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An overview of the possibilities, current status, and limitations of battery technologies to electrify aviation

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Abstract. One of the main concerns of the aviation industry is the reduction of dependence on fossil fuels, the reduction of emissions, and, ultimately, the development of a more sustainable air transport system. Emerging technologies, new operational concepts, and research will be essential to achieve this. Batteries are one of the emerging technologies that will play a key role in the electrification of aviation in the coming years. To ensure the scalability of this technology, an analysis of its possibilities, current status, and limitations is essential. The aim of this study is to carry out such an analysis, answering five key questions related to this technology: i) what is a battery?, ii) what are the key parameters of batteries?, iii) what are the possibilities of battery technology to electrify aviation?, iv) what are the main challenges to overcome?, and finally, v) how can batteries be classified? The answers to these questions will make it possible to present the state of the art of this technology, and to identify the main challenges to be addressed in its future development.

1. Introduction and background

Aviation is currently facing a profound transformation towards a more sustainable air transport. The European Union's objectives for 2050 are ambitious and, to achieve them, it will be necessary to carry out extensive research and develop emerging technologies that will contribute to making air transport a more environmentally friendly sector. To do so, emerging technologies are needed to meet a number of requirements. These include reducing emissions (CO_2, but also other emissions), decreasing dependence on fossil fuels, and mitigating the environmental impact of air transport.

Considering all of the above, one of the key concepts in the coming years will be the electrification of aviation. Within electric propulsion systems, three approaches can be distinguished, depending on the form in which the energy is stored for flight: battery power (energy is stored electrochemically), turboelectric (energy is stored as liquid fuel), and hybrid electric (energy is stored electrochemically and as liquid fuel) [1].

The current concern of air transport to achieve a more sustainable sector has been reflected in the implementation of large collaborative research projects at an international level.

In particular, this work is part of the Environmentally Friendly Aviation for All Classes of Aircraft (EFACA) project. This project is co-funded by the European Union through the Horizon Europe Programme. The objectives of the project are aligned with the environmental policies of the European Union. Specifically, it aims to achieve a more sustainable and environmentally committed aviation sector by using electric and hybrid thermoelectric propulsion technologies and prioritising new sustainable aviation fuels to replace fossil fuels.

For this purpose, the project organises its work in five main areas of knowledge: development of demonstrators of emerging technologies, study of emerging technologies and sustainable fuels, aircraft design, analysis of the impact of emissions and noise on the environment, and, finally, design of a global roadmap that considers the inputs of all the work accomplished.

This work is focused on the analysis of the possibilities, limitations, and current status of batteries for the electrification of aviation. Battery technology is a key component of electric aviation as a sustainable and clean source of energy. The remainder of the paper is structured to answer five basic questions about the use of batteries in aviation electrification. Section 2 presents the formal definition of batteries and the basic elements of an electrochemical cell, the fundamental building block of batteries. Section 3 then presents the key parameters that batteries must meet to be used in electric aviation. Section 4 discusses the possibilities of batteries, and, in contrast, Section 5 presents the main challenges that will have to be overcome in the coming years to scale up this technology. Section 6 describes the classification of batteries considered within the EFACA project and the main characteristics of each type. Finally, Section 7 outlines the main conclusions of the study and lists future work.

2. What is a battery?

The first fundamental concept is the definition of a battery itself. Batteries are devices that store chemical energy and convert it into electrical energy [2]. The basic element of a battery is an electrochemical cell. To properly understand the operation of a battery, it is necessary to present the main elements of an electrochemical cell in a summarised form. Electrochemical cells consist of two electrodes of different materials and a conductive electrolyte.

Both electrodes constitute the active material of the battery. The electrolyte is not part of the active material. Its function is to facilitate the reaction between anode and cathode through ionic conduction. As a final element to note, most cells include separators, a physical barrier between the electrodes. These separators must be permeable to ion movement. One of their main functions is to prevent short circuits from occurring.

As discussed above, batteries convert chemical energy into electrical energy. This is achieved by a chemical reaction of reduction and oxidation (called redox). The electrode where oxidation occurs is called the anode and is negatively charged. The electrode where reduction occurs is called the cathode and is positively charged. The reduction, i.e., the gain of electrons, takes place at the cathode. On the other hand, oxidation, i.e., the loss of electrons, takes place at the anode. The movement of the electrons produces the electromotive force in the cell. Figure 1 presents an example of an electrochemical cell using zinc (Zn) at the anode and copper (Cu) at the cathode.

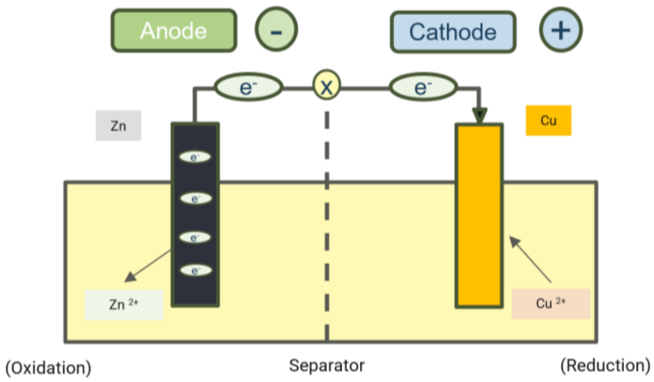

Figure 1. Diagram of an electrochemical cell and its main elements.

These electrochemical cells are connected in series until the desired battery voltage is reached. They can also be connected in parallel to increase the electrical capacity.

Batteries can be divided into three categories: primary batteries, secondary batteries, and speciality batteries [3]. Primary batteries are designed to be used until their charge is exhausted. Once discharged, they are discarded. Secondary batteries are those that can be recharged by supplying electrical energy in the opposite direction from the cell discharge. They are also called rechargeable batteries. Speciality batteries are specifically designed with limited production for a specific use. This group of batteries has limited use, e.g., in the medical industry or the military.

In a primary battery, once the redox reaction is complete, the battery must be replaced. At this point, all the available electrons will have moved from the anode to the cathode, and the activity will have ended. On the other hand, in secondary batteries, it is possible to reverse the redox reaction by connecting the battery to an external power source, which causes the electrodes to move back to the anode, allowing the redox reaction to resume.

Of the three types mentioned above, the secondary batteries will be the ones analysed in this study. For their use in electric aviation, it is essential that batteries have long life cycles and that they can be recharged quickly and safely.

3. What are the key parameters of batteries?

The use of batteries for the electrification of aviation is one of the most promising technologies. To be truly effective, the batteries to be used need to meet several key requirements. This section covers two objectives. On the one hand, it provides a clear definition of what these key battery parameters are. On the other hand, the requirements to be met by the batteries to be used in electric aviation are presented. In total, eight key battery parameters were identified. These are shown graphically in Figure 2.

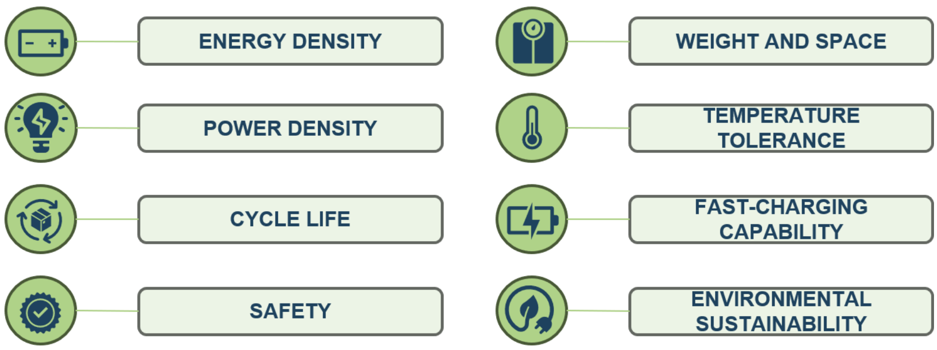

Figure 2. Key parameters of batteries for their potential use in the electrification of aviation.

The first key parameter is the energy density. This parameter expresses the amount of energy stored in a battery either per unit of mass or volume. This needs to be high for batteries used in electric aircraft. A high energy density value is important for aircraft to be able to fly long distances and carry a large payload.

The next concept is the power density of the battery. This parameter represents the ability of the battery to deliver power quickly. As in the previous case, for batteries used in aviation, it is important that this parameter is high. The objective is that the batteries can respond to rapid energy demands in aircraft, for example, during take-off.

Another parameter of great importance concerns the number of charge-discharge cycles that a battery can withstand before its performance drops significantly. This parameter is known as cycle life. For the use of batteries in electric aviation, it is important that this parameter is as high as possible. It should be noted that battery life is not only dependent on the rate and depth of charge and discharge cycles, but is also influenced by other conditions such as temperature and humidity [4]. If the battery cycle life parameter is high, the battery will need to be replaced at longer intervals.

Safety is a crucial aspect of aviation, and there should be no exception in the case of batteries. Batteries must be designed to prevent problems such as thermal runaway and overheating. To ensure up-to-date information on battery status, batteries will need to be equipped with battery management systems.

Two related parameters are weight and space constraints. Batteries used in electric aviation must be as light as possible, while ensuring an adequate energy density. This will make it possible to reduce the overall weight of the aircraft and carry a larger payload. The space for batteries will be limited, and therefore the battery packs should be compact.

A critical parameter for batteries is their tolerance to temperature changes. This is especially important in the case of batteries used in electric aviation, as they must operate at high altitudes and will be subjected to sudden temperature changes. This will be particularly important in the case of vertical take-off and landing aircraft. Therefore, batteries used in electric aviation must have a good tolerance to temperature changes and be certified to perform well at different temperatures.

For rechargeable batteries, it is very important to consider their charging capacity. In the case of batteries used in electric aircraft, they must be able to be recharged quickly, to minimise the time they are not available. The state of charge of a battery can be measured with the State Of Charge (SOC) parameter or with the complementary parameter, the Depth Of Discharge (DOD).

Finally, one aspect that should not be forgotten is the recyclability of batteries. While it is true that propulsion using batteries is clean and emission-free, these batteries may consist of toxic or polluting materials. Therefore, it is essential to ensure that once they are no longer suitable for use in electric aviation, they can be reused in other industries or recycled, to ensure a sustainable life cycle.

4. What are the possibilities of batteries to electrify aviation?

As mentioned above, batteries are a key technology for electric aviation. With battery propulsion, there are no direct emissions during flight. It also reduces noise pollution and dependence on fossil fuels compared to traditional propulsion methods.

The use of rechargeable batteries means that the same batteries can be used several times without having to be disposed of after each flight. In addition, if batteries with long life cycles and high recharge capacity can be developed, the time during which they are unavailable can be reduced.

5. What are the main challenges of this technology to overcome?

Up to this point, the requirements for batteries for electric aviation and their potential have been outlined. However, a number of challenges need to be overcome before this technology can be scaled up, and these will be the focus of this section. Four categories of challenges are identified: performance, safety, maintenance, and recyclability. Figure 3 provides a visual representation of these key challenges.

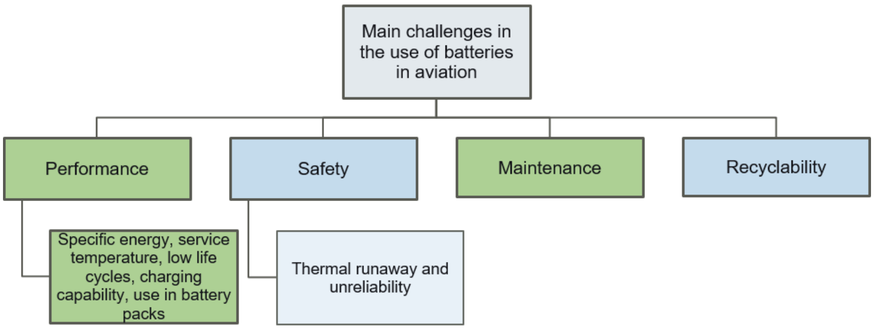

Figure 3. Categories of the main challenges of the use of batteries in aviation.

Interesting studies have been carried out to determine the performance characteristics required for batteries to electrically power different types of aircraft. A very interesting analysis is proposed in [5]. In this study, the results show that to power a regional aircraft with a range of up to 500 NM and carrying 30-75 passengers, a mean specific energy of 600 Wh/kg-pack would be required. At the other extreme, for a wide-body aircraft with a range of more than 2000 NM and 200-400 passengers, the mean value obtained is 1280 Wh/kg-pack. In between, to power a narrow-body aircraft with a range of about 1000 NM, a mean specific energy of 820 Wh/kg-pack would be required. The conclusions of the study show that the specific energy of the batteries is a real limiting factor in achieving these figures, since even the most optimistic values of some of the batteries under development would only allow small regional aircraft to be powered using this technology.

Compared to batteries used in electric vehicles, aviation electric batteries will operate at very low temperatures, which may affect their proper functioning by significantly reducing the kinetics of the reactions in the battery. Another problem that could occur is freezing of the electrolyte.

For batteries used in electric aircraft to be economically viable and sustainable on a large scale, their life cycles must be very long. The problem is that the most promising battery options in terms of specific energy often have the greatest life cycle problems. More research will be needed in this area until a balance is found.

As with the previous aspect, the charging capacity of the batteries will be a key aspect of their economic viability. This time should be as short as possible so that the batteries are inoperable for as little time as possible.

In a previous section, electrochemical cells were introduced as the basic component of batteries. However, a battery used in electric aviation is much more than a set of connected electrochemical cells. A battery pack is the concept that considers the necessary wiring, as well as any special casing and housing materials that may be required. The problem is that many of these elements are not active materials, i.e., they do not generate power but add weight to the aircraft.

In terms of safety, one of the main problems with batteries used in electric aircraft is thermal runaway. Thermal runaway is a phenomenon consisting of a chain of exothermic reactions within the battery. This causes a sudden increase in the internal temperature, which leads to destabilisation and degradation of the battery structure and can lead to battery failure [6]. To avoid this problem, additional materials are added to the battery pack, increasing the weight of the battery. Therefore, more research is needed to achieve a balance.

Other safety-related problems can be degradation, overheating of the battery, or failures in the battery health monitoring system. Therefore, it will be necessary to pay special attention to these phenomena in battery design.

To ensure the safe use of batteries in electric aviation, their maintenance will be an essential part. The maintenance of these propulsion systems will be very different from that of conventional engines. Firstly, the batteries will need to be recharged and their state of charge will need to be monitored. These maintenance tasks will also require new training for infrastructure personnel. An essential element will be the use of a battery management system (BMS), which will be responsible for monitoring various aspects of the battery pack to prevent failures or possible overheating.

As discussed above, to scale up the use of battery technology, the recyclability of batteries must be addressed. Currently, the main battery recycling techniques are associated with the use of acid or extreme temperatures. To ensure that the use of batteries is a sustainable propulsion system, they must be sustainable throughout their life cycle, including the stages after their disposal from the aircraft.

6. How can batteries be classified?

There are several battery classifications. The EFACA project aims to systematically analyse the possibilities and limitations of each battery category. Therefore, the first step was to define a battery classification. This classification is based on the chemical composition of the batteries. This section introduces each of the battery types considered: low energy density batteries, lithium-ion batteries, insertion electrode batteries, conversion electrodes batteries, solid-state batteries, flow batteries and structural batteries.

The first category to consider is low energy density batteries. These batteries have been used in aircraft in the past and are not suitable for use in electric aviation. However, it was considered important to include them in the study to analyse their operation in current aircraft and any incidents that may have occurred. This group includes lead-acid, nickel-cadmium, and nickel-metal hydride batteries.

The batteries that are currently operational and represent the immediate future of electric aviation are lithium-ion batteries. While the specific energy of jet fuel reaches 12000 Wh/kg, the equivalent figure for lithium-ion batteries is 250 Wh/kg [7]. Lithium-ion batteries are currently the most popular batteries with the highest specific energy. They have higher energy density, charging efficiency and cycle life values than the previous category of batteries [8]. They are also the batteries with the best prospects for the near future. The maximum specific energy of lithium-ion batteries has increased in recent years. Future maximum values are expected to be in the range of 400 - 500 Wh/kg at cell level [9]. Lithium has several fundamental chemical properties. Firstly, it has the lowest reduction potential of all the elements. It is also the third lightest element and has one of the smallest ionic radii of any single charged ion [10]. Despite all its advantages, the main limitations of this type of battery are related to the energy limit and certain safety issues.

However, lithium-ion batteries are not a homogeneous group with the same properties. There are different types with different values, which are worth analysing in detail. Lithium-ion batteries are named after their active materials. The words are written in full or abbreviated by their chemical symbols [11]. In particular, depending on the cathode options, the following options are distinguished: lithium cobalt oxide (LCO), lithium manganese oxide (LMO), nickel cobalt aluminium (NCA), lithium nickel manganese cobalt oxide (NMC) and lithium iron phosphate (LFP) [12]. Similarly, there are different options to be included in the anode. Among them, within the carbon-based anode options, there is the lithium titanium oxide (LTO) type. This technology has major advantages such as a very fast charge rate, a high charge/discharge ratio and a very long life cycle that is far superior to other lithium-ion options [13].

Much research is currently being undertaken to develop batteries with a specific energy greater than that of lithium-ion batteries. Through improvements in their basic composition, the following two categories of batteries can be distinguished beyond lithium-ion batteries: insertion electrodes and conversion electrodes.

In insertion electrode batteries, the aim is to achieve a higher energy density using additional electrodes, while maintaining the same operating principle as the reaction of lithium-ion batteries. Substituting lithium ions is a solution to their high cost, as well as a way to mitigate the depletion of this material [14]. In these batteries, the active lithium ion is replaced by another option. Examples of substituting lithium ion in redox reactions include aluminium, sodium, manganese, or zinc.

The other alternative is to use conversion electrodes. The reaction in these batteries involves the breaking of bonds and major structural changes in the electrodes during the redox reaction. In these batteries, the anode is made of metal. Lithium is the most common, but sodium, zinc, aluminium, or manganese are also used. If both electrodes are conversion electrodes, the cathode is usually sulphur or oxygen. Not all batteries in this category are at the same stage of commercialisation. To achieve wider commercialisation, further research is needed to achieve better performance metrics. An example is Li-S batteries, which have a future specific energy target of 500 Wh/kg to achieve large-scale commercialisation [15]. Another technology that is undergoing improvements is Zn-air batteries. They have the advantage of having a much lower manufacturing cost than current lithium-ion batteries. However, their full potential has not yet been achieved because of certain difficulties associated with this composition of the cathode and anode [16]. Sodium is a cheaper material than lithium and more widely available worldwide. If coupled as an anode with a suitable cathode, it is possible to create cells with a voltage above 2V. This is the case for Na-S batteries that are commercially available, but still require further research to overcome some challenges [17].

For higher energy densities, one option is to use alternative electrolytes. Typically, batteries use a liquid electrolyte. However, as an alternative, solid-state batteries propose the use of a solid electrolyte. These batteries typically use a metal anode (usually lithium, although sodium can also be considered) and a sulfur or oxygen cathode.

A different configuration of batteries are the flow batteries. In these batteries, tanks external to the battery are used, containing the liquid electrolyte, in which the battery energy is stored. The amount of energy will depend on the total amount of active substances available in the electrolyte.

Finally, there is an interesting concept worth mentioning, the use of structural batteries. The basic idea is to combine the ability to carry loads with the ability to store energy. Its main advantage is to compensate for the negative effect of the weight of the batteries on the aircraft [18]. In other words, these batteries perform a structural function within the aircraft while at the same time storing energy.

As mentioned above, not all batteries are at the same level of maturity. As many are still in the development phase, it is difficult to assess performance metrics for all of them in a comparable way. As an example of the batteries presented, Table 1 shows a comparison of eight key parameters of different batteries for which sufficient performance metrics data are available.

Table 1. Comparison of performance metrics of various battery types.

Battery type	Specific density [Wh/kg]	Power density [W/kg]	Self-discharge / month	Charge time [hours]	Cell voltage [V]	Cycle life	Temperature	Thermal stability
Lead-acid	30 – 50 [8]	180 [8]	5 – 20% [8]	8 – 16 [8]	2 [8]	200 – 400 [8]	C: -20ºC to +50ºC [8] D: -20ºC to + 50ºC [8]	Thermally stable [12]
Nickel–cadmium	45 – 80 [8]	150 [8]	20 – 30% [8]	1 – 2 [8]	1.20 [8]	500 – 1000 [8]	C: 0ºC to + 45ºC [8] D: -20ºC to + 65ºC [8]	Thermally stable, fuse protection [12]
Nickel metal hydride	60 – 120 [8]	250 - 1000 [8]	30 – 35% [8]	2 – 4 [8]	1.20 [8]	300 – 500 [8]	C: 0ºC to + 45ºC [8] D: -20ºC to + 65ºC [8]	Thermally stable, fuse protection [12]
LCO	150 – 200 [12]		2 – 10% [11]	3 [12]	3.60 [12]	500 – 1000 (80% DOD) [12]	C: 0 to + 45ºC [11] D: -20ºC to + 60 ºC [11]	Thermal runaway: 150ºC [12]
LMO	100 – 150 [12]			3 [12]	3.70 [12]	300 – 700 (80% DOD) [12]	5ºC to + 45ºC [11]	Thermal runaway: 250ºC [12]
NMC	150 –220 [12]		0.35 – 2.5% [11]	3 [12]	3.70 [12]	1000 – 2000 (80% DOD) [12]	-10ºC to + 45ºC [11]	Thermal runaway: 210ºC [12]
LFP	90 – 120 [12]			3 [12]	3.30 [12]	2000 + (80% DOD) [12]	C: 0ºC to +45ºC [11] D: -30ºC to + 60ºC [11]	Thermal runaway: 270ºC [12]
NCA	200 – 280 [12]		2 – 10% [11]	3 [12]	3.60 [12]	550 (80% DOD) [12]	0ºC to + 40ºC [11]	Thermal runaway: 150ºC [12]
LTO	50 – 80 [12]	3000 – 5100 [13]	2 – 5% [13]	3 [12]	2.40 [12]	3000 – 7000 (80% DOD) [12]		Thermal runaway: Very high [12]
Zinc- air	442 [16]	100 [16]			1.45 – 1.65 [16]		0ºC to + 50ºC [16]	
Sodium - sulphur	110 – 150 [17]	200 [17]			2 [17]	4200 (80% DOD) [17]	+100ºC to +150ºC [17]	

7. Conclusions and future works

The use of batteries is one of the key emerging technologies to facilitate the development of electric aviation. This technology presents many advantages, not least of which is that it is a clean form of propulsion, reducing emissions and dependence on fossil fuels. This study answers five key questions regarding the use of this technology in aircraft. These questions relate to the definition of a battery, its main elements, the main requirements for its use in aviation, its main possibilities and challenges, and a classification of the different types of batteries.

While it is true that batteries offer many opportunities for use in electric aviation, there are several challenges to overcome, particularly in the areas of performance, safety, maintenance, and recyclability. To ensure that battery propulsion is truly sustainable, additional efforts will be required after the batteries used in aircraft have been discarded, with particular attention to end-of-life and recycling.

As part of the EFACA project, a classification of the existing types of batteries has been carried out according to their chemical composition. The main characteristics of the seven different categories have been presented. This classification includes low energy density batteries, lithium-ion batteries, insertion electrode batteries, conversion electrode batteries, solid-state batteries, flow batteries and structural batteries. Once the fundamental characteristics of each of the groups have been presented, the possibilities and limitations of each of them will be studied in future stages of the project, considering the general framework presented in this study.

In addition, one of the future tasks will be the design of a roadmap of the intermediate steps in the development of the batteries, considering all the current developments to be able to scale up this technology in the coming years.

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