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Lithium-Based Batteries in Aircraft †

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Abstract: This paper delves into the present situation, challenges, and possible prospects of electrical energy storage systems in the aviation industry, specifically focusing on hybrid electric aircraft and their service industries. The use of energy storage systems in the aviation industry has been the subject of a thorough literature analysis spanning the last ten years. Moreover, adapting current technological solutions from other transport sectors, such as automotive and naval, to the aviation sector presents a complex challenge, particularly when considering the typical phenomenon of thermal runaway. This study focuses on the promising behavior of lithium-based batteries among various battery technologies in the aircraft sector. Based on data gathered from completed and ongoing electric and hybrid aircraft projects, this study deals with the suitability of many different types of lithium-based batteries for use in airplanes, including lithium–sulfur, lithium–air, lithium-polymer, and lithium-ion batteries.

Keywords: lithium–air; lithium–sulfur; lithium-ion batteries; electric aircrafts; electric hybrid aircrafts

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1. Introduction

Given the consumption of fossil fuels and the need to meet carbon neutrality requirements in aviation, researchers are exploring the potential development of next-generation electric/hybrid aircraft. Traditional aircraft engines release greenhouse gases, including carbon dioxide, water vapor, nitrous oxides, sulfates, and soot [1]. The increase in the number of electric vehicles on the market [2,3] has sparked heightened interest in electric aircraft. However, although the electrification of ground vehicles is progressing rapidly, the electrification of aircraft remains in its early stages.

Electric and hybrid planes are currently gaining significant attention. The advancement of environmentally friendly aircraft hinges on this, making it essential for the future of aviation [4]. Currently, various mission types, such as passenger, military, short-range, and long-range operations, guide the development of electric and hybrid aircraft. Challenges have emerged in the investigation and advancement of long-range hybrid-electric systems as a result of constraints in battery energy density. Subsonic Ultra Green Aircraft Research (SUGAR), a joint project between NASA and Boeing, is an example of an effort that combines hybrid-electric systems with cutting-edge aerodynamic designs to increase the range of aircraft while keeping costs low [5]. The aim of technologies such as Rolls-Royce's hybrid-electric propulsion systems is to facilitate the operation of commercial aircraft capable of transporting passengers over shorter distances. Midsize passenger aircraft are currently the

focus of efforts to explore environmentally friendly propulsion alternatives, including hybrid and hydrogen-electric systems, as part of the Airbus ZERO initiative [6,7]. At this stage, investigations into various promising concepts for extended-range and higher-capacity aircraft are just beginning.

Batteries serve as crucial elements in electric aircraft, primarily functioning to provide energy to the electronic systems located in the cockpit. Commercial, civil, and military aircraft use lead–acid and nickel–cadmium (Ni-Cd) rechargeable batteries. They are essential for starting the engines and auxiliary power units (APUs), as well as for navigation, communication, and emergency systems. Lithium-ion (li-ion) batteries have served these functions for the past ten years, especially in the Boeing 787 Dreamliner. Emergency backup power is essential for the operation of critical aviation equipment and instruments that necessitate the use of batteries. Indeed, Federal Aviation Administration (FAA) regulations mandate a minimum emergency power requirement of 30 min [8]. Batteries are a significant advancement in sustainable aviation, but before we can effectively scale the technology, we must address several limitations and challenges.

Our goal is to analyze whether lithium-based batteries have the potential to be the most suitable choice for electric and hybrid aircraft. Despite some inherent limitations, extensive research has shown that the lithium-ion battery family has potential properties for use in aircraft.

2. Electric and Hybrid Aircraft: History and Requirements

Historically, aircraft utilized vented lead–acid (VLA) batteries up until the year 1950. In the late 1950s, the adoption of vented Ni-Cd (VNC) batteries began. During the late 1960s, the adoption of sealed Ni-Cd (SNC) batteries for both military and commercial applications commenced. During the late 1970s, researchers developed sealed lead–acid (SLA) batteries for aircraft applications, which proved to be significantly more reliable and easier to maintain than VLA and VNC batteries. Consequently, SLA batteries found applications in various aircraft, including the C-130, C-141, F-4, F-117, F-16 fighter jets, and Boeing 777, among others [9]. Furthermore, researchers have developed 'low-maintenance' or 'ultra-low-maintenance' Ni-Cd batteries as alternatives to the traditional VNC batteries. The typical nominal voltage for most aircraft batteries is 24 volts. A 24-Volt Ni-Cd battery consists of either 19 or 20 cells connected in series to reach the appropriate voltage, whereas lead–acid batteries contain 12 cells connected in series. The Boeing 737 commenced operations in 1967, featuring a power capacity of 80 kilovolt-amperes (kVA).

Over the subsequent 35 years, there was minimal enthusiasm for enhancing the power capacity of aircraft—indeed, by the year 2000, the power demands for aircraft had only reached 200 kVA. In 2011, Boeing launched the 787, which exemplifies a modern electrical architecture with a primary power generation capacity of 1000 kVA. Furthermore, this aircraft boasts an auxiliary power unit capable of delivering 450 kVA, contributing to a total power capacity of 1450 kVA. When selecting a battery for an electric aircraft application, it is crucial to ensure that it can handle multiple scenarios, such as the aircraft's Electric Starter-Generator ESG system starting profile, emergency load profile, and transient profile. Additionally, it must adhere to the Federal Aviation Administration's (FAA) regulations. Environmental factors significantly influence battery performance, with temperature and humidity being critical elements to consider. It is crucial to consider the weight of the battery, as minimizing the overall weight of the aircraft is vital for reducing fuel consumption [10]. Nguyen et al. explored the potential for integrating structural batteries within the cabin floor panel of an A220-like aircraft. The study revealed that for a 1500 km mission of a More Electric Aircraft, achieving a minimum of 90 Wh/kg and 55 W/kg from structural batteries integrated into 50% of the aircraft's structure could result in a 5.6% enhancement in fuel

efficiency. In the context of a hybrid electric aircraft, it is essential for the specific energy and power density to reach approximately 200 Wh/kg and 120 W/kg, respectively. This is based on the premise of complete integration of the specific battery within the structure, alongside a primary conventional battery pack that offers energy densities ranging from 400 to 600 Wh/kg. In the case of all-electric aircraft, the values increase to 400 Wh/kg for the structural batteries and range from 700 to 800 Wh/kg for the conventional battery pack. According to NASA, 400 Wh/kg and 750 Wh/kg battery energy densities are required for general aviation and regional aircraft, respectively, in order to fully integrate electric aircraft. Viswanathan et al. validate these findings by suggesting that commercial regional and narrow-body aircraft need batteries with energy densities of 600 Wh/kg and 820 Wh/kg [3,11]. Based on Safran's research results, the minimal specific energy consumption for commuter applications is 500 Wh/kg. NASA reported an energy level of 600 to 750 Wh/kg. Boeing's study on larger aircraft supports this energy range.

Numerous electric and hybrid aircraft initiatives have encountered obstacles or setbacks stemming from technological, economic, or regulatory challenges, underscoring the complexities involved in shifting aviation toward sustainable energy alternatives. In 2017, Siemens, Rolls-Royce, and Airbus forged a cooperation agreement to construct the E-FAN X hybrid electric aircraft. The aircraft had a hybrid electric propulsion system known as the "E-Supervisor", as well as three turbofan engines and a two-megawatt electric motor. According to Siemens, the electric propulsion system was powered by a generator pushed by a turbine placed within the fuselage of the aircraft. Furthermore, the E-Fan X will have 700 kilowatts of power with lithium-ion batteries [6]. Electric propulsion techniques will reduce the airplane operational expenses by 90 percent. But, because of their low battery capacity, the Alpha Electro and the Airbus E-Fan were unable to cruise at 90 nautical miles. As a result, Rolls-Royce and Airbus opted against moving further with the E-Fan X project in 2020. They chose instead to concentrate on developing a less expensive alternative to fuel cells (FC) that combines hydrogen for aircraft propulsion [7,12]. According to H. Kuhn et al., lithium batteries have a 5% to 8% energy density comparable to aviation fuel. This means that the battery-electric aircraft's cruise range is just 10% that of a fossil-fuel aircraft.

A variety of companies and research institutions are investigating hybrid-electric aircraft concepts, with several still in the development phases. Boeing's SUGAR series represented an initial exploration, evaluating designs such as tube-and-wing and hybrid-wing-body configurations to align with NASA N + 3 objectives. The concepts encompassed innovations such as strut-braced wings and hybrid-electric propulsion, designed for missions extending up to 900 nautical miles, with a capacity of 154 seats, showcasing the promising future of sustainable aviation. Boeing's SUGAR (see Figure 1) Volt study demonstrated that hybrid-electric propulsion met NASA's N + 3 fuel reduction target, utilizing 28% less fuel than SUGAR High and surpassing traditional designs.

Launched in 2014, NASA's SCEPTOR project further explored distributed propulsion concepts like Leading Edge Asynchronous Propellers Technology, which uses small propellers on the wing's leading edge to reduce drag and enhance efficiency by increasing cruise wing loading and lift while minimizing the need for heavy flap systems [13]. NASA developed the X-57 Maxwell (see Figure 2), based on the Tecnam P2006T, which replaces traditional combustion engines with electric motors powered by lithium-ion batteries.

Since 2017, companies such as Zunum Aero and Wright Electric have been advancing the development of regional and short-haul electric aircraft aimed at passenger transport. Meanwhile, Ampaire is investigating hybrid propulsion concepts, including boundary layer ingestion, to enhance efficiency [13].



Figure 1. Boeing SUGAR Volt concept (NASA/Boeing image).



Figure 2. X-57 Maxwell demonstrator (NASA image).

As previously mentioned, various companies are involved in both published and undocumented hybrid-electric aircraft projects. Many research organizations are hesitant to make their findings public. The AMBER project (ongoing) intends to lower pollution by integrating fuel cells and lithium-ion batteries for regional hybrid-electric aircraft. Regional aircraft should be at least 50% better than a typical flight today, according to Clean Aviation. In addition to the Amber project, Clean Aviation is currently working on 20 additional projects [14]. Another significant project is the Eviation Alice, an all-electric commuter aircraft powered completely by lithium-ion batteries [15]. LiBAT (ongoing) aims to create lightweight lithium-ion batteries, reducing aircraft battery pack weight by one-third [16]. The SOLIFLY project (2021–2023) improved airplane efficiency by integrating lithium-ion batteries [17]. Innovative clean aviation programs that promote hybrid-electric aircraft development generate a more sustainable aviation sector. These programs (as cited, [18]) want to improve hybrid-electric and environmentally friendly airplane technologies, like fuel cells, batteries, lightweight hydrogen tanks, ultra-efficient airframes, and propulsion systems. They also talk about new designs, certification processes, and digital ecosystems for zero-emission and next-generation airplane solutions. A greener sky becomes more achievable with such collaboration, laying the path for an aviation future that balances technical advancement and environmental responsibility.

3. Lithium-Ion Batteries for Aircraft Applications

Lithium-ion (Li-ion) batteries have garnered significant attention within the transportation sector. Lithium-ion batteries have, among other benefits, a longer operational life, greater specific energy, and higher power densities than alternative energy storage technologies. However, achieving their full potential requires overcoming specific obstacles. While lithium-ion batteries offer several advantages, they also possess several disadvantages, including elevated costs, suboptimal performance at extremely high temperatures, costly recycling procedures, and potential safety hazards. The weight of lithium-ion batteries exhibits a direct proportionality to both their capacity and dimensions. To produce batteries that are both lighter and more powerful, researchers are concentrating on increasing specific energy by optimizing electrode materials, fabricating lighter battery casings, and developing new manufacturing techniques [19].

One issue with lithium-ion batteries that warrants consideration is the need for improved cathode materials. Many battery manufacturers now employ cathodes composed of cobalt and nickel, which are finite resources with potential shortages in the future. With graphite serving as the negative electrode and lithium metal oxides (mostly based on cobalt and manganese) serving as the positive electrode, lithium metal oxides have theoretical specific energies as high as 300 Wh/kg and specific powers as low as 100 W/kg. These figures, even for general aviation aircraft, are insufficient. For example, if we consider the Cessna 172 aircraft with an installed power of 120 kW, a capacity of 100 W/kg would require a battery with a weight of 1200 kg to supply the engine with the necessary power. This far exceeds the maximum launch weight of the aircraft, which is approximately 1115 kg [20–22].

Lithium-ion batteries power all electric aircraft, including the Airbus E-Fan and large electric aircraft like the Boeing 787 Dreamliner. These aircraft employ a lithium-ion ICR 18650 battery, which has a specific energy per cell of 207 Wh/kg and a total usable energy of 29 kWh for a battery weighing 167 kg. The battery has a thirty-minute reserve and a one-hour endurance rating. Other types of aircraft models, such as larger airplanes and helicopters, utilize nickel–cadmium batteries. Lithium-ion or lithium polymer batteries can store received or generated energy. Lithium-ion battery systems used in electric airplanes typically produce 25 to 40 kilowatt-hours (kWh) [23]. The specific energy of current-generation Li-ion batteries is approximately 250 Wh/kg-cell, reflecting a steady increase of around 5% over the past decade. The anticipated peak specific energy for upcoming Li-ion batteries is approximately 400–500 Wh/kg-cell, utilizing lithium metal anodes alongside high-voltage and high-specific-capacity cathodes. In addition to being 75% lighter than lead–acid batteries, they are eco-friendly, shockproof, waterproof, and size-adjustable. The most recent iteration of lithium batteries incorporates all-copper connections housed within an aluminum shell for enhanced protection. Lithium batteries outperform other battery types in terms of energy capacities, size, and longevity. They may power a wide range of aircraft, including fixed-wing aircraft, experimental planes, helicopters, gyrocopters, and light sport planes [24].

Significant occurrences involving lithium-ion batteries on the Boeing 787 Dreamliner encompass two critical events in January 2013, which led to the suspension of the entire fleet. On 7 January 2013, a fire in the auxiliary power unit (APU) battery resulted in considerable damage to a parked Japan Airlines 787 at Boston Logan International Airport. On 16 January 2013, an All Nippon Airways flight necessitated an emergency landing in Japan due to smoke emanating from the main battery. Thermal runaway and internal short-circuiting within the batteries were the causes of these incidents. These events underscored shortcomings in battery testing in practical scenarios, prompting redesigns that incorporated enhanced containment systems and ventilation.

The use of rechargeable lithium-ion batteries in airplanes is subject to certain certification rules established by the FAA. Thermal runaway represents the greatest safety concern because it enables battery cells to experience rapid and self-sustaining rises in temperature and pressure, which can result in overheating, fire, or explosions. Thermal runaway can happen for several reasons, including internal short circuits, overcharging, over discharging, and other scenarios [13]. The level of risk is contingent upon the particular chemistry, design, and conditions of use. Sophisticated battery management systems (BMS) should oversee temperature, voltage, and current for these types of batteries to prevent overcharging or deep discharge. The integration of non-flammable electrolytes or solid-state designs in emerging technologies mitigates potential hazards. To ensure optimal safety, it is essential to enforce compliance with rigorous design, usage, and transport regulations (such as the FAA and IATA guidelines) [25].

4. Lithium–Air Batteries for Aircraft Applications

Commercial-scale battery technology limitations currently prevent the manufacture of all-electric aircraft. This is due to the limitations of lithium-ion batteries, which restrict their specific energy and, in some cases, their specific power. Lithium–air batteries (LABs), a breakthrough technology, are far more promising than other battery types. We anticipate these batteries to have specific energies ranging from 1000 to 2000 Wh/kg and specific powers ranging from 0.4 to 0.67 kW/kg [26]. One particular point that has to be considered while building a lithium–air battery is that the battery will acquire mass due to the accumulation of oxygen particles on the cathode during discharge. There was hope that commercially usable lithium–air batteries would be on the market by 2030, but new evidence of serious design flaws casts doubt on that prediction. Lithium–air batteries possess significant theoretical energy densities and are attracting the attention of researchers because they have the potential to have a greater energy density than fuel cells or lithium-ion batteries (LI batteries). The energy density of LABs is five to ten times higher than that of current LIBs, measuring 5200 Wh/kg [27]. In the context of regional aircraft, the specific energy is approximately 900 Wh/kg-pack, indicating that a lithium–air battery could potentially reach about 60% of the existing passenger nautical miles. For narrow-body aircraft, we can achieve a maximum specific energy of approximately 600 Wh/kg, equivalent to approximately 10% of the current passenger nautical miles. For wide-body aircraft, developing significant models at the identified specific energy level is not possible. Consequently, LiO_2 presents a viable pathway, particularly for smaller regional aircraft [3]. These batteries have a theoretical specific energy of 11,500 Wh/kg, comparable to gasoline performance. However, their lifespan is much lower. Their precise theoretical performance is highly reliant on the kind of reaction used, which may be divided into aqueous and non-aqueous systems. The discharge rate of the aqueous system may reach 3460 watt hours per kilogram. Excluding oxygen from the charge state may result in 11,680 Wh/kg of electrical energy [28]. Li–air batteries are not suitable for further exploration due to their inability to charge and discharge at rates comparable to conventional batteries and their tendency to lose lithium during cycling [19].

5. Lithium–Sulfur Batteries for Aircraft Applications

In the decade of 2010 to 2020, scholars from all over the globe submitted 7448 papers on lithium–sulfur batteries. These papers account for about 96% of all results generated by a search for “lithium sulfur batteries” in the Web of Science database. For Li-S batteries to function, the active components are lithium and sulfur. Sulfur is a waste product of the oil industry. Reducing sulfur to Li_2S creates an electronegative solid element with a low weight and a theoretical capacity of 1672 mA/g(S). Furthermore, it is stable. Combining

lithium with sulfur in an electrochemical cell allows for one of the most energy-efficient material combinations [29]. The maximum specific energy of a Li−S system is about 500 Wh/kg-pack [30].

The impressive theoretical specific energy of 2567 Wh/kg and energy density of 2800 Wh/L of lithium–sulfur (Li-S) batteries have led to their increasing recognition as potential energy storage solutions. These values greatly exceed those of traditional lithium-ion batteries. Current commercial prototypes, including those from Oxis Energy and Sion Power, reach specific energies of approximately 250 Wh/kg, with ambitions to enhance this performance twofold in the next five years. Furthermore, laboratory evaluations have shown prototypes exhibiting a specific energy of 600 Wh/kg. Lithium and sulfur undergo the following chemical reaction:

$$S_8 + 16Li \rightleftharpoons 8Li_2S$$

Li-S batteries are widely available and reasonably priced, making them a compelling option. However, we must address issues like suboptimal efficiency and limited life cycles to promote their wider acceptance [6]. A lithium–sulfur (Li-S) battery has numerous advantages over competitors, including lighter weight, a longer life cycle (up to 1500 discharge cycles), high energy densities, and full discharge capabilities. The creator of Li-S batteries has stated that this material requires no maintenance. With a specific density of 325 watt-hours/kg and a specific capacity of 1600 mA h/g, the lithium–sulfur redox pair surpasses comparable lithium batteries by five times. Their theoretical specific energy is 2700 watt-hours per kg.

6. Lithium-Ion Polymer Batteries for Aircraft Applications

The Li-ion polymer (LiPo) battery is from the same battery family as the Li-ion battery but is lighter in terms of weight and easily designed in any desired shape. LiPo batteries and Li-ion batteries differ due to the type of electrolyte they use. LiPo batteries utilize gel-like polymer electrolytes, which contribute to a more flexible form factor and reduced weight, rendering them more susceptible to physical deformation or punctures, thereby heightening the risk of short circuits and fires. LiPo batteries exhibit a greater sensitivity to overcharging and overheating in comparison to Li-ion batteries. Devices that prioritize minimizing weight and size, such as drones and mobile devices, primarily utilize LiPo batteries. However, Li-ion polymer's energy density is considered insufficient [19].

7. Conclusions

The electrification of airplanes holds significant importance; however, achieving this requires advancements in energy storage batteries. In this context, our analysis of lithium batteries suggests that lithium–sulfur batteries appear to have greater potential than lithium–air batteries. In this context, while examining battery preferences for the aircraft sector, we have identified that lithium–air batteries exhibit exceptionally high theoretical energy capacities, rendering them suitable for various types of aircraft in the future. Our findings indicate that only advanced chemistries, such as Li−air, have the potential to fulfill certain requirements necessary for electric commercial aircraft to attain the range and payload capacities essential for widespread adoption. Therefore, we anticipate that lithium–air and lithium–sulfur batteries will significantly influence our future, potentially yielding a range of positive outcomes. The risks associated with them are clearly defined. Over the years, various incidents have raised concerns about the safety of batteries in airplanes. However, under stricter parameters, it is crucial to adhere to stringent design, usage, and transport regulations, such as those set forth by the FAA and IATA, to enhance safety measures.

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