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Analysis of the development of energy storage systems in regional aviation

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Regional aviation plays a crucial role in Europe's transportation system, connecting smaller cities and peripheral regions. In the face of growing demands for CO_2 emission reductions and improved energy efficiency, there is an increasing interest in hybrid and electric propulsion systems in this sector. A key component of these systems is rechargeable batteries, which must meet stringent requirements for energy density, weight, safety, and reliability. The article analyzes available rechargeable battery technologies that can power regional aircraft propulsion systems, including lithium-ion, lithium-sulphur, and metal-air rechargeable batteries. It also discusses current trends in energy storage technology development and the challenges of their implementation in aviation.

Key words: *aviation, regional aviation, rechargeable battery*

1. Introduction

Regional flights play a key role in the European transportation system, providing fast and convenient access to smaller cities, peripheral regions, and islands not served by larger airlines. Regional flights are usually shorter routes, usually within one country or between neighbouring countries. While between one and two hours. Regional flight airlines choose, with capacities ranging from 20 to 100 seats. These can be either jet-powered or turboprop aircraft. Turboprop planes, such as the ATR 72 or Bombardier Q400, are especially efficient on routes of approximately 500–700 km due to their fuel economy and ability to operate on shorter runways. As a result, they are ideally suited for serving smaller regional airports, providing transport connectivity in peripheral, island, and remote regions [37, 55]. For example, the flight from Copenhagen to Tórshavn in the Faroe Islands takes just 1.5 hours by plane, while the ferry journey takes a whopping 36 hours.

In 2023, approximately 1.5 million regional flights took place in Europe, accounting for about 30% of all passenger flights on the continent [60]. Although regional aviation is crucial for mobility, it also generates significant environmental challenges. These flights emit approximately 50 million tons of CO_2 annually in Europe, with an average CO_2 emission of 150 grams per passenger per kilometer [1, 57, 59]. Regional airports are also responsible for approximately 20% of the total noise pollution generated by aviation [60].

In light of the need to reduce aviation emissions, optimizing energy consumption in regional aircraft becomes crucial. In addition to the energy required for thrust generation, these aircraft must power numerous onboard systems, such as navigation, communication, flight control, safety, and passenger comfort systems [9]. Some of these systems rely on electrical power, whereas others, such as pneumatic or hydraulic systems, use compressed air from the engine or working fluid pumped by hydraulic pumps. It makes all these systems intrinsically linked to the processes occurring in the internal combustion engine. The More Electric Aircraft (MEA) concept aims to gradually replace traditional mechanical, pneumatic, and hydraulic systems with their electric counterparts [30, 43], which increases energy efficiency, reduces aircraft weight by eliminating complex installations, and improves reliability and system maintenance [43]. In the case of traditionally powered aircraft, even if they are based on the MEA concept, the electrical power required to operate systems other than propulsion, such as avionics, lighting, anti-icing systems, or air conditioning, usually comes from generators driven by the aircraft's main engines [5]. These generators convert mechanical energy from the engine shafts into electrical energy, and additional power sources may include rechargeable batteries, which serve as backup or supplementary power, particularly during system startup.

Hybrid-powered aircraft have been available on the market for some time [27, 64], and new designs of this type continue to emerge; however, their further development requires advanced energy storage technologies. Rechargeable batteries are most commonly used for this purpose [20], although fuel cells and supercapacitors are also being tested [33, 56]. The types of rechargeable batteries used in aviation include: alkaline, lead-acid, nickel-cadmium, nickel-metal hydride, lithium-ion, and lithium-polymer batteries, with the latter two being the most widely available [21] and developing lithium-sulphur batteries. It is important to say that research is also being conducted on the use of graphene and magnesium in rechargeable batteries [58]. However, not all of these are concerned with weight, energy density, reliability, and safety.

To summarize, the rechargeable batteries used in modern aviation are divided into those powering various onboard systems and those responsible for providing energy for thrust generation. The requirements for the chosen technology differ depending on the application.

This article aims to analyze available rechargeable battery technologies that can power aircraft propulsion systems. The authors focus only on those that can be used in regional aviation. This article also aims to highlight current trends in energy storage technologies and point out the main challenges and opportunities related to applying these solutions in aviation.

2. Battery parameters in the context of aviation applications

2.1. General considerations for aviation batteries

When evaluating rechargeable battery technologies for aviation, certain, performance factors become especially important. These include how much energy a battery can store and deliver, how long it lasts, and how efficiently it operates. Below is a breakdown of the most relevant parameters that engineers consider when determining whether a given battery can actually meet the demands of flight.

2.2. Energy density as a key factor in aircraft design

Energy density (Wh/kg or Wh/dm^3) [29] reflects how much energy a battery stores relative to its weight or volume. In aviation, where every extra kilogram is important, this is a top priority. Simply put, a higher energy density implies lighter systems and a longer range. For fully electric regional aircraft to become practical, experts suggest that they will need batteries with over 500 Wh/kg – something current technologies are still striving to reach [35].

2.3. Specific power and its role during critical flight phases

Specific power [W/kg] is about how fast a rechargeable battery can deliver energy relative to its mass. That matters most during phases like takeoff, where systems need much power in a short time. While there's no official minimum, higher specific power is always better in aviation because it helps reduce weight and improves responsiveness.

2.4. Cycle life and long-term reliability of aviation batteries

This refers to how many charge and discharge cycles the battery can go through before its performance starts to degrade. Aircraft rechargeable batteries are charged and discharged frequently, so a longer cycle life is not just convenient – it is critical. A, good target is around 3000 cycles with minimal capacity loss, though some advanced types can push this even further.

2.5. Energy efficiency and minimization of losses

Efficiency [%] [18, 40] measures how much of the energy used to charge the battery can actually be recovered during discharge. Losses here usually show up as heat. The more efficient the battery, the better it performs overall – especially important for electric aircraft where every watt counts.

2.6. Cost per unit of stored energy

Affordability still matters, even in aviation. The cost of storing each unit of energy [$/kWh] needs to be competitive, especially if electric aircraft are to scale commercially. Lowering this cost could be key to making the switch from fossil fuels.

2.7. Charging current and turnaround time

Charging current [A] [40] defines how quickly a battery can be safely recharged. Faster charging means less downtime between flights, which is particularly useful for short-haul or commuter aircraft that have tight turnarounds.

2.8. Discharging current and high-demand flight phases

Just like with charging, the discharge current [A] defines how much power the battery can release at any given moment. High discharge rates are needed during takeoff and other demanding situations, so this value directly affects aircraft capability and safety.

2.9. Depth of discharge as a compromise between range and durability

Depth of discharge (DoD) [%] [3] shows how much of the batteries total capacity can be used in a single cycle. Deeper discharge gives more energy per flight, but it can also reduce the batteries lifespan if not properly managed. In most aviation applications, staying under 80% DoD is seen as a good compromise between output and durability.

Each of these parameters has a direct impact on the viability of a battery system for flight. Some technologies might excel in one area but fall short in another. Among them all, energy density remains the biggest hurdle. Unless batteries can significantly close the gap with traditional aviation fuels in this regard, their role in long-range commercial aviation will likely stay limited.

3. First rechargeable batteries

The first useful alkaline battery was developed in 1949 by Canadian chemist Lewis Frederick Urry for Eveready (now Energizer). Replacing the acidic electrolyte with an alkaline one significantly improved efficiency and enabled the production of commercially viable batteries. Alkaline batteries are single-use, devices, although rechargeable alkaline, batteries are also available, their performance, however, is lower than, other types of rechargeable batteries [34].

The history, of rechargeable batteries begin in 1800 when Alessandro Volta created the first battery (disposable battery) made, of copper and zinc plates. The first mass-producing battery was created in 1802 by William Cruickshank, and the first rechargeable battery in 1859, when Gaston Planté developed the lead-acid battery, which is still in use today [34, 36].

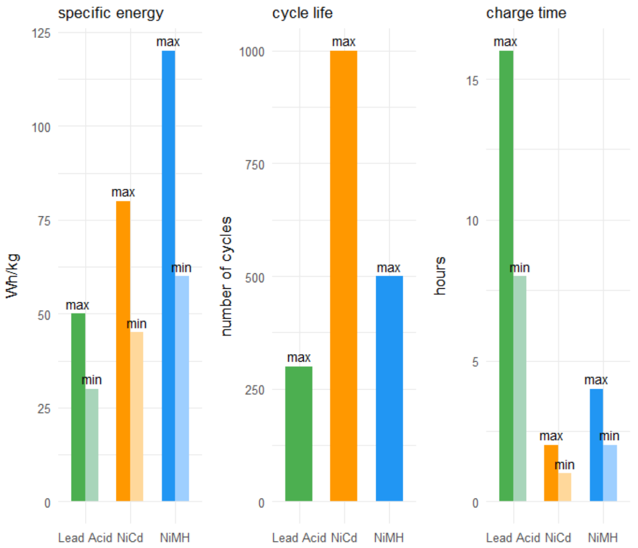

Fig. 1. Comparison of the most important parameters of lead-acid, nickel-cadmium (NiCd), and nickel-metal hydride (NiMH) rechargeable batteries [4]

The early 20th century saw the emergence of nickel-cadmium rechargeable batteries. They were slightly more efficient than lead-acid batteries but provided resistance to temperatures as low as –40°C and higher voltages [46]. However, due to the harmful cadmium content, they were banned throughout the European Union in 2004 [8].

Nickel-metal hydride (NiMH) batteries represent an improved version of nickel-cadmium batteries, offering higher capacity and, eliminating the toxicity issue of cadmium [7]. They, are lighter and exhibit less memory effect compared to NiCd. In aviation, they have been used in some auxiliary systems and portable devices.

Figure 1 shows a comparison of the key parameters of lead-acid, nickel-cadmium (NiCd), and nickel-metal hydride (NiMH), rechargeable batteries.

4. Lithium-ion rechargeable batteries

Initially, lithium batteries used pure metallic lithium as the anode material, providing exceptionally high specific energy and electrochemical potential. However, this design proved problematic because the charging process led to the formation of dendrites – needle-like, lithium structures that could pierce the separator, causing short circuits and a rapid temperature increase [53, 66, 78]. As a result, although lithium-metal rechargeable batteries were highly efficient, they were unsafe and had to be withdrawn from the market.

To address these issues, researchers began searching for a more stable solution. Instead of metallic lithium as the anode, graphite was introduced – a material capable of safely storing lithium ions within its layered structure [2]. In lithium-ion batteries, lithium ions, which are charged particles, move between the graphite anode and the cathode. This ion migration process is the core mechanism of the battery: during charging, lithium ions travel from the cathode to the anode, and during discharging, they return from the anode to the cathode, releasing electrical energy [24]. This structural change made lithium-ion batteries significantly safer and more stable while maintaining high energy density.

The previously mentioned cathodes are a key component affecting the performance, lifespan, and safety of the cells. They are made from various chemical elements, including nickel, manganese, cobalt, aluminum, phosphorus, and iron. These elements, in different combinations, enable an optimal balance between energy density, power density, durability, and safety [31, 75]. The most commonly uses types of lithium-ion rechargeable batteries include:

– Lithium iron phosphate (LFP)
– lithium nickel cobalt aluminum oxide (NCA)
– lithium nickel manganese cobalt oxide (NMC) [48].

Figure 2 presents a comparison of the key parameters of these lithium-ion battery types.

The Boeing 787 Dreamliner was one of the first commercial aircraft to use lithium-ion batteries to power auxiliary systems. In January 2013, two incidents occurred: an APU battery fire on a Japan Airlines aircraft and an emergency landing of an All Nippon Airways flight due to an issue with the main battery. The FAA grounded all Dreamliners, and Boeing introduced additional steel enclosures and ventilation systems to enhance safety [17, 71].

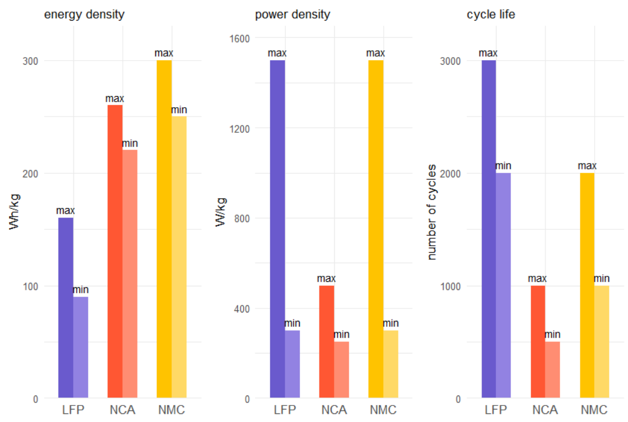

Fig. 2. Comparison of the most important parameters of different types of lithium-ion rechargeable batteries [52]

In December 2019, the first flight of a fully electric commercial aircraft powered by lithium-ion batteries took place. A modified de Haviland Canada DHC-2 Beaver, equipped with a magni500 electric motor producing approximately 552 kW (750 hp), took off for a 15-minute test flight in Richmond, Canada [23, 72].

Hyundai and Uber partnered to develop electric vertical takeoff and landing (eVTOL) aircraft. In 2020, during the CES trade show in Las Vegas, they unveiled the concept of a flying taxi called the S-A1. This vehicle is designed to be fully electric, powered by lithium-ion batteries, capable of reaching speeds of up to 290 km/h, and offering a range of approximately 100 km [68].

5. Lithium-ion polymer rechargeable batteries

Lithium-ion polymer rechargeable batteries (LiPo) are modern variant of lithium-ion batteries that use a polymer electrolyte instead of a liquid one [10]. Thanks to the use of a flexible electrolyte, LiPo batteries, can be shaped into various forms and, sizes, with an additional advantage of improved safety due to the elimination of flammable electrolytes [16, 38]. Their theoretical energy density is estimated to be between 500–800 Wh/kg, but currently achievable values range from 400–500 Wh/kg [52, 65, 77].

Additionally, LiPo batteries can provide better performance at high altitudes due to their lower sensitivity to pressure changes. However, they have a slightly shorter cycle life and greater susceptibility to mechanical, damage compared to lithium-ion batteries [16, 52].

The graph presented in Fig. 3 offers a visual comparison, of the properties of liquid electrolytes, which are standard in, lithium-ion batteries, and polymer electrolytes based on PEO, used in lithium-ion polymer batteries. It can be considered an indirect comparison of lithium-ion and lithium-ion polymer battery technologies through the lens of the type of electrolyte used.

Liquid, electrolytes are characterized by higher ionic conductivity and lower interface resistance, which contribute to better current efficiency. In contrast, PEO-based polymer electrolytes offer increased safety, higher electrochemical stability, and excellent electrode compatibility. Additionally, PEO polymers stand out due to their ease of ‚processing, better thermal stability, and more, effective suppression of lithium dendrite formation, minimizing the risk of short circuits and improving cell, lifespan. The cost, of both materials is comparable.

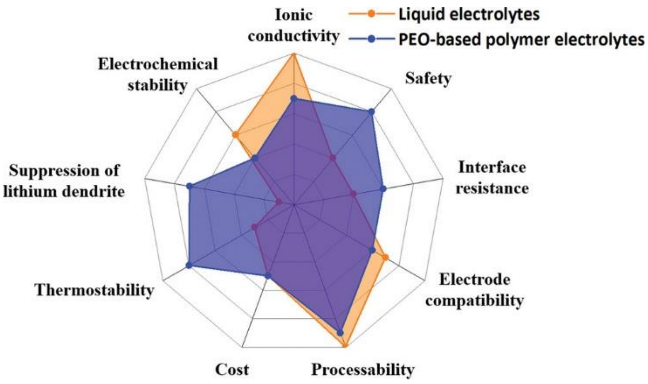

Fig. 3. Comparison of properties of liquid electrolytes and polymer electrolytes based on PEO [38]

6. Metal-air rechargeable batteries

6.1. Fundamentals of metal–air rechargeable batteries

Metal-air, rechargeable batteries are a group of energy storage systems in which metal serves as the anode, while oxygen from the air acts as the oxidizer at the cathode [6]. They are a promising technology due to their high theoretical energy density, making them attractive for transportation, and energy storage. Depending on the metal used, several key types of these batteries exist, each with different electrochemical properties.

6.2. Lithium-air rechargeable batteries

Lithium-air rechargeable batteries offer a very high energy density of 3600 Wh/kg, which is their biggest advantage and main superiority over other energy storage technologies [13, 38, 62]. Due to the use of lithium, a low-mass material, they provide high capacity at a relatively low weight. However, in practice, their performance is significantly lower than theoretical values, mainly due to clogging of the porous cathode by solid oxygen reduction products, which limits the amount of stored energy. Additionally, phase transitions between gaseous oxygen (charging product) and solid Li_xO (discharging product) cause large potential differences between charging and discharging, leading to energy losses [42, 54]. Limited cycle life and electrolyte degradation result in a rapid capacity decline after just a few charge-discharge cycles [12]. Problems also arise under high loads, where the stability of electrochemical reactions is compromised, and system efficiency decreases. The requirement for pure oxygen, supplied from external sources or through air purification systems, further increases complexity and limits the potential commercialization of this technology [22, 32].

6.3. Zinc-air rechargeable batteries

Zinc-air rechargeable batteries achieve a high theoretical energy density of approximately 1200 Wh/kg [51], while their production costs remain low. They are also environmentally friendly, as they do not contain toxic substances [6, 41, 70, 74]. Their ,main drawback is a limited number of charge cycles, leading to faster battery degradation. Cathode reactions are, slow, resulting in low energy efficiency. Additionally, the large voltage difference between charging and discharging reduces battery efficiency. Under high load and humidity conditions, performance decreases, and difficulties in controlling air access can cause operational instability, affecting their long-term functionality [9, 49].

6.4. Aluminum-air rechargeable batteries

Aluminum-air rechargeable batteries offer high energy density and relatively low production costs [19]. Additionally, aluminum, as an ,anode material, is safe, easy to transport, and recyclable without greenhouse gas emissions [67]. The main drawbacks include low reversibility of electrochemical reactions, which limits the number of charge cycles, and anode corrosion in contact with the electrolyte, leading to H_2 gas emissions and reduced battery lifespan [25, 63]. The aluminum, reduction process also requires significant energy input, lowering charging efficiency [61].

6.5. Sodium-air rechargeable batteries

Sodium-air rechargeable batteries have moderate energy density but offer a cheaper alternative to lithium-air batteries due to the wide availability and low cost of sodium [50]. Their development is still in an early stage due to limitations in efficiency, durability, and cycle stability. Nevertheless, these batteries are considered a promising solution for large-scale energy storage, particularly in stationary applications where cost outweighs energy density concerns [14, 73].

6.6. Potassium-air rechargeable batteries

Potassium-air rechargeable, batteries, like sodium-air batteries, have potentially lower production costs due to the broad availability of potassium, as a low-cost anode material. However, their development faces significant challenges, including limited reversibility of electrochemical reactions and cathode stability issues. These technological barriers currently make the commercial application of these batteries highly limited [11, 69].

6.7. Iron-air rechargeable batteries

Iron-air rechargeable batteries attract attention due to their exceptionally low material costs and high chemical stability, making, them a potentially cost-effective solution for large-scale energy storage. Although their theoretical energy density is approximately 1200 Wh/kg, current technological limitations result in significantly lower practical energy density. Ongoing research focuses on improving electrochemical efficiency, cycle stability, and reducing material, losses to bring their parameters closer to their full, theoretical potential and enhance commercialization prospects [15, 47, 76].

Lithium-air rechargeable batteries offer the highest energy density but have limited durability and low efficiency under high loads. Potassium-air batteries are the cheapest but have the lowest energy density and issues with reaction reversibility. Sodium-air, batteries, while cheaper than lithium-based ones, are less efficient. Iron-air batteries have low material costs and high stability, but their practical energy density remains significantly lower than theoretical values. Aluminum, air batteries offer high energy density, but their limitations include anode corrosion and low reaction reversibility.

7. Lithium-sulfur rechargeable batteries

A lithium-sulfur rechargeable battery consists of a cathode with a capacity of 1672 mAh/g, made of sulfur, and an anode made of metallic lithium, with a capacity of 3860 mAh/g. Due to these properties, these rechargeable batteries offer an exceptional theoretical energy density of 2600 Wh/kg [38]. Because sulfur is widely available, lithium-sulfur rechargeable, batteries are inexpensive. Unfortunately, their lifespan is limited due to processes like "stripping" (loss of lithium from the anode) and "shuttling" (migration of lithium polysulfides), which lead to capacity loss and degradation of active materials. Additionally, difficulties in controlling reactions during charge and discharge cycles affect the cell's stability, limiting the number of, cycles in which the rechargeable battery can maintain high performance [26, 39, 40, 44, 45, 79].

8. Summary

The COVID-19 pandemic, caused a significant reduction in air traffic, temporarily slowing the growth of emissions. However, the sector's return to full activity, with forecasts exceeding pre-pandemic emission levels [28], increases the pressure to introduce more environmentally friendly and quieter aircraft. As part of global efforts for sustainable development, progress towards low-emission technologies in aviation has become a key element of strategies aimed at minimizing the sector's impact ,on climate change. The, main challenge in the electrification of aviation is developing batteries that provide sufficient power at a low weight. The chart presented in Fig. 4 compares the energy density of various types of rechargeable batteries discussed in the article. The black horizontal line indicates the minimum energy density that batteries must achieve to provide sufficient energy for aircraft operations during regional flights. Among the currently available types of batteries, only lithium-ion-polymer and lithium-sulfur rechargeable batteries meet this requirement. Unfortunately, both types still face challenges related to production costs, chemical stability, and lifespan. Despite their potential, they are not yet widely used in aviation due to technological and economic limitations.

The chart, presented in Fig. 5 compares the life cycle of selected types of rechargeable batteries. The chart shows that lithium iron phosphate ,rechargeable batteries, despite having nearly, the lowest energy density, have by far the longest life cycle. On the other hand, rechargeable battery types that could potentially compete with aviation fuel in terms of energy density have a significantly shorter life cycle.

The literature, analysis shows that there is no single type of rechargeable battery that meets all the requirements for energy storage systems in aviation. Each mentioned type offers specific, benefits but also faces limitations that determine its application depending on the project's specific requirements.

Aviation rechargeable ,batteries must meet high demands for delivering large amounts of power, especially during the takeoff and climb phases. Lithium-ion rechargeable batteries, despite their good energy efficiency, offer a relatively low, power-to-weight ratio (1–2 kW/kg), making them unable to provide power levels achieved by jet engines (5–10 kW/kg). As a, result, larger and heavier battery packs must be used, which impacts the overall mass and design of the propulsion system.

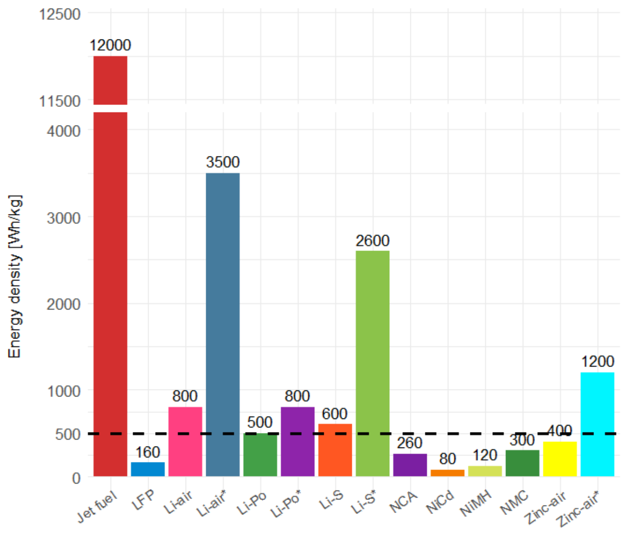

Fig. 4. Comparison of energy densities of different types of rechargeable batteries | * maximum theoretical energy density of a given type of rechargeable battery

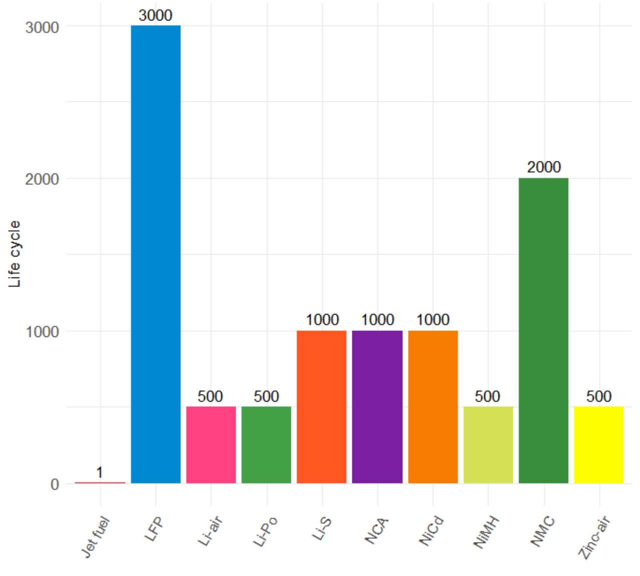

Fig. 5. Comparison of the life cycle of different types of rechargeable batteries

Additionally, frequent changes between high and low power states can accelerate the aging of rechargeable batteries, requiring the use of battery types that are resistant to these fluctuations.

Another challenge ,is the cooling system, which must adapt to changing thermal conditions during different flight phases.

Moreover, the environmental impact of battery technologies, particularly the extraction of raw materials such as lithium, cobalt, and nickel, can lead to significant ecological damage if these processes are not carried out sustainably.

Finally, the certification process for new battery technologies in aviation is complex, time-consuming, and expensive, presenting a significant barrier to the faster deployment of innovative solutions.

Therefore, the further development and implementation of energy storage technologies in aviation requires a balanced approach that considers both operational needs as well as environmental, ecological, and legal challenges facing the aviation industry.

Nomenclature

APU	auxiliary power unit
DoD	depth of discharge
FAA	Federal Aviation Administration
LFP	lithium iron phosphate
LiPo	lithium-ion polymer
MEA	more electric aircraft
NCA	lithium nickel cobalt aluminum oxide
NiCd	nickel-cadmium
NiMH	nickel-metal hydride
NMC	lithium nickel manganese cobalt oxide

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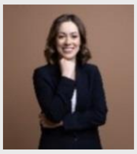

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