Electric Aviation: Development, Challenges, and Future Prospects

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Abstract. The escalating carbon emissions from machinery and transportation have intensified global warming and extreme weather events, driving a strong commitment to environmental protection. As a significant step towards reducing emissions, the adoption of electric vehicles over traditional fossil fuel-powered models is rapidly increasing. This shift has spurred many researchers to explore the electrification of aviation, a crucial and emerging mode of transportation. The focus has been on advancing battery technology and developing various configurations of electric aircraft. Although the widespread use of electric commercial airplanes remains a distant goal, several companies are on the brink of deploying light regional electric aircraft. This paper provides a comprehensive review of electric aviation, examining its environmental impacts and the technological challenges it faces, along with the demonstration of progress made by key industry players. This work also highlights the potential future directions for electric aviation as it moves closer to becoming a viable alternative to conventional aircraft.

Keywords: Carbon emission; electric aircraft; energy density; electric aviation.

1. Introduction

Recently, global warming has reached an unprecedented level, driven by carbon emissions from human activities. This rise has expanded the temperature difference between regions, contributing to more extreme weather and natural disasters. The carbon dioxide level has increased to be 50% higher than the pre-industrial level, methane more than two and a half times their pre-industrial level, and nitrous oxide 24% higher, respectively (Fig. 1) [1]. To mitigate the environmental deterioration, researchers have been focused on the adoption of renewable energy to replace traditional ones that emit greenhouse gases and other pollutants. One of the most popular adoptions of renewable energy products nowadays is electric vehicles, with production rates rising sharply in recent years (Fig. 2). The recent prevalence of electric vehicles encourages researchers to look at the electrification of another important means of transportation: electric aircraft. Traditional aviation accounts for 2.5 percent of global carbon emissions in total, and data from a paper by David Lee and colleagues shows that emissions have quadrupled since the mid-1960s [2]. This increasing trend will continue, given that the boost in aviation demand significantly surpasses the improvement of energy efficiency [3]. Notably, 2/3 of the pollutants released by conventional airplanes are non-carbon particles, such as nitric oxide, which can form acid rain with sulfur dioxide, contrails, which may potentially intensify global warming [4], and so on. Electric aviation offers a potential solution to these issues since electricity is renewable energy that does not produce carbon dioxide and other harmful pollutants.

Furthermore, electric aircraft have the economic benefit that companies can reduce airline operating and maintenance costs. However, the main technological difficulty remains battery technology, especially for aircraft which require higher specific energy than electric vehicles to sustain long distance traveling and whose working environment includes low temperature and low pressure that impedes batteries’ efficiency. Nowadays, several companies have already taken part in fulfilling electric aviation used for different covering lengths and purposes, such as Pipistrel, Boeing, Bye-Aerospace, Ampaire, Lillium, Wright/EasyJet and so forth, but only light electric airplanes have come to reality.

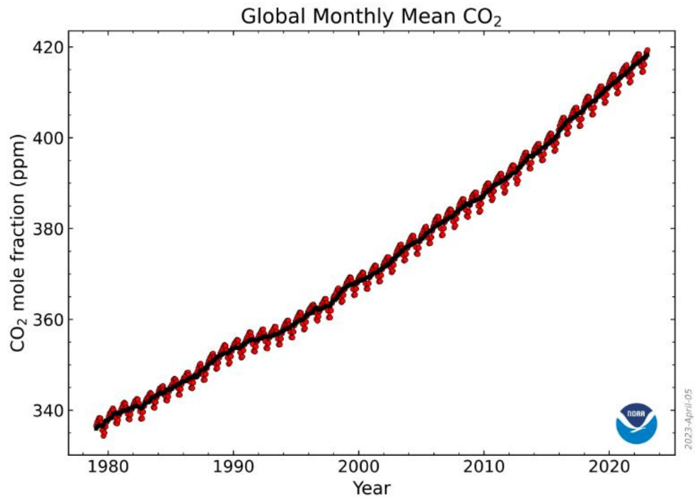

Fig. 1 Global monthly average levels of carbon dioxide measured at marine surface sites, compiled by NOAA's Global Monitoring Division, reproduced from the website: https://www.gml.noaa.gov/ccgg/trends/

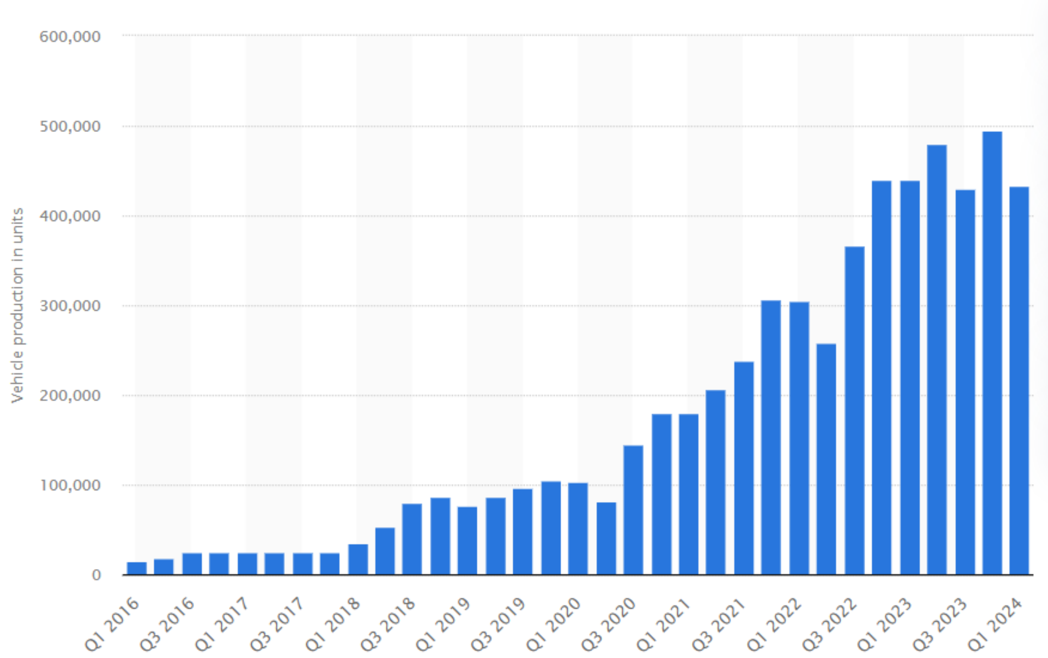

Fig. 2 Tesla Inc.'s quarterly vehicle production volume, showing a decrease of 12.4% quarter-on-quarter and 1.7% year-on-year in Q1 2024, with a total production of approximately 433,400 units, reproduced from the website: www.statista.com/statistics/715421/tesla-quarterly-vehicle-production/

2. Key Challenges

One of the main challenges for electric aviation is the battery technology, characterized by energy density. Due to the strict weight limitations and huge power requirements for takeoff, cruising, and landing in electric aviation, NASA has established a minimum energy density threshold of 400 Wh/kg for general aviation and 750 Wh/kg for commercial regional aircraft, considering the battery weight. However, the state-of-the-art Li-ion battery (LIB) only possesses an energy density of around 200 Wh/kg in reality and a theoretical maximum energy density of 300 Wh/kg, making it incapable of supporting big commercial electric aircraft [5]. Even though some batteries show prospects for application of electric aviation, as illustrated in Table 1, people can note that many of these batteries cannot meet the threshold made by NASA, with their energy density lower than 400 Wh/kg. While the Li-S battery in Table 1 reaches an energy density of 400-600 Wh/kg, it has a significantly shorter cycle life than other batteries whose energy densities are lower. Further advancements in battery technology are necessary for the realization of electrifying middle or large airplanes.

Table 1. Different types of batteries and their properties

Battery Type	Energy Density (Wh/kg)	Cycle Life	Weight	Advantages	Disadvantages
Lithium-ion (Li-ion)	150-250	500-1500 cycles	Moderate	High energy density, widely used, established technology	Risk of thermal runaway, heavy metals
Lithium Polymer (LiPo)	100-250	300-600 cycles	Light	Lightweight, flexible shapes, high power output	Shorter cycle life, risk of swelling
Solid State Battery	300-500	1000+ cycles	Moderate	Higher energy density, improved safety	Expensive, still in the development phase
Lithium Sulfur (Li-S)	400-600	300-500 cycles	Light	High theoretical energy density	Short cycle life, still in development
Zinc Air	300-400	1000+ cycles	Heavier	High energy density, eco-friendly	Limited rechargeability, lower power density

For different sizes of aircrafts, there are different specific energy requirements. A recent study shows that rechargeable batteries with specific energy ranging from 300 to 400 Wh/kg are needed to fulfill the energy needs of a standard 100-mile commercial flight. The estimated battery pack-specific energy requirements for longer-range hybrid-electric regional and narrow-body class aircraft are projected to be between 600 and over 800 Wh/kg, respectively. Considering battery packaging, electrical performance, environmental, and safety considerations, scaling analysis suggests that lithium-ion cell-specific energies greater than 500 to 600 Wh/kg would be necessary to meet the anticipated LIB level-specific energy demands [6]. Considering the technological obstacles, now only some small electric aircraft can fly within a short amount of time and carry a limited number of people.

The special environment of lower temperature and lower pressure during the flight adds further challenges for battery technology. The typical cruising altitude for a commercial airliner range from 30000 to 40000 ft, where the minimum external pressure is approximately 20 kPa. In contrast, an urban area electric aircraft capable of vertical takeoff and landing cruises at altitudes between 1000 and 10000 ft, with a minimum external pressure of about 70 kPa. It has been noted that the reduced pressure and temperature can impact the thermal runaway (TR) characteristics of LIBs [7,8]. Another factor that contributes to the battery safety problem is the growth of dendrite. Dendrites' formation begins as soon as the battery's cycling starts. The dendrites can keep growing after some charge and discharge cycles, reducing coulombic efficiency and lifespan and increasing capacity decay in the battery. More severely, the dendrites can cause short circuits between the anode and cathode, leading to fire and explosion [9]. A trend is made studying the growth behavior of lithium dendrite in solid-state electrolytes: the lower the temperature and pressure, the more growth of dendrite such condition can sustain (Fig. 3), therefore increasing the risk of battery malfunction and short circuit [10]. As a result, the battery safety problems become more intractable for electric aviation than other usage of battery because of its demanding need for high specific energy and its more extreme environment at high altitude.

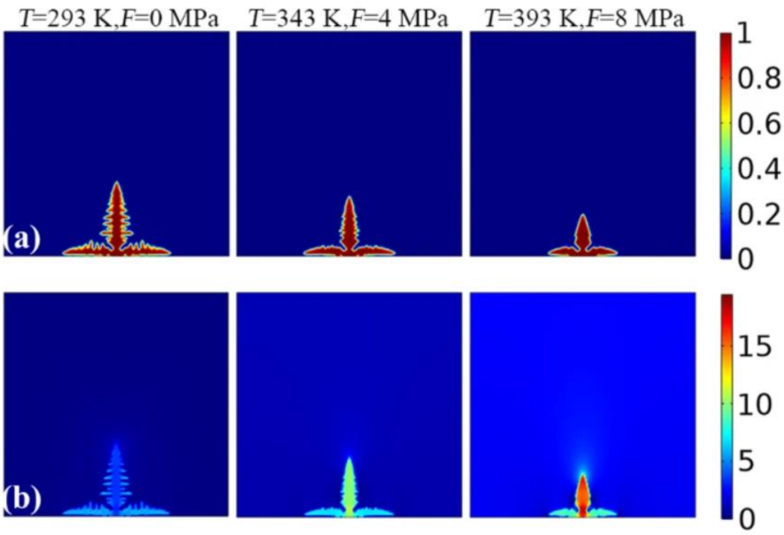

Fig. 3 Simulation results under different temperatures and different external pressures: a) phase field parameters, b) von Mises stress (MPa) [9].

3. Some Practices in Electric Aircraft

Even though it seems far for large all-electric planes to become a reality in the short term, some small planes did succeed and take off. In 2014, Pipistrel sent their first electric two-seated plane (Fig. 4), Alpha Electro into the air for the need of flight schools. It has a powerful 1000+ fpm capacity and a duration time of 1 h, and it has the power of 50 kW at 2200 rpm. This technology has cut the cost of pilot training by around 70% and reduced noise and carbon emissions.

Fig. 4 An Alpha Electro, reproduced from the website: http://wattsup.pipistrel.si/aircraft/

In 2022, the all-electric aircraft “Alice” from Eviation, founded by Israeli, successfully launched for a test flight, flying for 8 minutes at an altitude of 3500 feet [11]. Alice has seats for two crew members and seven passengers, and it has a battery that weighs around 3700 kg, provides 900 kW/h, and can be charged fully within 30 min. Eviation aims for regional flights ranging from 150 to 250 miles and hopes to deliver aircraft to customers by 2027.

Elysian is planning to launch the E9X jet (Fig. 5) by 2033, which will be equipped with a battery pack that has an energy density of 360 Wh/kg. This aircraft is designed to carry up to 90 passengers and can travel distances of up to 800 km. With its battery pack providing 360 Wh/kg, it is expected that the E9X will be able to cover routes of up to 800 km. Electric aviation has the potential to reduce 20% of all aviation CO_2 emissions. Eight propeller engines will power the E9X, and have a wingspan of almost 42 m.

Fig. 5 E9X jet. From Elysian, reproduced from the website: https://www.elysianaircraft.com/e9x

According to Lilium's official description, Lilium jets utilize only 10% of the available power during the longest phase of regional trips, which is the cruise phase. High-density batteries complement this level of efficiency at 330 Wh/kg. A typical charging session takes approximately 45 minutes. Once fully charged, the jet is capable of handling long-range missions at a cruising speed of 248 km/h and can achieve a maximum operational range of up to 175 km. The Lilium jet has a capacity for 6 passengers.

Many other companies strive to build electric aircraft and put them into practice as soon as possible, such as Ampaire, MagniX, Beta Technology, and Boeing, many of whom have already prepared for the test flight and the certification of their state-of-the-art airplanes.

4. Conclusion

This paper provides an overall review of the aviation industry, discussing the importance of building electric aircraft due to its environmental significance, the challenges this industry faces, such as battery technology, and some progress made by companies that concentrate on this industry. Readers can gain a notion of the development, challenges and prospects of electric aviation quickly from this paper. Recently, carbon emissions have escalated noticeably, sharpening the environmental issues. For the sake of alleviating the climate disturbance contributed by the aviation industry, researchers and companies have begun to explore the electrification of aircraft. Unlike other industries that are featured with electric power sources, such as the electric vehicle industry, electrifying aircraft poses more difficulties, mainly because of its stringent limitation on weight that makes the energy density of batteries extremely important.

To date, further advancements in battery technology are required to support middle and large commercial airplanes that need batteries of higher energy density and life cycle to support longer-distance traveling. Several companies have already produced light regional airplanes of up to 2-9 seats with a duration of flight for 1 hour or so. Society will continue to emphasize the environmental-friendly transformation in the following year, and since the demand for aviation is growing, people are quite likely to keep studying and exploring the electrification of airplanes. Many companies have already planned to set their test plan in the following years. This paper, however, is limited in its level of detail and coverage of all possible scenarios. For instance, it does not address challenges beyond battery technology, such as aircraft configuration and materials, which also require further study and investigation.

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