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A Comprehensive Review of Concepts, Benefits, and Challenges of a Battery-Powered Aircraft

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Abstract: The aviation industry plays a pivotal role in the transportation sector, which also contributes to significant emission and pollution rates. The primary objective of this paper is to elaborate on various aspects of battery-powered aircraft. As battery-powered aircraft have net-zero emissions, the emission rates in the future can be reduced drastically if efficient battery-powered technology is developed. This paper is dedicated to discussing the challenges and technologies in detail. While the Breguet equations are helpful in defining range and endurance for internal combustion engines, there is still much work to be done in the field of battery-powered aircraft. Different methods are employed to address certain challenges and performance parameters. Natural or forced air convection is one of the methods used for thermal management in a battery-powered aircraft. Findings from the study give a clear picture that a number of components need to be replaced by the current ones. Designing an electric aircraft according to the size of new components is crucial, and hybrid aircraft have the potential to reduce the emission rates. Implementation of new efficient technologies such as high-temperature superconducting motors are necessary. The development of all-electric aircraft with higher passenger capacity requires longer time and technological improvement; small-size all-electric battery-powered aircraft have already been developed by various organizations.

Keywords: Battery-powered aircraft; internal combustion engine; electric aircraft

Highlights

1. The development of electric aircraft leads to a larger drop in emission rate by the aviation industry.
2. Hybrid electric aircraft and electric aircraft are two architectures that utilize batteries to power the aircraft.
3. Major challenges include high energy density battery requirements, thermal management, lack of infrastructure, certification, and volume limitations.
4. The range and endurance of an aircraft are the most significant flight parameters, together with the payload it can carry.
5. Huge technological advancement and development are required for electric aircraft.

1. Introduction

Energy plays a vital role in meeting a majority of demands that fall under numerous sectors, ranging from industrial to transportation[1)]. The interest and effort in electric vehicles among people are increasing as we move forward for a sustainably developing environment[2)]. Electric transportation is a significant way to eliminate the dependency on fossil fuels, deliver more efficient operation, slow down global warming, and reduce the effects caused by carbon emissions[3)]. Developing countries in Asia have seen a rapid increase in their energy usage and the amount of carbon dioxide emission into the atmosphere[4)]. The aviation industry is responsible for about 3.5% of CO_2 production around the world, but the risk comes from the formation of nitrous oxides NO_x, Ozone O_3, and fine particulate matter PM2.5[5)]. Greenhouse gas concentrations in the atmosphere could lead to a 3.2°C temperature rise by the end of this century[6)]. Net-zero emission is now a goal of many countries, pursued via the development of cleaner energy infrastructure. 73.2% of the total emission comes from the energy sector, and 16.6% of the emission is from the transportation sector, including all modes of transportation[7)]. The ozone layer which prevents harmful ultraviolet rays exists above 11 km from the earth's surface, depletion of the ozone layer will result in a negative impact[8)]. Several nations globally have already set policies on banning the use of combustion engines in the next 20 years[9)]. If the energy demand keeps on increasing, the energy assets deteriorate, which further increases global warming throughout the world[10]. Although this battery-powered aircraft has all the pros of reducing emissions, challenges in technical, certification, and many other factors are delaying the electric aviation market[11]. There are multiple environmentally friendly ideas to update the current technology to sustainable energy sources, one such is using superconductors Hybrid and all-electric aircraft are being shown a huge interest in the research and development sector[2)12]. An engine plays a major role in a jet-propelled aircraft, the battery holds the same position as well for a fully electrified aircraft. The current battery technology can generate enough power for small aircraft only[13]. More than 70 lightweight all-electric aircraft including experimental, conceptual, and commercial were researched in the past decade alone[14].

Electric aircraft have relatively fewer maintenance and operational costs as compared to combustion engine aircraft. This could be the main reason many private companies are showing immense effort in this area. For urban end-to-end transportation eVTOL is most preferred, VTOL stands for vertical takeoff and landing, just like a drone or helicopter[15]. This review focuses mostly on fixed-wing aircraft. The battery system or electric propulsion doesn't emit any greenhouse gasses, but the manufacturing process of batteries does. However, with the help of several methods, we would be able to reduce that emission to some extent of about 2 to 10%[16]. Top aircraft manufacturing organizations such as The Boeing Company, NASA, and many more are showing keen interest in fully electric-powered aircraft, one such research program initiated by NASA is SCEPTOR, Scalable Convergent Electric Propulsion Technology and Operations Research Project, and the main goal of this project is to experiment distributed propulsion[17]. In the upcoming few decades, it is expected that the aviation industry will grow faster than any other industry, the reason being to meet the demands of developing countries in Asia and Africa[18].

The performance of an aircraft majorly depends on the propelling system; therefore, the battery plays a vital role in the performance[19]. Range and endurance are two important parameters designers take into account. The relations for range and endurance estimations for piston-powered and jet-powered aircraft are widely known as the Breguet Equations[20)21]. The interest in the estimation of the same parameters for a battery-powered aircraft is lacking behind. For instance, Traube used a lead acid battery to estimate range and endurance[22]. Similarly, Ezequiel Reyes Retana derived expressions to estimate endurance and maximum endurance for a fixed-wing aircraft by considering aerodynamic and battery characteristics[23]. Like Traube, Kapstove used a similar approach to estimate range and endurance with Lithium-ion batteries[24]. Dale A. Lawrence analyzed micro air vehicles (MAVs) performance parameters by considering a Lithium polymer battery[25]. In this paper, various challenges, factors, and battery technologies are discussed in detail and also this review will consider the approaches utilized by different researchers in analyzing the range and endurance of a battery-powered aircraft.

1.1 Contribution and Recommendation of the Research Study

The higher amount of emission from the aviation industry can be drastically reduced by electric aircraft. This study gives a broader view of a battery-powered electric aircraft. As this technology is not completely viable in the market currently, research and development is being carried out by multiple organizations. This review majorly contributes to concepts, challenges, benefits, and performance metrics. The performance metrics are range and endurance, which are not widely researched for a battery-powered aircraft as the battery chemistry won't be constant throughout.

2. Battery-Powered Aircraft: Concepts, Benefits, and Challenges

The development of electric aircraft concepts will see a significant rise as the world moves towards a more sustainable future, akin to what we are seeing for electric cars for road transportation. The concept of electric aircraft is not new, but to achieve the energy demands during takeoff and other phases of flight, huge technological improvements are needed. This includes improving the electric storage devices, i.e. the batteries, the power electronics, and the components should be small and weigh less[26]. For the aviation industry, safety and usable energy density are the main constraints. A battery pack that can deliver about 600 W/kg may be achievable in the next decade if sufficient investment is made in the aeronautical industry[27]. An efficient and ultra-reliable power system is the main keystone of electric aircraft and by recognizing this, NASA Lewis Research Center conducted a design study that led to the design of a 20kHz power bus and power converters. If implemented this technology, the fuel, and weight can be cut down by 9 percent[28].

2.1 Battery-Powered Aircraft Architecture

Architectures in battery-powered aircraft technology are discussed in this section. There are 2 aircraft architectures that use battery as a source of energy,1) Hybrid aircraft and 2) All electric aircraft, a list of aircraft are given in table 1,with the architecture implemented in it.

2.1.1 Hybrid aircraft

In this concept, electric power is used in combination with another power source, which is usually a fuel, and the battery uses power electronics to transfer and convert the energy to the motor. Both engine and battery contribute to the generation of power, this results in an overall increase in propulsive efficiency. In this concept, there are two types of arrangements, 1) Series and 2) Parallel[29].

In series configuration, the propeller is driven only by the electric motor, and the power generated by the engine will be converted into electrical energy through a generator. The major benefit of this system is that the engine can work in its most efficient manner during different working conditions, and the major drawback is, it offers less system efficiency as some power is lost during the conversion of combustion energy to electrical energy. The combustion is inefficient, about 30/40%, but converters can be as efficient as 95%[30].

In the parallel system concept, the engine and the motor are connected to the propeller, the power is either transferred individually or simultaneously. One advantage of the parallel concept over the series concept is, it requires only a motor and engine, which reduces the overall weight[31].

2.1.2 All electric aircraft

In this concept, the propulsive power produced will come from the energy of the batteries only. Electric or electrohydrostatic actuators could be the backbone for controlling the control surfaces and also for the engine management system. However, developing an all-electric aircraft is challenging, as currently, the level of technology is not mature enough to develop a fully or all-electric aircraft[32]. A study conducted by Lockheed for this architecture found that electrically driven compressors provide a 3-4% fuel advantage in terms of saving, as compared to engine-bleed systems. But if we take a closer look into modern-day aircraft, it already comprises about 92% electric/electronic, as hydraulic systems are mostly used in control surfaces during the cruise phase, and converting this percentage into 100% should be easy[33].

Table 1: List of aircraft and the architecture based on which it is being developed[11].

Aircraft Name	Organization	Architecture	PAX
VoltAir	EADS/Airbus	All-electric	68
E-Thrust	Airbus/Rolls Royce	SHE	90
X-57 Maxwell	NASA	All electric	87
SUGAR Volt	Boeing	PHE	154
Luftfahrt Ce-Liner	Bauhaus	All electric	189
PEGASUS	NASA	All electric, PHE	48
VoltAir	EADS/Airbus	All-electric	68
Alice	Eviation	All electric	9
ZA10	ZUNUM Aero	SHE	12

To commercialize battery-powered aircraft, first the challenges need to be overcome, and the development of new devices in this field is important.

2.2 Battery-Powered Aircraft -Benefits and Challenges

There are various benefits and challenges in the electrification of an aircraft, some major challenges include the energy density of the battery, thermal management systems, charging infrastructure, certifications, weight, and space limitations[34]. The current technology in motors, generators, and power electronics such as inverters and converters should be upgraded to the next level for an efficient electric aircraft[35]. The advancements in battery technology are continuing, which allows us to increase the range and reduce the charging time[36]. In this section, the recent developments and current battery technology overview will be discussed.

The first and foremost benefit of a battery-powered aircraft is its impact to the environment is considerably less as compared to combustion based aircraft. Other potential benefits are;

1. Low operating cost: As compared to conventional fuel, the price of electricity is much less, and so is the cost of operation.
2. Reduced noise: The noise level created by a battery-powered aircraft will be less, and it is normally quieter.
3. Higher efficiency: The efficiency of a battery-powered aircraft will be higher, as the energy lost in the conversion to mechanical energy is minimal.
4. Scalability: In electric aircraft, the designers have the freedom to use one large motor, or several small sized motors, which is called distributed electric propulsion [37,38].

An all-electric aircraft with battery packs of 800 Wh/kg and with a range of about 600 nm (1,111 km), could replace around half of all the aircraft, reducing airport side NOx by 40% and direct CO2 emissions by 15%. By assuming strong development in the battery technology, battery-powered aircraft with double the range of about 1200 nm (2,222 km) could replace more than 80% of the aircraft, reducing airport side NOx emission by more than 60% and direct carbon emission by 40%[39].

These are some major advantages of electric aircraft, on the other hand, critical challenges need to be overcome, and the challenges are elaborated below.

2.2.1 Energy Density

One of the crucial challenges is the energy density offered by current battery technologies. As said earlier, the propulsive system plays an important role because this will decide the range and passenger capacity of an aircraft [40]. Figure 1 shows the comparison of energy density between various batteries and aviation fuel. Some batteries show theoretically higher energy density, as shown in table 2, in comparison with gasoline.

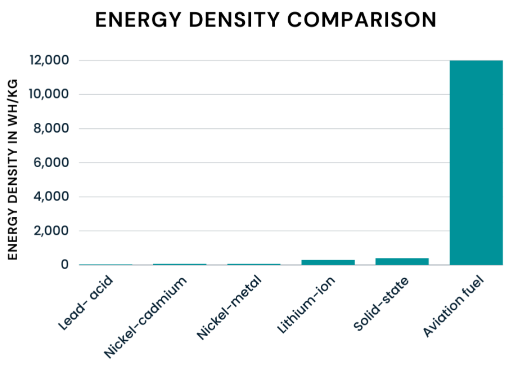

Fig 1: Comparison between different batteries, especially used in electric vehicles and with aviation fuel.

The demand for sustainable energy resources is increasing, and it is essential to have a safe, low-cost, and large-scale energy storage system[41]. Lithium-ion (Li-ion) batteries are most popularly used because the main reason being higher energy density, other reasons are, their higher life cycle and specific power[42)43]. The energy density of current state-of-the-art Li-ion batteries ranges from 200 to 250 Wh/kg [44]. The cell energy density of 300 Wh/kg can be reached with the help of high nickel cathode material, nonetheless, it won't be much safer[45]. Natural graphite is considered to be an important anodic material that can be used in Li-ion batteries because of its high reversible capacity, flat voltage profile, better cyclability, and low cost, still, it is not sufficient for high-power density batteries[46]. The Tesla model has the highest energy density battery (300 Wh/kg), which was only achievable with the help of a Lithium-ion battery made up of Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO2)[47]. It has been estimated that shortly battery technology will develop rapidly and a 500 Wh/kg energy density can be achieved, still, this energy is lesser by a factor of 25 than fuels that are used at present. Metal air electrochemical cells have a larger energy density than other battery technologies, and presently, there has been an increase in research on them.[48]. Still, a type of Lithium battery can satisfy the energy density needs, which is a Lithium-air battery which has 11,640 Wh/kg of energy density with 3v voltage[49].

Table 2: List of batteries with corresponding theoretical energy density[50].

Battery	Energy density
Lead acid	123 Wh/kg
Lithium-ion	250 Wh/kg
Zinc–oxygen	1084 Wh/kg
Sodium–oxygen	1605 Wh/kg
Lithium-sulfur	2600 Wh/kg
Magnesium–oxygen	6800 Wh/kg
Aluminum–oxygen	8100 Wh/kg
Lithium-air	11,140 Wh/kg
Gasoline	12,700 Wh/kg

2.2.2 Thermal Management and Safety Concerns

After energy density, the next major challenge is to manage the heat flux produced by the battery. Developing thermal management systems that are lightweight and can manage larger heat is challenging[51]. Not only the batteries heat up but also the motors used will generate a significant amount of heat, thermal management of motors is researched in detail by David C. Deisenroth and Michael Ohadi[52]. In this paper, the authors have discussed the emerging technologies that can be used for thermal management. Talking particularly about Li-ion batteries, if the heat is not managed effectively, the efficiency will drastically reduce, if the operating temperature is above 35°C[53]. A detailed review of the Li-ion battery thermal management system is given by Qian Wang[54]. Qian included various strategies which included natural or forced air convection, and liquid as a medium for is extremely effective for cooling because of its higher thermal conductivity, other strategies includes using phase change materials, and heat pipes.

Batteries work more efficiently between the range of 0 to 40 °C and the thermal management system needs to maintain this temperature range[55]. Mainly the thermal energy is transferred externally from the surface rather than managed internally, however, the temperature is higher in the internal surface of the battery only[56]. The main cause of heat generation during charging and discharging at higher rates is due to the leakage of electrolyte solution[57]. Several models are used to study the thermal behavior of battery systems. Yoshitaka Inui gave detailed methods to estimate the heat generation of Li-ion batteries during charging and discharging[58]. Battery thermal runaway occurs when the battery produces too much heat that the thermal management system is unable to control, this results in the production of a large amount of smoke as well[59]. To summarize, thermal management systems should be given more importance and should not be undervalued. Moreover, they should be lightweight to improve efficiency and safety[60].

2.2.3 Charging Infrastructure

Charging infrastructure is a crucial element in airports for charging aircraft and should be planned properly because of the huge demand[61], and importance must be given to reduce the charging time[62]. Another method to reduce the time for charging is the battery swapping technique, in which batteries are removed for charging and another battery is replaced in that slot, but this technique needs special processes to implement[63]. If we are considering narrow-body aircraft such as the B737-800, the charging time of a battery to power the aircraft will be extremely large[64]. If the charging infrastructure is implemented in the airports, the energy consumption will significantly increase, which also requires distributed energy resources[65]. The authors evaluated the use of microgrid infrastructure to reduce the electric load on the main building for charging electric aircraft and electric vehicles. Salucci and his co-authors have given special attention to the charging infrastructure requirements in an airport for hybrid-electric aircraft[66].

As charging brings a lot of electric consumption in the aircraft, Rao mentioned bringing renewable solar energy sources to meet the demand[67]. Among the methods of charging mentioned before, the plugin charge method will take longer duration, which results in more turnaround time[68]. The authors used a methodology called Airport Recharging Equipment Sizing (ARES) to determine the best charging way for a hybrid electric aircraft. Patel used a system-of-system approach to design and model energy infrastructure for (UAVs) Urban Aerial Vehicles[69].

2.2.4 Certifications

Electric aircraft differ greatly from current combustion-based aircraft, and as a result, current certification policies will also need to be changed[11]. Small electric aircraft capable of taking up to 19 passengers are certified through FAR Part 23[70]. Velis Electro, from the aircraft manufacturer Pipistrel is the first fully electric type certified by EASA in 2020[71]. Take-off, landing, and climb performances are taken into account for the certification for a hybrid electric aircraft[72]. Driver components for electromechanical actuators should be tolerant to faults for electric aircraft to be certified[73]. The changes made in FAR 23 recently allowed it to have a standard certification, particularly for electric aircraft[74]. There will be changes in the architecture of the onboard systems for the electric aircraft which includes adding electric motors, power converters, and energy sources such as a battery, which also requires more effort in terms of certification[75]. Jean Claude Derrien and Sagem Défense Sécurité mentioned The SAFRAN/Sagem 'SMART WINGS' project, where the wings are completely flexible and thin, offer more safety, and also can be certified[76]. FEA 23 has a limit for a maximum take-off weight of 12500 lbs to be certified[77]. Particularly the battery management system should pass various tests to ensure its safety and reliability, one such test is the explosion containment test requirement[78]. A battery management system in a vehicle ensures that the batteries are working in safe mode[79]. Telford utilized Fault Tree Analysis, called the FTA, to determine the probability of undesired events for the certification of electric aircraft[80]. For the successful implementation of electric aircraft for urban air mobility, certification comes out to be a critical hurdle to overcome[81].

2.2.5 Weight and Space Limitation

The weight of an aircraft has a significant impact on its performance, which is why the electric motors used in electric aircraft should be light[82]. The development of new and modified materials are vital for the progress of engineering and technology[83]. Aluminum and alloys are considered to be the primary materials used for the construction of body structures in military and civilian aircraft, as they offer higher strength, stiffness, and also less in weight[84]. Carbon Fiber Reinforced Plastic (CFRP) materials are replacing stainless steel and other materials due to their unique characteristics such as high strength-to-weight ratio, high stiffness-to-weight ratio, high damping, and good corrosion resistance capacity[85]. Current battery technology has a weight limitation, which is hindering the process of larger electric aircraft[86]. Not only the battery should be considered for weight limitations, but also the electrical machines and power converters should have limits for their weight[26]. Figure 2 compares the weight of an electric engine and a turboshaft engine. The fan is kept constant, if both the engines have the same size, and the compressor, combustor, and turbine are replaced by a high-temperature superconducting (HTS) motor. By using superconducting motors and cryogenic motors, the weight can be reduced as compared to the current technology[87].

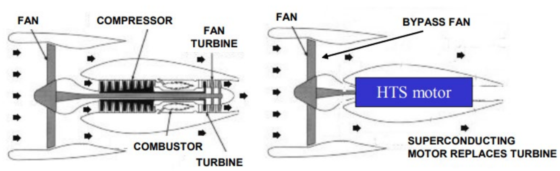

Fig 2: Comparison between combustion and electric engine configuration with the same fan design [61].

88) also stated that we need superconducting materials to reduce the size of motors to yield higher power density. Electrical systems used in electric aircraft can be reduced by using AC voltage above 112 v, and other electrical components such as motors may also lead to weight penalties[89]. Solid-state electronic converters are widely used AC to DC converters, but this converter adds further weight to the system and the major drawback is its efficiency[90]. Extensive development and research are shown in this particular area to reduce the total weight of

the aircraft[91)].

2.2.6 Power electronics

Power electronics show significant efficiency in the transmission, conversion, utilization, and distribution, and play a crucial role in the electronic architecture of an aircraft[92)]. As the failure of electrical systems can't be predicted in an electrified aircraft, we require multiple protection devices for diverse electrical system requirements[74)]. To improve the performance of power electronics, Falck mentioned active methods which utilize software-based control systems to change the desired operation of the system[93)]. Smart grids use power electronic converters, which replace conventional power grids, as they offer higher-quality energy storage[94)]. A review of power electronic units is given by Barzkar, in which the author briefly discussed power electronic converters, electric machines, electrochemical energy units, circuit breakers, and wiring harnesses[95)]. The current power electronics technology cannot transfer megawatt-level power during takeoff, and it is also restricted by weight and cost[96)]. In order to increase the power density of the power electronics for future electrical aircraft, new materials with the aid of superconductivity are necessary[97)]. Huai Wang mentioned the development in power semiconductor technology, power electronics, and reliability engineering, which depicts about the technological development in this field over a century, and yet exceptional advancement is required for electric aircraft[98)].

3. Battery technology

Multiple factors decide the battery type for a specific use, such as energy density, power density, safety, life cycle, energy capacity, and voltage[36)]. Current battery types used in plugin electric vehicles and battery energy storage systems are lead acid, nickel metal hydride, lithium-ion batteries, sodium sulfur batteries, and redox flow batteries[99)]. The performance of a battery is related to the cathode material properties used in it[100)]. Although no current battery technology can power a larger aircraft, these batteries have the potential for future electric aviation.

3.1.1 Lead acid battery

Even though new battery technologies are being developed, lead acid batteries were invented way back, more than 160 years ago, are still in use[101)102)]. Currently, lead acid batteries are used widely in transportation systems for starting the engines, as it is less expensive than other battery systems[103)]. However, due to comparatively less cycle life, poor performance at lower temperatures, and specific energy, its applications are limited[104)].

3.1.2 Nickel metal hydride battery

In this battery, hydrogen is stored in the solid hydride phase, NiMH batteries offer many advantages, which include, high energy density, long life, and efficient at a wide range of operating conditions[105)106)]. These batteries can provide a range of 100 km for electric vehicles[107)].

3.1.3 Lithium-ion battery

Current storage systems use lithium-ion batteries, because of their unique advantages which include their energy characteristic, long life cycle, and high power density with low self-discharge[108)]. On the other hand, lithium-ion battery consists of flammable organic electrolytes, which might result in intense smoke, and even fire if the battery is overcharged or short-circuiting[109)]. Li-ion batteries fall under the category of rechargeable secondary batteries[110)]. The availability of lithium and minor metals in the earth's crust is less, lithium-ion batteries are believed to be very expensive for larger battery systems[111)]. Li-ion batteries have different types of next-generation batteries, such as metal/Sulfur, metal/air, and metal/oxygen, which are collectively called post-lithium-ion batteries[112)], safety is the main factor that restricts the development of large-scale li-ion batteries[113)].

3.1.4 Sodium sulfur and redox flow batteries

The sodium sulfur batteries show high theoretical energy density and energy capacity; these batteries should work at room temperature to keep the electrode materials in the molten state[114)]. Sodium sulfur batteries still need further research and development to get the most out of them[115)116)]. Redox flow battery is also a promising battery type for low-cost energy storage, vanadium redox flow batteries are the most common in the market, as they perform well[117)]. Redox flow batteries also have a longer life cycle than lithium batteries[118)]. The main difference between redox flow batteries from other types is the electrolyte storage system. The electrolytes are stored separately in a tank away from the battery[119)].

Apart from these types, manganese dioxide-based batteries have higher performance[120)], the author has also reviewed a number of ion-based batteries, some of which include magnesium ion batteries (MIB), sodium-ion batteries (SIB), and zinc ion batteries (ZIB). Considerable improvement should be made in the energy density of the current battery technologies to enable a fully electric aircraft [121)].

4. Alternate sustainable fuel

Biofuels are the alternate fuels which have shown immense interest in recent times. Although it is not relevant to the current topic of battery-powered aircraft, one of the purposes behind the paper is to discuss the ways of mitigating pollution associated with the aviation industry. The aviation industry uses petroleum-based kerosene, also called jet fuel. Various biofuels exist in the current scenario, such as biodiesel, biogas, and synthetic fuels. The alternate fuels considered should be able to be used in the current fuel systems, storage systems, and transferring process, in this case, the renewable and synthetic fuels are most suitable for the aviation industry. It has the advantage in terms of choice of feedstock, production processes, fuel properties meeting standards, safe storage, and easy transportation[122].

5. Evaluation of Battery-Powered Aircraft- An Overview of the Present Research Agenda

Takeoff, climb, glide, turn, and, most importantly, range and endurance should be evaluated properly for an aircraft during the preliminary design stage. Using a battery in an aircraft has led to multiple analysis techniques, and one major factor that restricts the approximate estimation of these parameters is the irregular degradation of the battery. There is little research shown in this area for battery-powered aircraft. Researchers assumed multiple conditions in the aim to predict the range and endurance parameters effectively, we reviewed all the current research in this area. The range can be technically defined as the total distance measured in the ground that is traveled by an aircraft with a particular amount of fuel, endurance is the total time an aircraft stays in the air for the same amount of fuel[123].

5.1 Performance Metrics as realized by other researchers across the globe

5.1.1 Range and endurance estimations

Maxim Kaptsov and Luis Rodrigues did an analytical study on estimating the maximum range and maximum endurance and the corresponding velocities[124]. The optimal range and endurance of a battery powered aircraft by considering the battery degradation is discussed by PAEK[19] by continuing the research work of Kaptsov[124]. This research considered the beginning life of the battery only, and during the end life of the battery, particularly the lithium-ion battery, will degrade faster than usual as compared with the battery when it has maximum charge. The author also evaluated different degradation scenarios which include linear, proportional to square root of time, and exponential. From19), the following equations give the maximum range, endurance, and their corresponding velocities for a cruise flight;

Maximum range and the velocity at maximum range:

$$R_{max} = \frac{Q_0 \eta U_{nom}}{2W\sqrt{C_{D.O}K}} \quad (1)$$

$$v_r = \sqrt{\frac{2W}{\rho S}\sqrt{\frac{K}{C_{D.0}}}} \quad (2)$$

Maximum endurance and the velocity at maximum endurance:

$$E_{max} = \frac{3^{3/4}\eta U_{nom} Q_0 \sqrt{\rho S}}{2^{5/2} C_{D.O}^{1/4} K^{3/4} W^{3/2}} \quad (3)$$

$$v_e = \sqrt{\frac{2W}{\rho S}\sqrt{\frac{K}{3C_{D.0}}}} \quad (4)$$

These two equations are derived in the aim to reduce the cost of operating, which the author states as the direct operating cost (DOC).

A notable work by [22], examined the range and endurance of an electric aircraft, considering Peukert's effect, which states that a battery will lose its efficiency when the discharge current is higher. To estimate performance parameters in a battery-powered aircraft, the losses due to propellers and motors to overcome the drag should be examined, and for which the battery behavior should be considered for the analysis.

The expression given by [22] are:

$$R_{max} = Rt^{1-n}\left(\frac{\eta_{tot} V \times C}{(1/\sqrt{\rho S}) C_{D.0}^{1/4} (2W\sqrt{K/3})^{3/2}}\right)^n \sqrt{\frac{2W}{\rho S}\sqrt{\frac{K}{C_{D.0}}}}.3.6\,km \quad (5)$$

$$E_{max} = Rt^{1-n}\left(\frac{\eta_{tot} V \times C}{(2/\sqrt{\rho S}) C_{D.0}^{1/4} (2W\sqrt{K/3})^{3/2}}\right)^n h \quad (6)$$

Here n, i.e., Peukert's exponent, it will change as the battery life and efficiency changes, and it generally ranges between 1 - 1.28 for a Li-ion battery[125].

The efficiency of the gas turbine engines will remain constant, whereas the efficiency of the battery will vary depending on the operating temperature, and 126) derived an expression for fixed-wing aircraft. The expression of range for vertical takeoff and landing (VTOL) type aerial vehicle is also given by 127).

$$R_{elec,fixed} = \eta_{drive} \frac{3.6\epsilon}{g} \frac{C_L}{C_D} \frac{W_{batt}}{W_{TKO}} \quad (7)$$

The range value obtained by equation (1) with the E Fan 1.0 data from124) is approximately equal to the range value obtained by equation (7) as verified by Kaptsov, and Rodrigues.

6. Challenges and Development

The US used electric aircraft during World War II, but unfortunately due to a lack of power storage, the development was closed. Electric aircraft has been under development since the 1980s, NASA Langley Research Center studied the benefits of electric aircraft in 1983. Hydraulic systems were replaced with electrical power during the 1990s, and other aircraft manufacturing companies are also developing electric aircraft, such as Airbus and Boeing[128]. Figure 3 shows the number of electric aircraft development programs from 2006 to 2030 (including future developments).

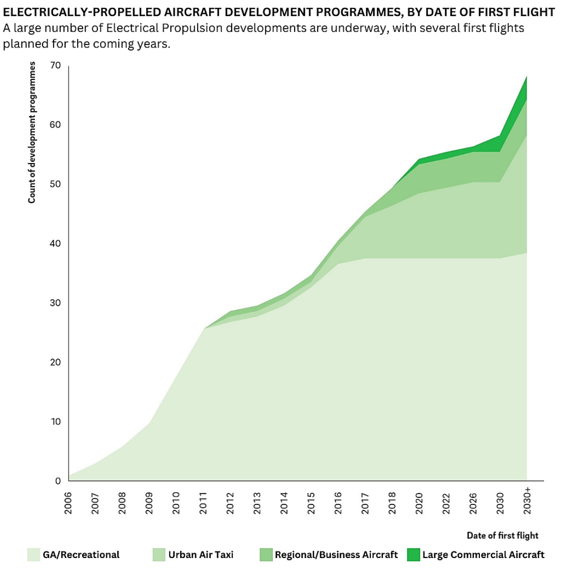

Fig 3: Electrically propelled aircraft development programs, by date of first flight[129].

6.1 Operational Challenges and Development

Apart from the challenges discussed in Section 2, other operational challenges come into the picture. Converting an aircraft powered by fuel to fully electric needs tremendous changes concerning architecture, electrical power for operation, and also improvements in power generation, distribution, and conversion. The current aircraft are mostly equipped with hydraulic and pneumatic systems, which require huge technology leap[74].

Battery powered aircraft technology can be less reliable in the starting stage, as it may lead to failure or due to other critical issues[130], some major operational challenges are discussed in table 3.

Table 3: List of Major operational challenges in an electric aircraft[131].

Major Systems	**Operational challenges**
1. Electronic power systems.	In all applications, power quality is very important, and operating the power electronics to deliver high-quality power is a challenging task in the electric aircraft scenario.
2. Main engine start.	Starting the main engine will be a hurdle in battery powered aircraft, as in electric aircraft, the electric, thermal, and magnetic starter will be a part of this subsystem, which should be properly analyzed.
3. Environmental control system.	The operational challenge in the environmental control system is the estimation of the required power for all phases of flight. An electric ECS is needed to be reliable and redundant.
4. Electrification of hydraulics systems.	A major challenge in the electrification of hydraulic systems is the potential of mechanical jamming of electromechanical actuators, which should be addressed as it will be used in critical components such as primary surfaces and the deployment mechanism of landing gears.
5.Charging infrastructure.	Currently, there is less development in the charging infrastructure specifically for electric aircraft, as the number of electric aircraft in use is little. To reduce the operational time, numerous charging stations needs to be built.

6.2 Battery-Powered Aircraft Sizing Challenges and Development

A crucial challenge for battery powered aircraft is deciding the fixed volume to accommodate the battery. The only benefit of fixed mass of battery is, the designer will be able to place the battery at any position in the

aircraft as there won't be any change in mass unlike in a combustion aircraft[132]. An environmental control system (ECS) is a system that keeps the cabin pressure and temperature in nominal condition, and sizing electric ECS is a challenging problem[133], and sizing of the thermal management system (TMS) is considered to be challenging, it needs careful design to keep the weight and drag minimum to avoid configuration issues. ESAero is particularly researching to develop TMS of electric aircraft[134]. There are 3 different types of electric propulsion design systems,
1) Distributed electric propulsion system,
2) Boundary layer ingested electric propulsion system and
3) Electric energy boost design,
and sizing the propulsion system is considerably challenging[135]. There are various literature sources available for the sizing procedures for internal combustion engine-type aircraft, but in the case of electric aircraft, the procedures are not widely researched and documented. Some documents in this area are done by[136] and[137] in which the authors have discussed the sizing procedures for light electric aircraft in detail.137)used the statistical regression of data from the existing models.

7. Summary

Throughout this review, various aspects of electric aircraft have been assessed, which pushed us towards a deeper insight into the sustainable electric aviation technology. The challenges, benefits, and performance metrics of electric aircraft are discussed. There is a need for the improvement of technologies, from various electronic components to the invention of new lightweight materials.

7.1 Technology Gap

Take Boeing 787 and Airbus A380 as an example, which have significantly larger electrical systems that ultimately lead to a larger technological development. In the present day scenario, electrical systems are used in actuation systems, wing ice protection, and ECS as well. Because of these new systems and technologies, it is possible to make quieter and high energy-efficient aircraft in the future26⁾. By considering all the studies, we can summarize the following major technology gap that needs to be advanced for deep electrification of aircraft, as presented in table 4.

Table 4: List of technology gaps hindering the process of introduction of electric aircraft[138].

Technology	Requirement
Battery	• High energy density battery. • Winding insulation at a higher altitude
Cables	• High energy efficient and low weight cables • Prevention of overvoltage problems during transmission.
Power converters	• Tracking and surface flashover prevention. • Thermoelectric stress management.
Superconducting equipment	• Feasible superconducting system. • Designing a superconducting system with increased operating lifetime.

7.2 Performance Assessment Study Gap

The energy stored within the weight limits in the current state-of-the-art battery is a fraction as compared to the energy of aviation fuel. The battery technology performance should be improved, followed by the battery management system and thermal management system to ensure safety and reliability. Other battery technologies apart from lithium-ion batteries should also be studied, which may result in development of better efficient batteries. The performance of power electronics, motors, and controllers is lagging behind, special focus should be given in this area to improve overall performance. As compared to ICE aircraft, the range, and endurance of current advanced electric aircraft are way less due to various reasons discussed above. No proper electric aircraft charging infrastructure facility is available, which also needs to be improved to reduce turnaround and operational time.

7.3 Safety, regulatory, and Certification Procedure

As in battery-powered aircraft, various components work with higher voltage and current, with this regard safety needs to be ensured. To ensure the safety of an aircraft, several analyses should be done in the starting phase of design. The aircraft must incorporate safety features or safety devices, warning or caution systems, use of placards, and protective equipment[139]. As the aviation industry is highly regulated, all aircraft need to be certified by regulatory bodies, such as the Federal Aviation Administration (FAA) and European Union Aviation Safety Agency (EASA). More than 200 projects of electric aircraft are going through the certification process, but the issue is there is a lack of resources, knowledge, and experience for this new type of aircraft as there is a gap from the existing standards and rules. Small electric aircraft capable of taking up to 19 passengers or a maximum mass of, 19000 lbs are certified through FAR Part 23. (American Society for Testing and Materials) ASTM 3264 is one such industry-based standard accepted by the FAA as a means of part 24 standard, and ASTM 3264 is being updated by the F44 committee, which enables the certification of an electric aircraft. ASTM 3264 will allow certifying an aircraft by a risk assessment, in which all the parameters are taken into account and differentiated by its severity, i.e., high, medium, or low severity. For certification purposes, the hazard is accepted only when it falls under low or medium severity[70)].

7.4 Future prospects:

If more electric aircraft are introduced in the upcoming years, electricity prices may go down in the distant future[140)]. Developing an electric aircraft needs vigorous research, modeling, and tests for various scenarios to ensure safety and reliability[141)]. Cryo-electrification of aircraft needs to be implemented in the current technology to introduce electric aircraft in the near future[142)]. Superconducting technology will be a game-changer for distributed propulsion systems in an electric aircraft, but the use of superconducting technology has not yet been discovered fully[89)], also research in composite materials, new cooling methodologies, and insulation materials with high thermal conductivity should be improved further to increase the efficiency of electric aircraft[143)].

8. Conclusion

As per the current scenario, battery powered aircraft with lesser passenger capacity are more likely to become viable, as compared with larger aircraft. Research and development of various electronic components are essential for electric aircraft development. Further, some major challenges should be addressed efficiently, among them the energy density of batteries is the prevailing challenge, and current battery technology needs to be improved. Lithium-ion batteries have the highest interest, and it does not offer sufficient energy density to power a large commercial size aircraft. Other battery technologies should be explored for the possibility of being used in an electric aircraft. The use of superconducting technologies will greatly move us forward in enabling battery powered aircraft to be more reliable and feasible, but the current technological advancements are less in this field.

Despite the efforts made in research and mathematical development to estimate the range and endurance of a battery-powered aircraft, it is still more challenging to accurately determine these parameters. As the battery is a volatile component, the efficiency of batteries won't be linear at all times, especially during when large current is drawn, i.e, during take off. The expressions mentioned in this literature are developed to give an accurate value to roughly estimate the range and endurance of an electric aircraft. The possibility of normalizing electric aircraft technology is only achievable when consistent research and development are done to reduce carbon footprint and promote sustainable development.

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Nomenclature

eVTOL	Electric Vertical Take-Off and Landing (–)
SCEPTOR	Scalable Convergent Electric Propulsion Technology and Operations Research Project (–)
MAVs	Micro Aerial Vehicles (–)
Li ion	Lithium ion (–)
LiNiCoAlO2	Lithium Nickel Cobalt Aluminum Oxide (–)
ARES	Airport Recharging Equipment Sizing (–)
UAVs	Urban Aerial Vehicles (–)
FARs	Federal Aviation Regulations (–)
FTA	Fault Tree Analysis (–)
HTS	High temperature Superconducting (–)
DOC	Direct Operating Cost (–)
ECS	Environmental Control System (–)
TMS	Thermal Management System (–)
TASOPT	Transport Aircraft System Optimization (–)
R_{max}	Maximum range (Km)
V_r	velocity at maximum range (m/s)
E_{max}	maximum endurance (h)
V_e	Velocity at maximum endurance (m/s)
U_{nom}	Nominal Voltage (V)
Q_o	Initial Charge (A)
S	Wing Area (m^2)

C_{DO}	Zero Lift Drag Coefficient (–)
R_t	Battery hour ratting (Ah)
V	Voltage (V)
C	battery capacity (Ah)
W	Weight (N)
K	Induced drag coefficient (–)
n	Peukert's exponent peukert exponent (–)
$R_{elec, fixed}$	Range of fixed wing aircraft (km)
CL/CD	Lift to drag ratio (–)
W_{batt}	Battery weight (Kg)
W_{TKO}	Aircraft Take off weight (Kg)

Greek symbols

ρ	density of Air (kg/m^3)
η	total System Efficiency (%)
$\in$	energy density of the battery (Wh/kg)
η_{tot}	total efficiency (%)
η_{drive}	Product of every drive-train component efficiency from the propeller to the battery (%)

Subscripts

tot	total
TKO	Take off weight
max	maximum
e	endurance
r	range
DO	zero lift drag
drive	drive
batt	battery
nom	nominal
o	initial
$Elec_{,fixed}$	Fixed wing electric aircraft

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