such as thermal runaway, pose significant challenges that can lead to explosions or fires[42]. The unique operating environment for flights, which include low pressure and high altitude, can exacerbate these risks, necessitating rigorous testing and validation of battery systems under these conditions. Moreover, the integration of machine learning and IoT technologies for predictive maintenance could enhance the reliability of battery systems by optimizing performance and preemptively addressing potential failures[43,44]

The aviation industry has established stringent reliability standards, necessitating extensive testing and validation of battery systems. This includes accelerated life testing, where batteries are subjected to extreme conditions to simulate years of use in a short period[5]. Furthermore, the integration of advanced monitoring systems, such as battery management systems (BMS) equipped with machine learning algorithms, can enhance reliability by predicting potential failures and optimizing battery performance in real-time[41].

The development of redundancy systems is also vital for ensuring reliability in electric aircraft. For instance, implementing multiple battery packs that can operate independently can provide a fail-safe mechanism in the event of a battery failure[40]. Additionally, the aviation industry is increasingly focusing on the concept of "design for safety," which involves incorporating safety features into the design phase of battery systems to proactively address potential risks[14].

3.4 Environmental Factors

The environmental impact of battery technologies in aviation is a multifaceted issue that encompasses the entire lifecycle of batteries, from raw material extraction to end-of-life disposal. The extraction of lithium, cobalt, and nickel - key components of lithium-ion batteries - can lead to significant ecological damage if not managed sustainably[45,46]. For example, lithium extraction often involves the use of large quantities of water, which can deplete local water resources and disrupt ecosystems[42]. Additionally, the mining processes for these materials can result in habitat destruction and pollution, raising concerns about the sustainability of current battery technologies[43].

To mitigate these environmental impacts, the aviation industry is exploring alternative battery chemistries that utilize more abundant and less environmentally damaging materials. For instance, sodium-ion batteries are being investigated as a potential replacement for lithium-ion batteries, as sodium is more widely available and less harmful to the environment[44]. Furthermore, the development of recycling technologies for lithium-ion batteries is crucial for minimizing waste and reducing the demand for new raw materials. Current recycling processes are often inefficient, recovering only a fraction of the valuable materials contained in spent batteries[45]. Advancements in recycling technologies, such as hydrometallurgical and pyrometallurgical methods, could significantly improve recovery rates and promote a circular economy in battery production[46].

Lifecycle assessments, which are essential tools for evaluating the environmental impacts of battery technologies, must consider not only the emissions during operation but also the environmental burdens associated with material sourcing and end-of-life disposal[47]. As the aviation industry seeks to minimize its carbon footprint, the development of a circular battery economy and sustainable material-sourcing practices will be essential[45,46].

3.5 Regulatory and Certification Challenges

Finally, the regulatory landscape for electric aviation is complex and still evolving. Certification processes for new battery technologies can be lengthy and complex, often requiring extensive testing to meet safety and performance standards[48]. Stringent standards have been established to ensure the safety and reliability of aircraft systems, but they can also create barriers to the rapid adoption of innovative battery technologies. The certification process also often requires extensive testing and documentation, which can be time-consuming and costly for manufacturers. The aviation industry must navigate these regulatory challenges while also advocating for policies that support the development and deployment of innovative battery technologies[46]. Collaboration between industry stakeholders, regulatory bodies, and research institutions will be crucial to streamline these processes and facilitate the adoption of electric aviation solutions. One of the key challenges in the regulatory framework is the need for harmonization across different jurisdictions. As electric aviation technologies develop, regulatory bodies worldwide must collaborate to establish consistent standards that facilitate international operations. This is particularly important for battery technologies, as manufacturers may face different certification requirements in various regions, complicating the global market for electric aircraft.

Moreover, the rapid pace of technological advancement in battery technologies poses a challenge for regulators. As new chemistries and designs emerge, existing regulations may need to be updated, necessitating continuous updates to certification processes. To address this issue, regulatory bodies are increasingly engaging with industry stakeholders to develop adaptive regulatory frameworks that can accommodate innovation while maintaining safety standards.

In addition to safety certification, there is a growing need for environmental regulations that address the lifecycle impacts of battery technologies. As the aviation industry seeks to reduce its carbon footprint, regulators must establish guidelines for the sustainable sourcing of materials, recycling practices, and end-of-life disposal of batteries. This will require collaboration between industry, government, and environmental organizations to develop comprehensive policies that promote sustainability in electric aviation.

To summarize, while the adaptation of battery technologies for flight presents significant challenges, ongoing research and development efforts are paving the way for innovative solutions. Addressing the issues of energy density, power requirements, safety, environmental impact, and regulatory compliance will be essential for the successful integration of electric propulsion in aviation.

4 Prospects and Outlook on the Future

The future of electric aviation is poised for significant transformation through the integration of emerging technologies that promise to revolutionize aircraft design, propulsion systems, and operational efficiency. This section explores key advancements and their potential implications for the aviation industry.

4.1 More Electric Aircraft (MEA)

The concept of More Electric Aircraft (MEA) is central to the evolution of electric aviation. MEA focuses on replacing traditional hydraulic and pneumatic systems with electrical counterparts, which enhances reliability and efficiency while reducing fuel consumption and emissions[49]. This shift, besides simplifying aircraft systems, also enables the integration of advanced technologies such as electric motors and power electronics, which are critical for the development of electric vertical take-off and landing (eVTOL) aircraft[50]. The MEA approach is expected to lead to lighter aircraft designs, improved fault tolerance, and reduced operational costs, thereby making electric aviation more viable[51].

4.2 Hybrid-Electric Propulsion Systems

Hybrid-electric propulsion systems represent a promising pathway to address the limitations of current battery technologies, particularly their energy density. By combining conventional engines with electric propulsion, hybrid systems can achieve greater range and efficiency while reducing greenhouse gas emissions[52,53] This approach allows for the use of smaller, lighter batteries, which traditional fuel sources can supplement during longer flights. The flexibility of hybrid systems also enables the optimization of power distribution and energy management, enhancing overall aircraft performance[54].

4.3 Superconducting Technologies

The development of superconducting electric propulsion systems is another groundbreaking advancement. Projects like Airbus UpNext's ASCEND initiative aim to create superconducting powertrains that can operate at cryogenic temperatures, significantly improving efficiency and power output[55,56]. Superconductors can reduce energy losses in electrical systems, making them ideal for high-power applications in aviation. This technology could lead to lighter and more efficient aircraft, capable of meeting the increasing demands for performance and sustainability in air travel[55].

4.4 Structural Batteries

Innovations in structural batteries, which combine load-bearing capabilities with energy storage, could fundamentally change aircraft design. These multifunctional materials can help reduce the overall weight of the aircraft by integrating energy storage directly into the structure, thus addressing one of the primary challenges of electric aviation—battery weight[57,58]. Structural batteries could enable the design of lighter, more efficient aircraft while simplifying the integration of electrical systems[59].

4.5 Advanced Thermal Management Systems

As electric and hybrid-electric aircraft incorporate high-power electrical components, effective thermal management becomes critical. Advanced thermal management systems utilizing nanofluids and other innovative cooling technologies are being developed to ensure optimal performance and safety of batteries and electric motors[60]. These systems can help dissipate heat generated during operation, thereby enhancing the reliability and longevity of electric propulsion systems[61].

A quick review of the current literature regarding the future projections for energy densities of battery technologies by the year 2035 at the highest TRL is also given in the table 3.

Battery Chemistry	Energy Density (Wh/kg)	Cycle Life
Lithium-Sulfur (Li-S)	400-600[62–65]	500-1000
Lithium-Air (Li-Air)	500-800[66,67]	200-500
Sodium-Ion (Na-Ion)	200-300[68,69]	1000-2000
Lithium-Metal	400-600[70,71]	500-1000
Solid-State Lithium	400-600[26,72]	1000-2000
Zinc-Air	300-400[73,74]	200-500

Table 3. Battery Chemistries with Projected Energy Densities and Cycle Lives by 2040

Among these battery chemistries, lithium-sulfur (Li-S) and solid-state lithium batteries hold the maximum promise for the future of aviation applications. Li-S batteries offer high energy densities of 400-600 Wh/kg, while solid-state lithium batteries provide similar energy densities with improved safety and cycle life. Both chemistries have the potential to significantly outperform current lithium-ion batteries in terms of specific energy, which is crucial for reducing aircraft weight and improving range and endurance. The continued development and commercialization of these advanced battery technologies will be key enablers for the electrification and decarbonization of the aviation sector.

The integration of these emerging technologies is expected to significantly impact the future of electric aviation. As battery technologies continue to advance, with ongoing research into higher energy densities and faster charging capabilities, the feasibility of fully electric commercial aircraft will improve[13,75]. The aviation industry is also likely to see an increase in the adoption of eVTOL aircraft for urban air mobility, driven by advancements in battery technology and regulatory support for new air transportation models[76,77].

Moreover, the push for sustainability will drive further innovations in electric aviation. Regulatory bodies are increasingly setting ambitious targets for emissions reductions, which will necessitate the adoption of cleaner technologies in aviation[78]. The development of all-electric and hybrid-electric aircraft aligns with these goals, offering a pathway to significantly reduce the environmental impact of air travel.

Therefore, the future of battery technology in aviation looks bright, with numerous emerging applications poised to revolutionize the industry. The transition to more electric and hybrid-electric aircraft will contribute to a more sustainable aviation ecosystem while enhancing operational efficiency and safety. Continued investment in research and development, coupled with supportive regulatory frameworks, will be essential to realize the full potential of these innovations.

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Author contributions statement

T.P. conceptualized the review, collected and synthesized the literature, and drafted the manuscript. D.M. provided guidance on the review's scope, critically reviewed and edited the manuscript, and contributed to refining the conclusions. Both authors reviewed and approved the final manuscript.