# Batteries on Aircrafts: Challenges & Expectations

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**Abstract.** Growing inconsistency of fossil fuels have generated increased push for new energy researches. Electrifications of transportations are undergoing for ground vehicles and aircrafts. Current developments of electric aircrafts are facing significant challenges that prevents it from becoming a replacement to traditional aircrafts. This paper examines the challenges faced by electric aircrafts and the current progresses made to counter those challenges. Current small electric passenger jets are catching up with fuel jets of similar sizes in terms of their payloads, but still lacking the range and passenger capacity compared to similar fuel jets. Existing batteries are having significantly lower energy density compared to fossil fuels, which limits other performances on an electric aircraft. Developments of new genres of lithium-type batteries with higher energy density is underway. Thermal management of batteries is critical as the high altitude of aircrafts brings low operating temperatures that can be devastating especially for lithium-type batteries. Progresses are being made to seek materials and protections for low temperature applications. With electric motors being the source of propulsions, there is limited improvement on the thrust necessary to power aircrafts. Researches are focusing on improving the aerodynamics of the plane and using turbo-electric propulsion to increase the thrust on the aircrafts. This paper addresses the critical challenges faced by electric aircrafts and offers potential directions, based on existing progresses, for researches on these matters.

**Keywords:** Battery, Fossil fuel, Electric aircraft, Aerodynamics

## 1. Introduction

Gasoline powered jumbo jets have been the workhorse for medium to long distance transportation of people in the past decades. Conversely, with the growing recognitions of environmental issues and decreased availability of fossil fuels in the future, there’re increased pushes for battery revolutions. With Tesla electrifying ground transports in progress, people turn their attention to the electrification of air traffics. Despite the progresses made by various parties around the world, electric planes themselves at this stage faces significant issues before putting them into service. First and foremost, the battery energy density issue that prevents battery from fully replacing fossil fuels. This ratio of energy to mass for battery is orders of magnitude less than that of fossil fuel. A small battery is not sufficient to power a large airplane nor generate the thrust necessary to lift the plane; yet a battery too large will affect the number of passenger available onboard that flight, thus decrease the economic outcomes from each flight. A second issue is thermal managements on the aircraft. The high altitude of flights, leading to an extremely low operating temperature, posts unique challenges for battery packs that serve the aircrafts. With electric motors alone as the source of thrusts powering the aircrafts, the amounts of thrusts generated are facing a celling with existing electric motors technologies. These shortcomings in performances are what’s holding electric aircrafts, large and small, from entering the fleets of aerial transportations.

Different parties have looked at the individual challenges, faced by electric aircrafts, in or out of context [1-3]. have examined the performance issues of lithium-type batteries in low operating temperatures [4]. gives a general overview of the challenges faced by electric aircraft from the issues battery density and thrust generations. Despite examining the issues on batteries, aerodynamics within the context of themselves, a comprehensive review of electric aircrafts’ realistic challenges is still absence. Which could be misleading for the electric aircraft researches. Meanwhile, existing work focuses on the scientific aspects of the challenges, and it is necessary to apply them in an engineering manner that's feasible for commercialization.

This report will present the challenges of commercial performance, battery energy densities, thermal management and insufficient thrusts on an electric aircraft, respectively. In the first part, a comparison of electric aircrafts versus fuel jets will be given; following will be a review of the actual challenges and the current states of progress will be given, alone with expectations drawn the problem-solution comparisons.

## 2. Economic analysis

Current fuel powered jumbo jets are successful because of their high economic effects. Primarily within the few most important aspects: the operating cost, the passenger capacity, the range of the aircraft, etc. Aviation company will have to manage the optimization of these variables before building a fleet of these brand new electric jumbo jets, which is a similar process when commercializing fuel powered jets: each flight should carry enough passengers to desired destination so that it generates revenues, while the cost of the energy source should not be overwhelming. Of course, with electric planes, the amount of time required to charge the batteries should also be considered since in business, time is money. Below are some relevant details from some most common jumbo jets (fuel powered) used around the world, as well as private jets, in comparison to a potential project of small electric passenger plane.

**Table 1.** Comparison of Several Aircraft Models [5-7].

| | Range (nm) | Maximum Payload (lb) | Passenger Seats | Fuel Type |
|---|---|---|---|---|
| Boeing 737-10 | 3300 | 41,400 | 230 | Jet fuel |
| Pilatus PC-24 | 2000 | 2500 | 10 | Jet fuel |
| Eviation ALICE Project | 440 | 2500 | 7 | Battery |

When reviewing the specifications of one of the most commonly used fuel for jumbo jet, alone with another most successful fuel private jets, then looking at a potential project of electric private jet shown in Table 1, the differences reveal themselves. The Boeing 737-10 carries at least 172 people on board and can cruise at least 3,300 nautical miles Pilatus PC24, a popular model of private jet, has a maximum range of 2,000nm and a maximum passenger capacity of 12 people, including the pilots. Eviation company is currently working with NASA to develop more powerful motors to power their electric jets in the air [6]. In comparison to a PC24, their proposed project with a Magni650 electric motor as power source can almost catch up in terms of payloads, but still lacking the range and passenger capacity (9 people for the Eviation Aircraft) [7].

Through the simple comparison, the weaknesses of current electric jets are obvious. Despite the payload and take-off-landing specs are somewhat catching up with traditional fuel jets, their range and passenger capacity are still way to catch up with its counterparts. In order to commercialize electric jets in the first place, the performances of batteries and electric motors should upgrade itself on orders of magnitudes in order to fully fit themselves into commercial aviation market.

## 3. Challenges

### 3.1. Battery energy density

In terms of the genres of battery used on an aircraft, a larger amount of energy is required to power the aircraft. On board a fuel-powered jet, battery primary functions to power the electronic systems in the cockpit, which is manageable compared to lifting a thousand-tons jet into the sky solely by batteries themselves. The main setback for battery packs is that their energy densities are orders of magnitudes smaller compared to fossil fuels. In other word a functional battery will squeeze out available payloads on an aircraft and raise more technical difficult when designing the rest of the aircrafts.

Lithium-ion batteries so far have the highest energy densities, charge-discharge cycle compared to other battery systems like a Ni-Cd battery or lead acid [4]. A lithium-ion battery cell consists of Lithium ions in solutions and Cobalt oxide solids in the cathode; separated by a porous insulator, the anode sides is consisted of $LiC_6$, a graphite interaction compound. The cathode reaction reduces the Li ion in solution to form a solid compound and absorb electrons (equation (1)).

$$Li^+ + CoO_2 + e^- \rightarrow LiCoO_2 \quad (1)$$

Whereas in the anode side of the cell the graphene compound deposits into pure graphene and lithium ions while release electrons (equation (2)).

$$LiC_6 \rightarrow C_6 \text{ (graphene)} + Li^+ + e^- \quad (2)$$

The anode and cathode are connected by metallic wires so that the electrons can flow from anode to cathode. The general layout of a Lithium-ion battery is illustrated in the figure 1.

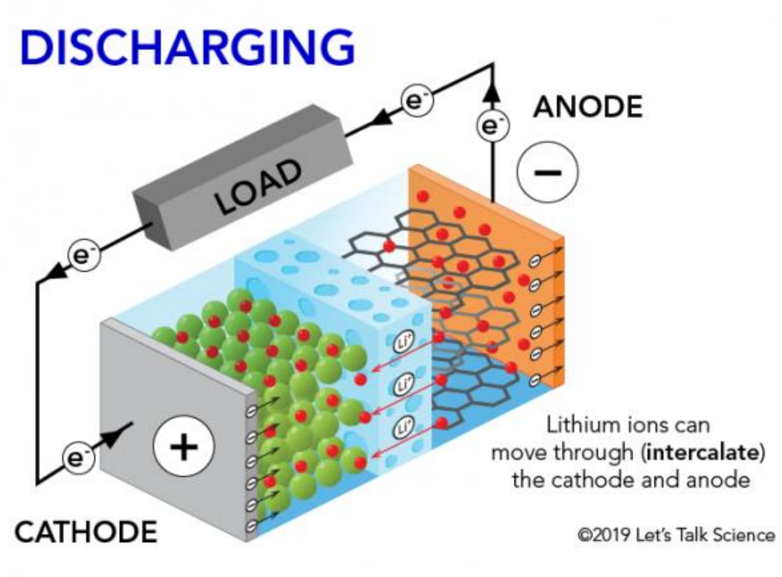

**Figure 1.** Picture Illustration of a Lithium-Ion Cell [8].

### 3.2. Thermal management of batteries

Just the opposite of thermal management task on a car, batteries on airplanes faces devastatingly low temperature which will stall the battery of its duty. Given that temperature drops 0.6°C per 100 meters of elevation, an aircraft that cruises at 7,500 meter will face at least -30°C right above the tropics. The low operating temperatures will stall the battery of its electrochemical reactions, as well as freezing the electrolytes within the cell. Materials on the battery packs potentially face unexpected phase transformations or ductile-to-brittle transition for certain structures of metallic materials which can lead to further complications on the aircrafts. An aircraft losing its power source 25,000 feet above ground is a terrifying accident.

Various literatures show poor performance of lithium-type batteries in a low operating temperature which many materials within the battery contributes to the failure [1]. suggests that the slowed diffusion of lithium ions, reduced kinetics of reactions, as well as nucleation of undesired graphite phase in the anode all contribute to the poor performance of lithium batteries in low temperature. Furthermore, low temperature affects the batteries' capacity and discharge cycles.

As shown in Table 2, there are little to no effect on the performance of lithium-ion batteries above room temperature. Conversely, cell capacity, discharge time and internal resistance worsened in performance as temperature decreases below freezing temperature. Due to the slowing-down of the cell reaction, the amounts of available ions in reaction decreases drastically, resulting in what looks like an increased discharge time, yet with operation voltage not meeting the designed value. As temperature continues to drop, the active ions are all frozen and the discharge time drops again. At these temperatures, the graphene compounds in the anode phase transformation into $LiC_{12}$ instead of the regular $LiC_6$, causing the increased difficulty of compound degradation with the electrochemical reactions.

**Table 2.** Impact of Low Temperature on Li-Ion Batteries [1].

| Temperature (°K) | Cell Capacity (mAh) | Discharge Time ($10^4$ s) | Charged Internal Cell Resistance (Ω) | Discharged Internal Cell Resistance (Ω) |
|---|---|---|---|---|
| 300 | 2400 | 2.8 | 0.5 | 8 |
| 260 | 2400 | 3 | 0.6 | 15 |
| 240 | 1550 | 10 | 0.9 | 40 |
| 220 | 200 | 1 | 25 | 80 |

### 3.3. Thrust & energy consumptions

Aircrafts undergoes various phases within a flight mission, including a climbing phase, a cruising phase and a descending phase. Unlike electric ground vehicles, the energy consumption between each phase is different, and thus can complicate the energy consumption of the battery.

Hepperle examines energy consumption of an electric aircraft during the 3 significant stages mentioned above. In the climbing phase, the aircraft must break ground level into the sky, in which the battery will have to supply a few times greater power than that of the cruising phase in order to airborne. During this phase, the power output of the battery will increase and lead to temperature increase drastically, which could lead to overheating problems that’s common in an electric car on the ground. During the cruising phase, the battery operates in exceedingly low temperature and the electric motor operates continuously for most of the flight mission. In the descending phase, the aircraft can take advantage of the existing altitude and speed for a descend. The battery can stop supplying power for the propulsion of aircraft and retrieve some energy from the descend process. The issue of thrust ultimately links itself to the to-improve battery energy density challenge, for the same amount of “take off fuel” added, the same mass addition of battery material if far from resolving this issue.

## 4. Current Progress

### 4.1. Battery weight-power balance

Obviously, a single lithium-ion battery is not sufficient to power a hundreds-ton jet into the sky. A single battery with power too great will also jeopardize aviation safety. Tariq et al. looked at set of 5 lithium batteries in series, as shown in figure 2.

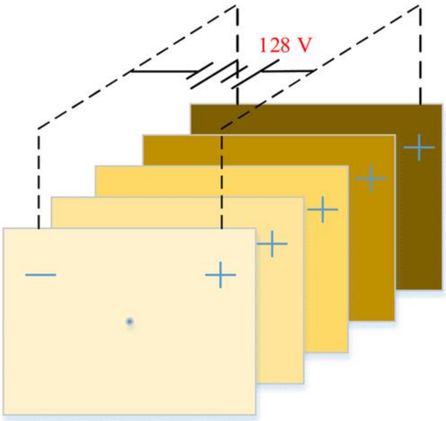

**Figure 2.** Air Grade Li-Ion Battery Packs [9].

As shown in figure 2, reduced power battery individually does mitigate the danger of high-power devices on an aircraft. The connection of those batteries can still yield a reasonable voltage of 128V. Conversely, the increased amounts of electrodes and wiring increases the risk of short-circuits in case of an emergency, thus complicates the safety features applied on the battery packs. Future progress should focus on finding improvement to the electrode cell materials so that they can carry more energy per unit and reduce the number of metallic contacts within the pack.

Through years of research, the battery industries are working towards lithium-type batteries for their by-far highest energy densities and little memory effects. Despite the above-mentioned lithium-ion batteries, industries are working on the lithium-sulfur battery and lithium-oxygen, where their reactions are presented in figure 3.

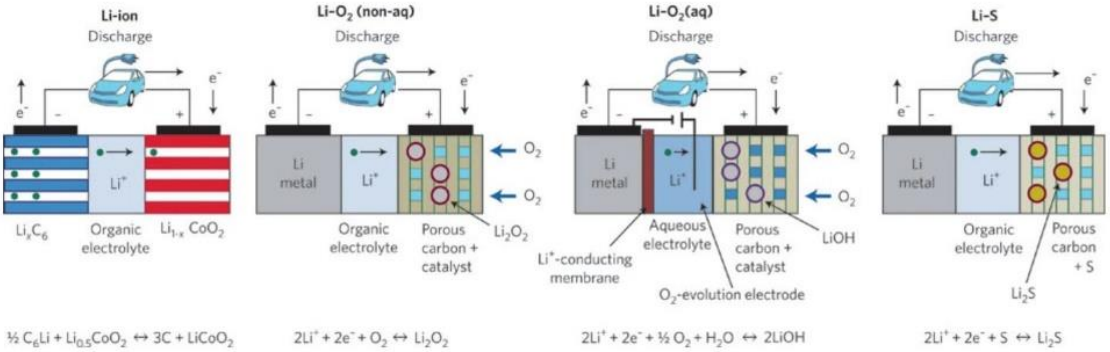

**Figure 3.** Battery Cell Reactions of Li-S and Li-$O_2$ Cell [10].

Bruce et al. discussed the mechanisms of these cells in detail. As shown in figure 3, the lithium-sulfur cell functions by reduction of sulfur in the cathode and then the formation of sulfide on the anodes, eventually producing lithium sulfide in the anode. This cell is advantageous in terms of the natural abundance of sulfur and good energy capacity. However, the lithium-sulfur batteries are still not suit for commercialization for its poor charge-discharge cycles and fast decrease of capacity overtime, from the large amount of insulating lithium disulfides formed. Lithium-oxygen battery cell, or the lithium-air cell is under development as well for its promising energy density. The lithium ion is reduced by oxygen to produce lithium dioxide. The energy density of the above-mentioned electrodes is summarized in the Table 3.

In Table 3, Hepperle calculated the theoretical specific energy of each cell are calculated in the most optimistic conditions possible, that is, disregarding all memory effects and operating in the most optimistic conditions possible. The engineering value of the specific energy density would be much lower considering all the actual operation conditions. Yet still the future of these new battery cells looks promising.

**Table 3.** Theoretical Specific Energy of Various Battery Cells [4].

| System | Theoretical specific energy | Expected in 2025 |
|---|---|---|
| Li-Ion (2012) | 390 Wh/kg | 250 Wh/kg |
| Zn-air | 1090 Wh/kg | 400-500 Wh/kg |
| Li-S | 2570 Wh/kg | 500-1250 Wh/kg |
| Li-$O_2$ | 3500 Wh/kg | 800-1750 Wh/kg |

### 4.2. Material improvements for low temperature applications

Attempts in trying to improve the low temperature performance of Li-ion batteries focuses on material attempts [2]. has proposed ethylene carbonate (EC)–dimethyl carbonate (DMC)–ethyl methyl carbonate (EMC) in 1:1:1 ratio of mixture. This electrolyte is found to have good conductivity and electrochemical stability in low temperature and boosts improved performance compared to regular electrolytes. The EC-DMC-EMC electrolyte promotes the diffusions of ions and formations of expected graphene products towards a lower temperature, as well as a low freezing point compared to conventional electrolytes used in regular applications.

Despite using cold-proof electrolytes, improvements on the electrodes are also under research. With graphene electrodes being the predominant electrodes for lithium-type batteries, they cause decreased performance issues in the above discussion, as well as promoting the formation of Li metal on the electrode surface, causing severe safety issues [11]. examines the applications to counter the issue of Li metal nucleation on surface of graphene electrodes. Those including developing new electrode materials like lithium-rich electrodes or aluminum fluoride which have tetrahedral or face centered cubic structures that can tolerate very little lithium precipitation on the surface, while having good capacities. Additional approaches include doping metal nanoparticles in the electrode materials. The doped nanoparticles are able to promote lithium-ion formation and accelerate the dissolutions of lithium metals on the electrode surface [11].

### 4.3. Thrust efficiency improvements

The issue of insufficient thrust can be mitigated by increasing the capacity of battery source as discussed above. Other solution comes from replacing the solely reliance of electric motors by turbo-electric system, to potentially increase the performance of the aircraft during critical stages of the flight [4]. Unlike turbo engines that generates thrusts by passing of high-speed air, electric motors generate thrusts solely by self-rotations. The amount of thrust generated is directly proportional to the size of the fan blades as well as the speed of rotation. Given the limitation of aircraft size, there are not much room for making mega fan-blades. The rotation speed of the electric motors is reaching a technical celling with the existing battery power as the limiting factor. A coupling system shown in the figure 4 can serve as improvisation to such problem.

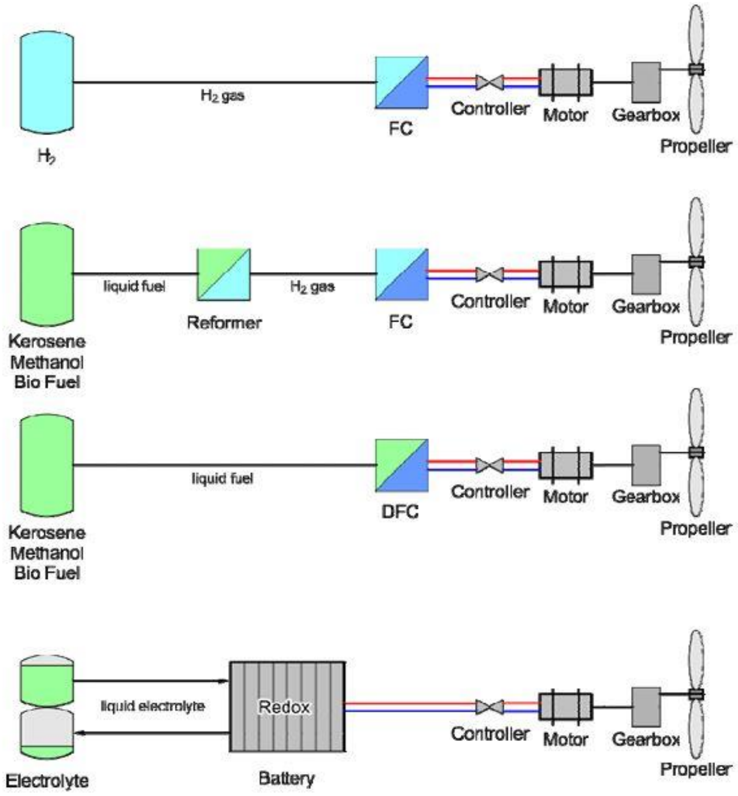

**Figure 4.** Various Types of Electric Turbo Systems [4].

The benefit of a turbo-electric system, in contrast to a motor-only system, is that the turbo rotation speed is detached from the fan rotation speed [4]. As shown in figure 4, with an energy source that's higher in energy density like hydrogen gas, the turbo fan can rotate in a speed that favorably transmit the energy through to the motor, aiding its rotation and boost the motor to an even higher rotation speed. With the progress of battery energy density, such system can be installed on board and mitigate the insufficient thrust issue with the electric aircraft.

## 5. Conclusion

Pushes for alternative energy source have also come to the aviation industry. Electric-powered aircrafts have promising future but still facing challenges technically and economically. Through the statistical comparison of electric passenger jets with fuel jets of similar size, it still lacks the comparable range and passenger capacity to be commercialized. Battery capacities are still not able to live up to that of fossil fuel. With lithium-ion battery packs in series providing just enough power to fly a small jet, the research for lithium-sulfur batteries and lithium-oxygen batteries are still underway to become an engineering prototype. Battery packs on aircrafts are also challenged with severe low operating temperature, which is particularly devastating to lithium-ion batteries. Their performance like battery capacity and discharge time drops exponentially with the drop of temperature. New materials like low-freezing point electrolyte and low-temperature proof electrode materials are to be introduced for low temperature applications. Electric motors face limited improvement space in terms of providing thrust, thus limits the performance of the aircrafts. Despite keep increasing the power output of batteries, a turbo-electric system can increase the amounts of thrusts generated with the aid of a second high energy-density fuel source, allowing for further improvement in propulsions. The challenges and progresses are crucial to advance electric aircrafts out of testing grounds and being able to replace traditional fuel-powered aircrafts, taking aerial transportations to a cleaner future.

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