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Research Article

Battery Technologies to Electrify Aviation: Key Concepts, Technologies, and Figures

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Abstract

Aviation is undergoing a paradigm shift to become a more sustainable industry. Priorities include reducing fossil fuel consumption, cutting carbon dioxide and other emissions, and developing new technologies. One of the major enabling technologies is the electrification of aircraft. Batteries are a key part of this revolutionary concept. This paper aims to provide key insights into battery technology and its potential to electrify aviation. Therefore, it proposes a comprehensive presentation of this technology following a detailed research process. Five different topics are addressed. The first is a general overview of the chemistry of electrochemical cells, the basic element of batteries. This is followed by a presentation of some of the most relevant previous work in this topic, highlighting their contributions and their main outcomes to be considered in further research. The main performance metrics used to compare the different batteries are presented next. For each of them, the definition, and related requirements that batteries used in electric aviation must meet are included. The paper then analyzes the possibilities for battery use in aviation and identifies some key challenges that need to be overcome to scale-up this technology. Finally, some battery technologies, their current uses, and their potential for further progress toward a more sustainable aviation are presented in detail.

Keywords

Electric Aviation,
Batteries,
Emerging Technologies,
Sustainability,
Environmentally Friendly Aviation

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1. Introduction

One of the current priorities of the aviation industry is sustainability. Currently, the main propulsion system for commercial aircraft are turbofan engines, and they are directly involved in many of the environmental impacts caused by aviation (Ranasinghe et al., 2019). This type of engine produces several environmentally harmful emissions. The most important emission is carbon

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dioxide (CO2), a greenhouse gas. However, other emissions, such as nitrogen oxides, hydrocarbons, sulfur oxides, and contrails, are also associated with aircraft.

In particular, emission reduction strategies could be divided into two distinct categories: technological innovations and the development of interventions to influence behavioral change (Gössling and Dolnicar, 2023). All improvements related to propulsion systems, that is, the development of new propulsion technologies and the replacement of fossil fuels with Sustainable Aviation Fuels (SAF), fall into the first category. Other measures to offset emissions or reduce the number of flights fall into the second category.

The focus of this paper is on a specific case of the first category, namely the use of battery technology as an enabling technology for a more-electric aviation. Electric aviation involves the use of new propulsion technologies. The benefits of electric aviation have been analyzed in several studies.

In particular, the authors of (Moua et al., 2020), after analyzing various prototypes, present as the main advantages of all-electric aircraft a reduction in noise of around 17%, a reduction in greenhouse gas emissions of around 80%, and a reduction in operating costs and pilot training of around 70%. However, to scale-up the use of this technology and overcome some of its major limitations, an international effort is needed to develop new technologies. This study is of great interest because it analyzes different prototypes of short-range aircraft. For each of them, the main characteristics are analyzed, and the study concludes with some interesting recommendations. One of the most interesting aspects is the great contribution that this type of aircraft could make to serving small communities.

Depending on how energy for flight is stored, three different approaches can be distinguished in electric aviation: battery, turboelectric, and hybrid electric (Epstein and O'Flarity, 2019). This previous relevant study is of great interest as it presents the main characteristics of each of these architectures. At a general level, it identifies five key challenges for electric propulsion, namely weight, efficiency, heat rejection, reliability, and cost.

For battery technology to reach its full potential in electric aviation in the coming years, several limitations must be overcome. Today, the technology with the greatest potential for commercialization is lithium-ion batteries. However, this technology also presents several challenges. One of the main concerns is the thermal stability. Therefore, it is necessary to continue developing various research to determine techniques for monitoring battery temperature, as well as optimal battery management systems. An example of this type of study is (Yetik and Karakoc, 2022a) where the authors investigate the effects of cooling a system of 15 prismatic batteries connected in series using air and alumina nanofluids. Currently, the use of massive data analysis and machine learning techniques is a tool with great potential for application in this field. For example, in (Yetik and Karakoc, 2021) a study is carried out that focuses on the thermal stability of different materials as elements of lithium-ion batteries using artificial neural networks techniques. Thermal stability is one of the critical safety issues for the certification of batteries for use in aviation. For this reason, research efforts should be directed towards improving their thermal stability.

Due to the great potential of the use of this technology, there are many international projects that address the assessment of battery technology and try to define different roadmaps to evaluate its development in the coming years.

An example of these roadmaps is (Battery 2030+ project, 2023). This is the result of the Battery 2030+ project, which presents a long-term vision beyond the 2030 horizon. This roadmap has been regularly updated to reflect the latest developments in this well-researched field of innovation. This initiative is a major project at the European level, integrating contributions from different sectors. Contributions from a total of 24 countries and various stakeholders have been considered in the preparation of the updated version of the roadmap. One of the most interesting aspects is the research areas related to batteries covered by the roadmap. These include research into new materials, the integration of smart functionalities into the battery, manufacturability, and recycling.

Specifically, the work presented in this paper is part of the Environmentally Friendly Aviation for All Classes of Aircraft (EFACA) project. This project is co-funded by the European Commission through the Horizon Europe program. The aim of the project is to promote a more environmentally friendly aviation sector and the development of new technologies using electric and hybrid thermoelectric propulsion systems (EFACA project, 2023). To this end, it is divided into several work packages (WPs), each focusing on one of the emerging technologies that will change the world of aviation. Figure 1 shows some details of the project.

In the EFACA project, WP6 is dedicated to the study of battery power for small, short-range aircraft. This category includes a new disruptive concept, the so-called urban air mobility (UAM). The work presented in this paper is framed within this WP, which takes as its starting point an assessment of the current state of batteries, their possibilities, and limitations. As mentioned above, the development of electric aviation in general and battery technology in particular is a cutting-edge topic. The scalability of this technology would be a breakthrough because of its contribution to reducing dependence on fossil fuels and the reduction in greenhouse emissions.

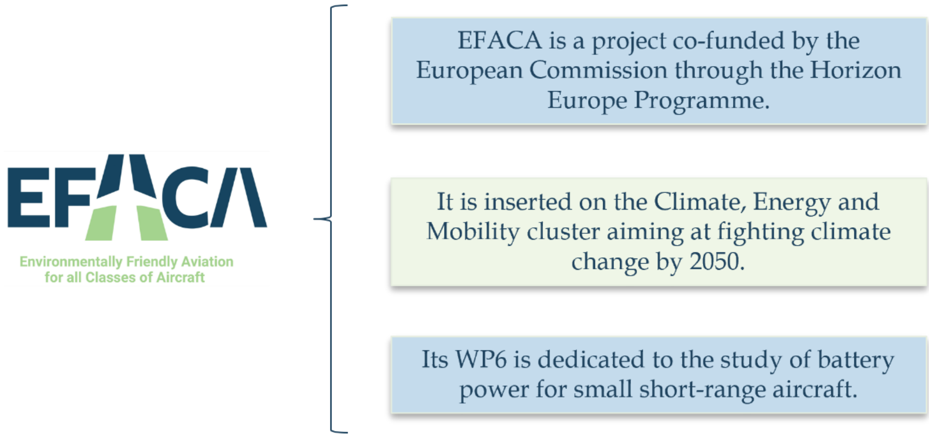

Fig. 1. Key ideas regarding the Environmentally-Friendly Aviation for All Classes of Aircraft (EFACA) project. The information included in the figure has been obtained from (EFACA project, 2023).

1.1. Originality and objectives of the present study

The originality of the present study is that it integrates an overview of the possibilities of using batteries in aviation. At the same time, it provides a list of the main battery performance metrics that will determine their use in aviation. Additionally, it provides an overview of the batteries used in aviation over the last decades and includes the most promising current and emerging technologies that will advance the concept of electric aviation.

The aim of this paper is to introduce a very complex subject, on which a great deal of literature has been published in recent years, for new researchers in the field or for those who, even if they have considerable knowledge of chemistry or technology, are interested in learning about the applications of this technology in the world of aviation.

To this end, the paper provides a general overview of the subject, from the most general concepts, defining the elements of the electrochemical cell, to the most detailed ones, reviewing the different technologies.

The aim is to present all these concepts in a general, but at the same time visual, manner. For this reason, figures and diagrams have been included to illustrate the main concepts highlighted in the paper.

Interesting previous studies are listed in the different sections of the paper. In addition, a list of 10 previous works is proposed in Section 3.2, which are useful references to extend the information on the key concepts presented in this paper. The order of the previous work included follows the outline in which some of the most important concepts are presented in this paper.

The main objective of the paper is to answer five research question. The questions have been formulated to cover the main aspects of the state-of-the-art in the use of batteries in aviation. These questions are as follows.

- What is the main element of batteries and what are their basic components?
- What list of previous works could be of interest to other researchers to present an overview of this technology, its main characteristics, and applications?
- What are the main parameters to consider for the use of batteries in aviation?
- What are the main advantages of this technology in aviation? On the other hand, what are the main challenges to overcome?
- Is it possible to present a chronological overview of the application of batteries in aviation, considering not only past experience but also future developments?

To answer the aforementioned research questions, the remainder of the paper is structured as follows. Section 2. Method presents the structure of the research developed, as well as the main expected results of each of the stages. Section 3. Results presents the outcomes of the five stages of the methodology, focusing on presenting the key concepts of battery technology in aviation. Finally, Section 4. Conclusions and future work, presents the main conclusions of the work carried out, and outlines relevant future works.

2. Method

The methodology followed in the study was to identify certain key areas to present the basic concepts of battery technology and its potential for use in aviation. The first step was to identify these key areas to properly answer the five research questions previously stated. A chronological process was then followed to address them, considering how they would be of the greatest interest to a researcher who was not familiar with the subject but was interested in learning about it. Figure 2 shows an outline of the different stages of the study. Furthermore, the stages described in the diagram correspond to the structure of the following sections of this paper.

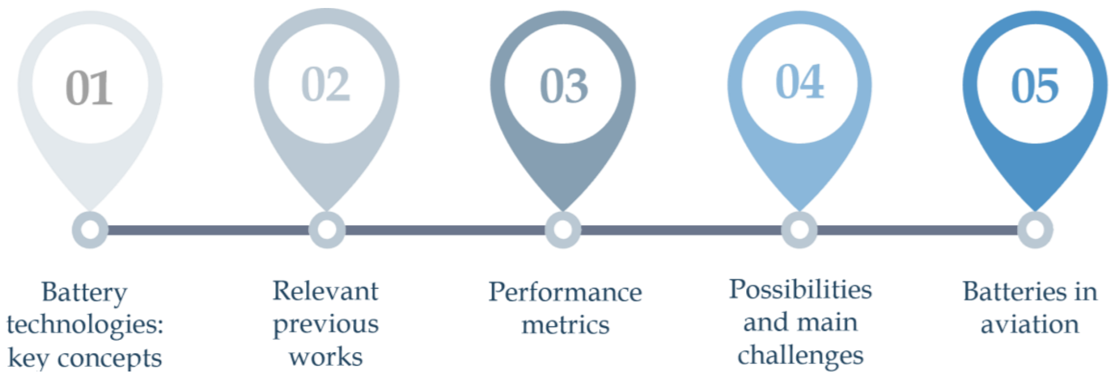

Fig. 2. Methodology followed in the study: from the key concepts of battery technologies to their use in aviation.

The first stage of the study was to define the basic concepts of a battery, in particular its basic element, the electrochemical cell. These are general aspects related to the chemistry of the cell and are common to the use of batteries in aerospace and other industries.

Battery technologies and their application in aviation are a currently well-researched topic. For this reason, many papers have been published, some of them very specific. However, it is difficult to identify certain key references that need to be read and understood before moving on to more specific topics. For this reason, it was considered relevant that one of the outcomes of the study was a set of 10 references that address key topics and can be used as a starting point before conducting further research.

There are many battery options available on the market and in development. To decide which battery is best for each application, it is necessary to compare some parameters, such as the energy density or the number of life cycles. Therefore, it was essential to include in the study an overview of these parameters and some reference values.

As mentioned in Section 1. Introduction, electric aviation has significant potential to achieve sustainability in air transport. However, to realize the full potential of battery technologies, several limitations need to be overcome. To identify the directions in which research needs to move forward, this paper identifies some of the main limitations of battery use.

Finally, the last step of the methodology was to present a chronological view of the use of batteries in aviation. First, those batteries that belong to the low-energy density category, which, although not used in electric aviation, constitute a precedent of great relevance. Then, lithium-ion batteries are included as the most promising technology in electric aviation today, and, finally, this overview presents other options currently under development to replace lithium in these batteries and limit some of their problems.

Section 3. Results is divided into five different subsections, each presenting the research results of the five stages presented and described in the methodology.

3. Results and Discussion

In this section, the answers to the five research questions considered in the study are presented in a structured and detailed manner. To this end, the research findings are divided into five different subsections, following the order in which the questions were presented.

The approach taken in this section starts with a presentation of the main elements of an electrochemical cell and continues in depth, ending with an overview of the different types of batteries that have been used or may have interesting applications in aviation.

3.1. Key concepts of battery technology

This first subsection answers the first research question. Electrochemical cells are the main element of batteries. Within these cells there are different elements that have important functions for the correct functioning of the battery.

Batteries, by definition, are electrical energy storage devices that convert chemical energy into electrical energy and can store this energy for long periods of time (Gabbar et al., 2021). The basic element of batteries is the electrochemical cell, in which chemical energy is converted into electrical energy by a reduction and oxidation (redox) reaction.

The basic structure of an electrochemical cell consists of two active materials that are used as electrodes and an electrolyte that facilitates the reaction between the cathode and the anode. The anode, cathode, electrolyte, and separator are the main elements of the electrochemical cell (Winter and Brodd, 2004). Figure 3 shows schematically the main elements of an electrochemical cell and a definition of each. The diagram shows the structure of an electrochemical cell, indicating the position of the cathode and anode and the type of reaction that takes place in each. The direction of motion of the electrons is also shown. Below the diagram, the definitions of the main elements of the electrochemical cell are presented.

In a very simplified form, batteries used in aviation consist of a series of electrochemical cells connected in series until the desired voltage is reached. They are also made up of several additional coating elements, wiring, and other elements necessary to protect them from undesirable phenomena, such as thermal runaway. The combination of all of these elements is called a battery pack.

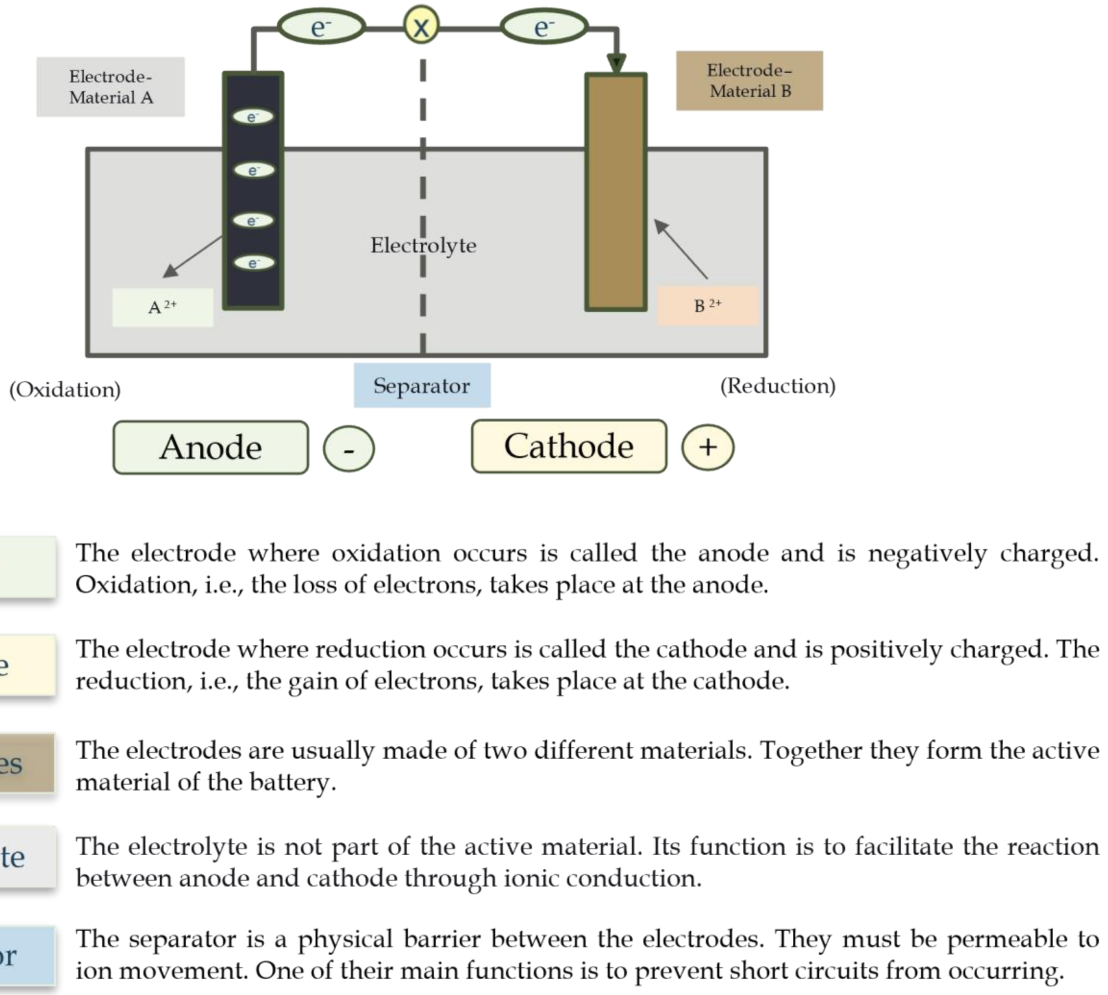

Fig. 3. Representation and description of the fundamental elements in an electrochemical cell. For the definition of the elements included in the figure, the main reference was (Winter and Brodd, 2004).

The electromotive force of the cell is generated by the movement of the electrodes from the anode to the cathode. In primary batteries, once the redox reaction is complete, the battery must be replaced. If the battery is rechargeable, also known as a secondary battery, this reaction can be reversed by connecting the battery to an external power source, which causes the electrodes to return to the anode and restart the reaction. Batteries of interest in electric aviation are secondary batteries.

3.2. Getting an insight into battery technology: previous relevant works

This subsection contains a list of relevant previous work. It has been included to answer the second research question, which relates to a body of previous work that could serve as a reference for other researchers. The aim is to identify several contributions that support the main concepts presented in this paper.

The aim of this paper is to explain the basic characteristics of the use of batteries as an aircraft propulsion technology. Although these concepts will be explained progressively in the sections below, it is worth giving an overview at this point to justify the interest of the references that will be presented and to help build the global vision that will be explained later.

The use of battery technology in aviation can be divided into three stages. The first corresponds to the use of low-energy density batteries used in aircraft with conventional propulsion systems. This group includes lead-acid, nickel-cadmium (Ni-Cd), and nickel-metal hydride (NiMH) batteries. Later came lithium-ion batteries (LIBs), which are used in the technology industry and in other electric vehicles.

Although lithium-ion batteries are currently the most promising option for electric aviation, they face some limitations. As a result, much research and investment are currently being made to develop batteries that

overcome the limitations of lithium-ion batteries. Some of these new batteries are already commercially available, but most are still in development.
Given the number of different batteries and the maturity of each, the research papers published on this topic are very heterogeneous. Although some provide comprehensive and detailed reviews of certain types of batteries, others present experimental results of new chemistries under development.
As a result, it is not easy for a new researcher in the field to get a comprehensive overview of the current state-of-the-art. Following detailed research, this subsection aims to overcome this limitation by presenting 10 relevant previous studies that can serve as a general reference on the key concepts and developments of battery technology.
This selection is based on an extensive prior review of papers and previous work. A total of 10 contributions were selected as a compromise from a list that was not overly extensive but included references of great interest that focused on the key concepts discussed in this paper.
These 10 papers are presented in Table 1. Each row of the table contains a different reference, the title of the publication, and the main topic addressed.
In addition to including these papers, the aim is to summarize their main contributions, to identify certain sections of their content that are of great relevance, and to identify methodologies and models of interest to be considered in further research.
The order in which they are presented in Table 1 corresponds to the structure of this paper, with the first references of a more general nature and the latter more specific to the different types of batteries.

Table 1. List of previous relevant works: reference in the study, title, and main topic addressed.

Reference	Title of the publication	Topic
(Schmidt-Rohr, 2018)	How Batteries Store and Release Energy: Explaining Basic Electrochemistry	General insights into cell electrochemistry
(Barzkar and Ghassemi, 2020)	Electric Power Systems in More and All Electric Aircraft: A Review	Electric power systems in more and all-electric aircraft
(Tariq et al., 2017)	Aircraft Batteries: Current Trend Towards More Electric Aircraft	Comparison of batteries used in aviation
(Bills et al., 2020)	Performance Metrics Required of Next-Generation Batteries to Electrify Commercial Aviation	Specific energy calculation for regional, narrow-body and wide-body aircraft
(Deng, 2015)	Li-ion: Basics, Progress and Challenges	General concepts of lithium-ion batteries
(Shen et al., 2021)	Advanced Electrode Materials in Lithium Batteries: Retrospect and Prospect	Review of electrode materials used in lithium-ion batteries
(Shahid and Agelin-Chaab, 2022)	A Review of Thermal Runaway Prevention and Mitigation Strategies for Lithium-Ion Batteries	Key ideas regarding thermal runaway in lithium-ion batteries
(Gao et al., 2022)	High-Energy Batteries: Beyond Lithium-Ion and Their Long Road to Commercialization	Detailed review of different battery alternatives to overcome the disadvantages of lithium-ion batteries
(Takada, 2013)	Progress and Prospective of Solid-State Lithium-Ion Batteries	Review on lithium-ion solid-state batteries
(Kühnelt et al., 2022)	Structural Batteries for Aeronautic Applications – State of the Art, Research Gaps and Technology Development Needs	Review on the use of batteries with dual functionality: energy storage and structural support

The first paper included in the table above is (Schmidt-Rohr, 2018). It presents the general electrochemical concepts of how batteries store energy. It also explains some key concepts that, as the author points out, are often missing from general descriptions of how cells work. A general summary of the ideas contained in the study is given in the 'Implications for Teaching' section. Of particular interest to electric aviation is the section of the paper devoted to lithium-ion batteries, which explains some of their key electrochemical characteristics.
To understand the changes to be introduced by electric aviation in terms of propulsion systems, it is essential to understand electrical power systems. For an overview of this, a great previous work is (Barzkar and Ghassemi, 2020). It explains in detail the different architectures of

electrical power systems. Also of great interest is the section of the paper entitled 'Towards All-Electric Aircraft'. In this section, additional weight of the aircraft and the development of batteries are listed as some of the main challenges that electric aircraft will have to overcome. Future research on this topic will need to evaluate these limitations.

The study published in (Tariq et al., 2017) is a good complement to the work mentioned above. When selecting a battery for electric aviation, it is of great interest to establish comparisons between the parameters of the different types. This study presents a comparison between lithium-ion, lead-acid, and nickel-cadmium batteries. It also includes a compilation table of different batteries used in aircraft throughout history. From a more quantitative point of view, the methodology proposed in the study is relevant to the cost and weight factors of nickel-cadmium and lithium-ion battery systems. This methodology distinguishes between two aspects. On the one hand the batteries and on the other hand the charger, the coating and the sensing circuits. This methodology may be of interest to other researchers who wish to develop a similar analysis with other types of batteries.

The two papers mentioned above present an overview of the use of batteries in electric aviation. The authors in (Bills et al., 2020) present the calculation of the specific energy required at the pack level to power three categories of aircraft: regional, narrow-body, and wide-body. The methodology used for the calculation is explained in detail and is accompanied by graphs and diagrams that may be of great interest to researchers. The results of the study show that, considering current developments, only next-generation battery chemistries would be able to meet all the requirements to power small regional aircraft.

As mentioned above, the commercially available batteries with the greatest potential for use in electric aviation are lithium-ion batteries. The author of (Deng, 2015) presents the basic principles of how these batteries work and reviews the characteristics of their main elements, including the cathode, anode, electrolyte, and separator. Although the reference may be outdated in terms of future predictions, it may be of great interest to other researchers to understand the basic concepts behind lithium-ion batteries and their main components.

In the general category of lithium-ion batteries, there are many different batteries depending on the cathode and anode components. The work published in (Shen et al., 2021) provides a detailed and comprehensive review of the different electrode materials used in these batteries. It distinguishes between different categories of electrodes, from the first designs, through those currently on the market, to promising materials with the aim of increasing the specific energy. In addition to its detailed review, this paper is of great interest because of the diagrams and graphs it contains, which clearly show the structure of the different materials used in the electrodes.

(Shahid and Agelin-Chaab, 2022) provides a detailed review of the risk of thermal runaway in lithium-ion batteries, including the mechanisms that initiate thermal runaway, how it propagates, and a characterization of the gases emitted from the battery. The paper explains that thermal runaway can occur as a result of various forms of mechanical, chemical, or electrical abuse of the battery. In addition to a detailed review of this phenomenon, the paper presents numerical and mathematical models for predicting thermal runaway based on previous studies. These models can be of great interest to other researchers. Finally, various strategies to prevent and mitigate thermal runaway are presented. In particular, a summary of thermal runaway prevention strategies based on previous work is shown in a table. The paper points out that one of the ways to prevent thermal runaway is to have an adequate thermal management system in place.

To the best of the authors' knowledge, (Gao et al., 2022) is the most comprehensive study focusing on the investigation of other types of batteries beyond lithium-ion to overcome their main limitations. This review proposes other active ions beyond lithium to address the cost issue of LIBs. If the aim is to increase the capacity of LIBs, conversion electrodes are proposed. Finally, to address the safety issue, beyond-liquid electrolyte batteries are proposed to avoid the high flammability problems of LIBs. For each of these categories, the different options on the market or in development, their advantages and disadvantages, and the state-of-the-art are presented. It is an excellent reference for the development of future work, combining general considerations with more specific electrochemical and manufacturing details. It also discusses the long road to commercialization of many of these innovative batteries, pointing out that there are sometimes significant differences between the theoretical performance results obtained in the laboratory and the large-scale manufacturing of these batteries. The final conclusion from all of the work presented is that lithium-ion batteries are currently the best performers in terms of energy density, cycle life, and cost. However, higher capacity alternatives are expected to co-exist with or surpass them in the 2020s.

As mentioned above, one of the solutions to overcome the safety problems of lithium-ion batteries lies in research into solid-state batteries, where the electrolyte is solid. A review of this technology is presented in (Takada, 2013). As this is a reference published several years ago, the expected developments may not be up to date. However, it is included as a relevant previous work to understand the possibilities of this technology, which

is necessary for the development of more complex batteries. The main advantages of this technology listed in the paper are the simplification of the safety mechanism of lithium-ion batteries, the possibility of simplifying the battery structure, and the possibility of incorporating new materials in the electrodes of the batteries.
Previous work has been included to highlight developments around the primary function of batteries, which is energy storage. However, there are developments in the use of batteries in aviation that aim to combine this traditional function with a complementary load-bearing function. These batteries are known as structural batteries and are the focus of (Kühnelt et al., 2022). Their advantage is that they are designed to compensate for additional weight restrictions imposed by the use of batteries in aircraft. These batteries are characterized by parameters related to their ability to store energy and also to support loads. As a conclusion of the review, it is recommended that future research address certain limitations of these batteries, focusing on materials, their integration with aircraft, testing methods, and performance monitoring.
This section presented an overview of the 10 previous relevant publications and some recommendations for further research based on them. Additionally, relevant previous studies will be cited in other sections of the paper to provide figures or more specific information on the characteristics of different types of batteries.

3.3. How to compare batteries: performance metrics

In this subsection, the main performance metrics of batteries are presented to answer the third research question. These are a series of parameters that characterize the behavior of batteries and are very useful for comparing their performance and applicability in electric aviation.
Many batteries have already been commercialized and many others are currently in development. To select the best option for each application, batteries are characterized by several key parameters, referred to by many authors as performance metrics. Although the list is extensive, the six most relevant are included in this section. First, a definition of each of them is presented and then the requirements to be met by batteries that can be used in electric aviation are specified.
The performance metrics considered are six: energy density, power density, service temperature, charging capacity, cycle life, and weight.

- Energy density. This parameter represents the amount of energy stored by the battery per unit of mass. It is considered the fundamental parameter in battery selection. The achievement of ever higher specific energy values motivates the development and research of new types of batteries. It is measured in Wh/kg.

- Power density. This parameter represents the battery's ability to deliver power quickly when required. It is measured in W/h.

- Service temperature. This parameter quantifies the temperature ranges in which the battery can operate safely. Temperature ranges are usually expressed differently for charging and discharging. It is measured in °C. According to several studies, for example (Yetik and Karakoc, 2022b), the parameter that most affects the performance, lifetime, safety, and cost of batteries is their operating temperature.

- Charging capacity. For rechargeable batteries, a parameter of great importance is their charge capacity, which quantifies the time it takes for the battery to recharge.

- Cycle life. This parameter represents the number of charge and discharge cycles that a battery can withstand without significantly affecting its performance.

- Weight. Weight is a fundamental parameter in aircraft design. It is also very important for batteries, as their additional weight can severely limit the range of the aircraft and the payload that can be carried. When evaluating the weight of a battery, it is necessary to consider not only the weight of the electrochemical cells but also the weight of the coatings and other additional systems required for the battery to function properly.

These parameters have been selected as the most relevant for the selection of batteries for aircraft use. However, the list of parameters to be considered to explain the specifications of a battery is much longer. An example of these specifications can be found in (MIT Electric Vehicle Team, 2008). After a general presentation of the concepts associated with performance metrics, Figure 4 presents their specific requirements for the use of batteries as a propulsion system for electric aircraft.
The performance metrics presented in this section are essentially technical, related to the design and configuration of electrochemical cells and battery packs. However, to compare and select batteries for different aeronautical applications, it is essential to consider some additional parameters.
The first of these refers to the materials used in the battery design. Some promising battery options contain rare earth elements, the extraction of which may have a significant impact or pose a problem for the scalability of the technology. In this context, it is important to consider the safety and environmental impacts of the battery throughout its life cycle, from the extraction of raw materials to recycling at the end of its service life.

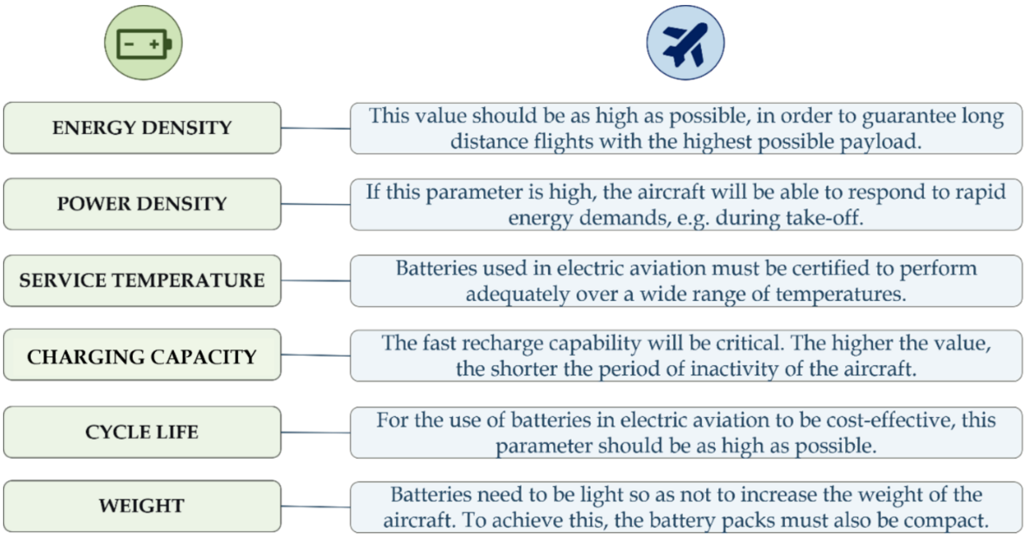

Fig. 4. Key performance metrics of batteries to be met for their use in electric aviation: energy density, power density, service temperature, charging capacity, cycle life, and weight.

3.4. Possibilities and limitations of the use of batteries in electric aviation

The fourth research question posed at the beginning of this paper related to the opportunities and main challenges of using batteries in aviation. After presenting the chemistry of batteries at the cell level and the main performance metrics used to characterize and compare them, this subsection summarizes the main opportunities and challenges for the use of batteries in aviation.

As mentioned in previous sections, the great potential of batteries in aviation is that they are an enabling technology for more-electric and all-electric aircraft. Using this propulsion technology, it is possible to reduce dependence on fossil fuels, limit the noise impact of operations, and reduce in-flight emissions compared to other propulsion technologies.

Figure 5 presents an overview of the potential of batteries in aviation electrification. The upper part of the figure highlights the main rationale for the electrification of aviation and the objectives to be achieved, such as reducing greenhouse gases, eliminating dependence on fossil fuels, and reducing environmental impact. In the lower part of the figure, the two approaches that consider the application of battery technologies to achieve this are presented. These two alternatives are the direct use of battery technologies and their use in collaboration with other technologies in hybrid-electric configurations.

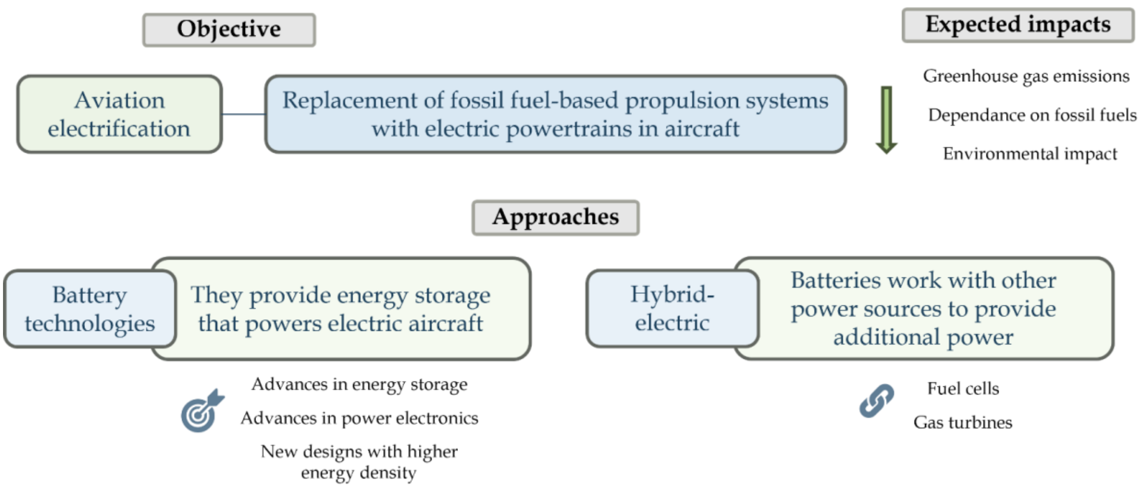

Fig. 5. Possibilities of battery technologies for electric aviation: objective, expected impacts and approaches.

Batteries themselves can be used as a propulsion technology. Scaling-up of this technology will require innovation in several areas. These include advances in energy storage, power electronics, and new chemistries of batteries to achieve higher energy densities.

There is also an intermediate option, hybrid-electric propulsion, in which batteries work with other energy systems to provide electric power. In these cases, batteries could work in conjunction with fuel cells or gas turbines.

The use of batteries in aviation represents a great opportunity and a breakthrough towards greener aviation. However, this technology will have to overcome several challenges. Although each type of battery has its own limitations, some general aspects are presented in this subsection.

These challenges are shown schematically in Figure 6. These challenges can be grouped into two categories. The first group of challenges is related to battery design. These include achieving sufficient energy densities, achieving designs that are sufficiently light, thermally stable, with high cycle life, or preventing thermal runaway. A second category of challenges relates to the difficulties in scaling-up the use of batteries as a propulsion system. Challenges related to maintenance, raw materials used and other impacts on the battery life cycle are included in this category.

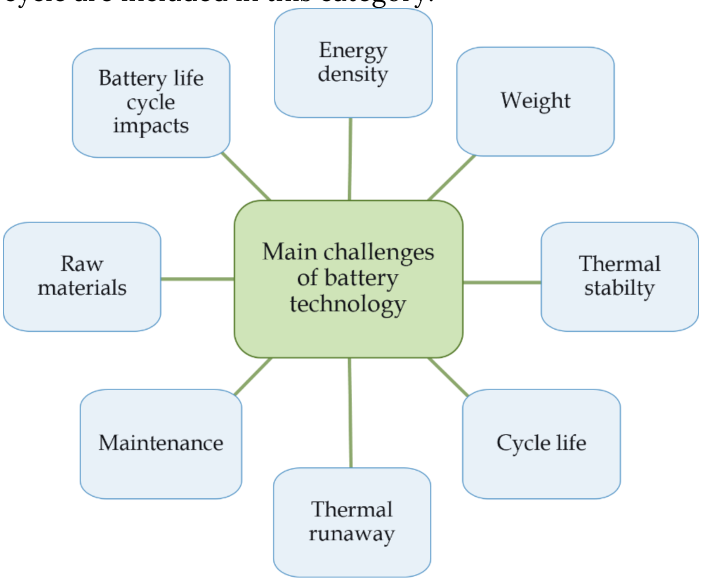

Fig. 6. Main challenges of battery technologies related to their design (energy density, weight, thermal stability, cycle life and thermal runaway) and the scalability of this technology (maintenance, raw materials, and battery life cycle impacts).

The most limiting performance metric in terms of the distance the aircraft can fly and the payload it can carry is energy density. Therefore, it is not surprising that it is the most important factor in battery selection. The trend in research is towards higher energy density batteries. A fundamental aspect to consider is that high values of this parameter are often obtained at a theoretical level. In practice, however, these values are significantly reduced during the manufacturing process compared to laboratory studies.

Another key constraint is weight. As in the case of an aircraft, batteries should be as light as possible. The problem is that weight is often the trade-off to solve other problems. For example, additional materials can be included in the battery pack to mitigate overheating. Therefore, while improving safety, this increases the overall weight of the pack, in turn limiting the range and payload of the aircraft.

Another important challenge is thermal stability. One of the specific requirements for batteries to be used in aviation is the wide range of temperatures to which the aircraft is exposed during flight. These temperature changes can affect battery performance and alter the chemical reactions involved. It is important to monitor the temperature of the batteries to ensure that they function properly. If the limits of the battery's operating temperature range are exceeded, the battery life may be shortened. Additionally, undesirable situations, such as fire, may occur (Yetik, 2020).

As mentioned above, batteries of interest for electric aircraft applications are rechargeable batteries. For their use in aviation to be cost-effective, they must be able to withstand a large number of charge and discharge cycles. As will be seen below, some of the most promising compositions (e.g., lithium-sulfur or lithium-air) present certain recharging limitations, which result in shorter life cycles than desired.

The fundamental safety issue with some batteries is thermal runaway. Specifically, this is a major problem in lithium-ion batteries. This is a process associated with overheating of one of the electrochemical cells as a result of various triggers. If this first stage is not controlled, the cell separator will degrade, making the problem worse and extending it to other cells connected in series in the battery (Shahid and Agelin-Chaab, 2022). In the third stage, the electrolyte burns, which can lead to explosions. For this reason, it is very important to develop mathematical models that address the propagation of thermal runaway and to design mitigation measures to be implemented during the first stage of this phenomenon.

Maintenance will be a key element to ensuring battery safety. To this end, it will be essential to establish procedures for monitoring the state of charge of batteries and implement battery management systems (BMS) that evaluate key battery parameters to schedule maintenance tasks accordingly.

The raw materials needed for battery manufacturing are a major challenge. Some solutions with great potential require the use of rare earth elements. This is associated with an increase in environmental impact and in the energy used to manufacture batteries. Another related issue is the availability of some of these materials. Lithium is an example. For this reason, alternative materials must be sought for their design. A third issue related to raw materials is the political or social conflicts that arise from their extraction. An example of this challenge is the mining of cobalt. These issues apply not only to the materials used in the manufacturing of the electrochemical cell but also to the battery management systems and the battery pack.

There are several environmental impacts throughout the battery life cycle. These range from mining for some of the raw materials to recycling at the end of its service life. Modeling and trying to mitigate these impacts are two of the major challenges in scaling-up the use of this technology.

A major challenge that combines the above is the certification of these new propulsion architectures. Standards and certification procedures will need to adapt to these technological developments. Although progress has been made in recent years, many challenges remain. In addition to the technical certification of the battery life cycle itself, certification of other elements of the system, such as infrastructure or personnel, will be required. A previous work of great interest in this aspect is (Yildiz, 2022). It provides a detailed review of the progress made in the certification of electrical aircraft architectures. It also identifies various limitations of current standards and some gaps that need to be addressed. An example of this is the certification process for large aircraft with electric architectures. In addition, this study proposes a new definition of common unit to simplify the hybrid electric propulsion architecture of commercial aircraft, with a positive impact on the certification process.

3.5. Battery technology in aviation: past, present, and future

The previous sections have provided an overview of the use of batteries in aviation, including relevant studies and an analysis of their performance metrics, possibilities, and challenges. This section aims to integrate all the above and provide an overview of the specific batteries used in aviation, including the past, present, and expected future technologies used. The chronological overview of the use of batteries in aviation presented in this section allows the fifth and final research question to be answered. This chronological overview ranges from the first batteries used in aviation a few decades ago to new developments with great potential for the electrification of aviation.

Figure 7 shows the categorization of the batteries that will be presented in this section: low-energy density batteries, lithium-ion batteries, and beyond-lithium-ion batteries. The three categories shown in the diagram, from left to right, correspond to the chronological development of the three types of batteries described. Low-energy density batteries have been used in aircraft throughout the 20th century. Lithium-ion batteries emerged in the 1990s to revolutionize the technology industry and are now being used in electric vehicles. Beyond-lithium-ion batteries are currently under development to overcome the drawbacks of lithium-ion batteries. Most of the batteries in this group are still in the development stage or have been commercialized on a very small scale.

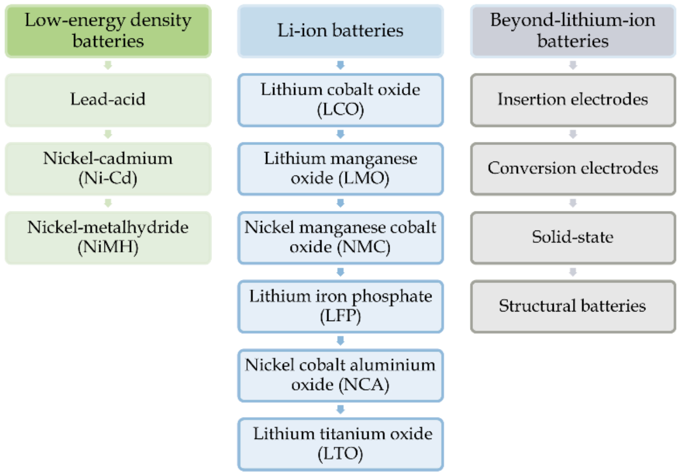

Fig. 7. Overview of batteries used in aviation over the years and those under development for future use: low-energy density batteries, lithium-ion batteries, and beyond-lithium-ion batteries.

The first batteries to be considered are those with low-energy density. This category includes batteries that are not suitable for use in electric aircraft but have been used regularly in aircraft with conventional propulsion systems.

The first group in this category is lead-acid batteries. They have low specific energy values but high specific power, which is useful for starting engines. This was their main application before they were replaced by Ni-Cd and lithium-ion batteries.

The second category is Ni-Cd batteries, which became commercially available in the 1950s. They can operate at higher charge and discharge rates than the former. However, they are more expensive and have a lower specific power. They have been used in aviation as the main aircraft battery for engine ignition, auxiliary power units, and emergency power ("Aircraft Batteries," 2023).

The latest batteries in this category are nickel-metal-hydride batteries, which were introduced in the late 1980s. They are more expensive than lead-acid batteries but have comparatively higher values for specific energy, specific power, cycle life, and, most importantly, recyclability ("Aircraft Batteries | SKYbrary Aviation Safety," n.d.).

A comparison of some key performance metrics has been made based on the information consulted in (Liu et al., 2018). Lead-acid batteries have an energy density of 30-50 Wh/kg and between 200 and 400 cycle life. Nickel-cadmium batteries have a specific energy of 45-80 Wh/kg and 500-1000 cycle life. Finally, NiMH batteries have a specific energy of 60-120 Wh/kg and 300-500 cycle life.

Lithium-ion batteries were introduced in the 1990s to improve performance in terms of energy density. Their operation is explained in detail in (Deng, 2015). The main idea is as follows. These batteries consist of a cathode and an anode connected by an electrolyte containing lithium ions. The battery is assumed to be assembled in a discharged state. During the charging process, the electrodes are connected externally to an electrical source. The electrodes are released at the cathode and move externally towards the anode. Lithium ions move in the same direction, but inside the battery. The discharge process is the opposite.

These batteries have been used in most modern generations of commercial aircraft. The most famous example is its use in the Boeing 787 and the overheating problems that these batteries have suffered (Williard et al., 2013). They are also the frontrunners for use in electric aircraft in the coming years. There are many studies that present the development of hybrid aircraft using lithium-ion batteries for different uses and applications (Farsi and Rosen, 2023).

Within the lithium-ion battery category, there are different batteries with different characteristics. Figure 7 shows the main types. The first five are named after the abbreviations of their cathode materials. The last one is found in the carbon-based anode material options. The performance metrics of each type vary considerably. As an example, specific energy and cycle life values are presented for comparison with low-energy density batteries. In ("Batteries in a Portable World," 2017) it was reported that the energy density and cycle life values for the different cathode material alternatives are as follows. LCO batteries have specific energies between 150 and 200 Wh/kg and between 500 and 1000 cycle life. For LMO the values are specific energies between 100 and 150 Wh/kg and between 300 and 700 cycle life. For NMC, the values are higher, with specific energies between 150 and 220 Wh/kg and between 1000 and 2000 cycle life. LFPs have specific energies between 90 and 120 Wh/kg and more than 2000 cycle life. Finally, NCAs have energy densities between 200 and 280 Wh/kg and 550 cycle life. Of the anode options, LTOs have the advantage of a much longer cycle life. According to ("All About Batteries, Part 12", 2015), their specific energy is between 50 and 80 Wh/kg, but the number of cycles increases to between 3000 and 7000. All cycle life values are at 80% battery depth of discharge (DOD).

However, in view of the large-scale scalability of battery technologies expected in the coming years, lithium-ion batteries have some drawbacks. These include insufficient specific energy, the price of lithium, problems with material depletion, and safety problems due to short circuits or overheating that can lead to thermal runaway. For this reason, alternatives to lithium-ion batteries have been extensively researched in recent years. Some of these alternatives are presented below.

To replace lithium, the first option is to keep the working principle of lithium-ion batteries but substitute the lithium with other materials with similar properties in the periodic table. These are so-called insertion-electrode batteries with ions other than lithium. These ions include magnesium (Mg), aluminum (Al), sodium (Na), zinc (Zn), potassium (K), and calcium (Ca). (Gao et al., 2022) provides a detailed review of each of these options, analyzing their advantages and limitations from an electrochemical point of view. In summary, sodium ions are the most similar to lithium ions. However, apart from cost savings, they have the same problems as lithium-ion batteries. As demand for lithium-ion batteries increases, the relative price of lithium-ion batteries decreases, so the advantage is less significant.

Another alternative is the use of conversion electrode batteries. Unlike insertion-electrode batteries, conversion electrode batteries undergo significant structural changes in the electrode materials during the redox reaction. Within this group, there are two main promising battery types: lithium-sulfur (Li-S) batteries and lithium-air batteries.

Li-S batteries have undergone significant development during the 2010s, with important progress made at the laboratory level (Zhao et al., 2020). These batteries have theoretical potential to improve current lithium-ion batteries by about five to six times in terms of specific energy and specific capacity (Arote, 2022).

Another chemistry with great potential is lithium-air batteries. According to (Ding et al., 2023), the development of these solid-state batteries with a very high energy density would allow their use in electric vehicles for long-distance travel.

Some of the key previous works cited in Section 3.2 present these batteries as one of the most promising technologies. For example, (Barzkar and Ghassemi, 2020) points out that the specific energy of jet fuel is 12000 Wh/kg. For comparison, the equivalent figure for lithium-ion batteries is 250 Wh/kg, so further research is needed on higher energy density alternatives. Li-air batteries with a specific energy of 2000 Wh/kg are mentioned as potential batteries for use in electric propulsion systems.

Additionally, in the study on the performance metrics required to power different types of aircraft included in (Bills et al., 2020), Li-air batteries are presented as those whose progress could make it possible to power small regional aircraft, for which the average specific energy requirement has been set at 600 Wh/kg-pack.

The development of some of these batteries, such as the Li-S and lithium-air batteries mentioned above, is also dependent on the development of solid electrolytes. Current requirements for batteries used in electric aviation require larger batteries, an application for which solid-state batteries are essential. Furthermore, because their electrolyte is solid, they have other advantages, such as no electrolyte leakage, no vaporization problems, and longer cycle life, as well as increased safety due to the elimination of electrolyte flammability problems (Takada, 2013).

Compared to other novel configurations under study, structural batteries are cutting-edge technology. The idea is to reduce the extra weight associated with the use of batteries so that they fulfill a dual function: energy storage and structural bearing. In this case, in addition to the standard performance metrics, others are used to characterize the load-bearing function of batteries. Among these, Young's modulus is beginning to be considered as the most representative (Kühnelt et al., 2022).

As outlined in this section, there are many battery developments with potential applications in aviation. At present, lithium-ion batteries are the most promising in the short term, but future development of other alternatives, particularly those based on conversion electrodes, could represent a major leap forward in terms of the scalability of this technology.

Throughout this subsection, the main characteristics of each type of battery have been presented according to their chemical composition and main properties. As a final remark, it is of interest to highlight some ideas on the characteristics presented.

- For many batteries currently under development, the values obtained in the various studies and tests are theoretical or can only be obtained under laboratory conditions. For industrial production, therefore, the values of the parameters may be affected.
- When choosing one type of battery over another, it is necessary to consider the whole system. Depending on the configurations used, some batteries that present lower values for some parameters at the cell level can improve their performance. In addition to the cell-level components, the battery pack consists of several additional elements. Examples include the cooling system, isolation components, or electrical connections.
- Although some battery configurations present better characteristics than others, it will be necessary to consider more than just technical aspects for future development. Examples of these parameters have been mentioned in previous sections of the paper. Examples include the use of rare earth materials, the availability of materials used in their manufacturing, safety considerations, certification, or the environmental impact of the battery life cycle.

4. Conclusions and Future Work

The aviation industry has a strong commitment to sustainability. Electrification of aviation is one of the most innovative approaches to achieve this. Batteries are presented as an enabling technology for this paradigm shift. This paper presents an overview of the use of batteries in aviation, covering five fundamental topics.

First, a general overview of the chemistry behind an electrochemical cell, the basic element of the battery, is presented. The important elements at cell level are the electrodes, the electrolyte, and, if present, the separator. It is within these cells that redox reactions occur.

With so many battery technologies under development, the literature on the subject is extremely large and heterogeneous. This can be a problem for new researchers in the field. Therefore, as part of this work, 10 key papers have been identified to provide an overview of the use of batteries in aviation. Their main contributions have been explained, and recommendations for other authors have been included.

As the existing batteries are many and varied, it is necessary to define a set of performance metrics to compare them and select the most suitable for each application. These performance metrics have been defined in the paper and their requirements for batteries to be used in electric aviation have been indicated.

The potential of this technology is linked to a reduced environmental impact and dependence on fossil fuels. However, to scale it up, several constraints need to be overcome. Eight of these have been presented and analyzed: energy density, weight, thermal stability, cycle life, thermal runaway, maintenance, raw materials, and battery life cycle impacts

Finally, considering all these concepts, an overview of the batteries used in aviation has been presented, divided into three different groups. The first group consists of low-energy density batteries, which have been used for various purposes throughout the 20th century. Lithium-ion batteries are the main batteries that will be used in electric aviation in the coming years. However, important work is being done to develop safer, lower cost or higher specific energy alternatives. These include other insertion-electrode batteries, conversion electrode batteries, solid-state batteries, and structural batteries. The development of these latter prototypes will undoubtedly be essential to scale-up the technology and achieve a more sustainable aviation.

Future work will be directed towards further investigation of each of the battery types and finding detailed information on their performance metrics. Developing a complete a comparison between them as possible will be the ultimate objective.

In later stages of the research, a detailed study will be necessary that involves the evaluation of the battery system as a whole. In this first stage of research, a classification of batteries has been made based on their electrochemistry. However, to select the best batteries to be used in different types of aircraft, it will be necessary to consider other important elements of the system beyond the electrochemical cell. These include: the battery management system, the electrical connections, the isolation system, the location of the batteries within the aircraft, or the redundancy systems that will need to be implemented in the event of battery failure.

Nomenclature

Al	: Aluminium
BMS	: Battery Management System
Ca	: Calcium
CO2	: Carbon Dioxide
DOD	: Depth of Discharge
EFACA	: Environmentally Friendly Aviation for All Classes of Aircraft
K	: Potassium
LCO	: Lithium Cobalt Oxide
LFP	: Lithium Iron Phosphate
LIBs	: Lithium-Ion Batteries
Li-S	: Lithium-Sulfur Batteries
LMO	: Lithium Manganese Oxide
LTO	: Lithium Titanium Oxide
Mg	: Magnesium
Na	: Sodium
NCA	: Nickel Cobalt Aluminum Oxide
NMC	: Nickel Manganese Cobalt Oxide
Ni-Cd	: Nickel-Cadmium
NiMH	: Nickel-Metal-Hydride Batteries
SAF	: Sustainable Aviation Fuels
S	: Sulfur
UAM	: Urban Air Mobility
WP	: Work Package
Zn	: Zinc

CRediT Author Statement

María Zamarreño Suárez: Conceptualization, Methodology, Investigation, Data Curation, Visualization, Writing-Original Draft. **Francisco Pérez Moreno**: Methodology, Data Curation, Visualization, Writing – Review and Editing. **Raquel Delgado-Aguilera Jurado**: Data Curation, Visualization, Writing – Review and Editing. **Rosa María Arnaldo Valdés**: Conceptualization, Supervision, Funding Acquisition, Writing – Review and Editing. Víctor **Fernando Gómez Comendador**: Supervision, Project Administration, Fundinc Acquisition, Writing – Review and Editing.

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