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Promising electric aviation industry and its bright future

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Abstract. There have been rising concerns about the amount of greenhouse gas emissions that commercial aviation produces each year. Greenhouse gases generated by aircraft trap the sunlight in the ozone layer, causing the planet's temperature to rise yearly. Thus, developing more electric aircraft (MEA) and all-electric aircraft (AEA) is crucial to serve as alternatives to traditional fossil-fuel airplanes to avert climate change. Although electric aircraft theoretically provide numerous benefits in improving efficiency, reducing noise levels, and cutting emissions, numerous challenges exist, such as energy density, cost, and power distribution. This paper aims to analyze these challenges and looks for potential technologies or systems, including electromechanical actuators, high energy-density lithium batteries, and superconducting motors, to resolve these challenges. Overall, the electric aviation industry is promising with further improved new technologies. While MEA will become common shortly, there will still be at least two to three decades before AEA establishes ground and become prevalent in the commercial aviation industry.

Keywords: electric aircraft, emission, battery, electric motor, airframe.

1. Introduction

When traveling around 800 to 1000 km/h, the airplane is the safest and most reliable vehicle globally [1]. Nevertheless, as a consequence, tons of emissions are produced each year since the aircraft's engines require fuel to create thrust to operate. Commercial aircraft emissions comprise 2.4% of all CO_2 emissions worldwide [2]. As air travel becomes more prevalent since more people are able to afford to travel by plane, it is estimated that overall global greenhouse gas emissions as a result of the aviation industry will multiply by a factor of 2-4 in 2050 compared to the 2015 level [3]. To avert the climate change issue caused by greenhouse gas emissions, researchers and engineers have switched to a new direction of commercial aircraft powered by electricity, promising numerous advantages. Electric batteries are more efficient than fuel-generated turbines, allowing minimum energy loss during flight performance. In addition, aircraft turbines run by electricity exclude the need for internal combustion, significantly reducing the noise.

Most importantly, since an aircraft's engine is powered by electricity instead of burning fuel, little or no emissions will be produced. These aircraft are still not prevalent in society due to numerous challenges. Thus, this article drives a deep dive into electric aircraft's current issues and challenges and potential solutions to overcome these challenges. Various electric aircraft prototypes and designs have emerged involving the Alice passenger plane, Airbus A3 Vahana, and Alef Aeronautics Model A [4-6]. While these planes may only accommodate a few passengers and have short flight times, the most

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promising, Wright 1, 186-seat commercial electric passenger jet, is targeted to enter service around 2030 [7]. In the future, it is perfect to say that electric-powered aircraft will become more popular in the aviation industry as researchers and engineers make more breakthroughs by inventing different technologies and systems.

2. Superiorities of electric aircraft

Electric aviation provides common society with multiple benefits and advantages. For one thing, it enhances total efficiency which makes flying an airplane much cheaper allowing more people to afford to travel by plane. For another, electric aviation is projected to solve one of the most detrimental problems of aircraft: noise levels. Lastly, it provides a major solution to the long-lasting effects of climate change by cutting emissions.

2.1. Improving efficiency

First of all, compared with traditional gas turbines, which operate on average with an efficiency of 33%, the energy efficiency of lithium-ion batteries (LIBs) to power an electrical motor is on the average of 90-95% [8]. This means that electric aircraft are able to complete their flight with less energy input since the battery remains capable of converting most of that electric energy to useful work like providing thrust for the turbines. To extend it further, the rise in efficiency also contributes to other gains. The efficiency boost by implementing electric batteries contributes to less energy usage and reduces cost and emissions.

2.2. Cutting noise levels

Furthermore, electric aircraft are promised to cut noise levels, which proves to be one of the most damaging effects of aviation. People constantly exposed to that noise may experience sleep deprivation and even increase the risk for cardiovascular diseases [9]. Therefore, researchers and scientists have recorded the potential data on how much can an electric aircraft reduce noise levels by examining a Canadian Beaver short-range propeller plane made in the 1940s [9]. Surprisingly, the electric Beaver aircraft reduced its noise level to an extent between 16-22 dBA throughout the flight time [9]. Especially during the cruise phase, the noise difference between traditional Beaver jet and electric Beaver plane reached a maximum of 21.7 dBA [9]. This marked a total of 27% decrease in noise level. The case study of Beaver jet may not apply to all specific commercial aircraft; however, it demonstrates the big picture that electric aviation vehicles can tackle the problem of high noise levels. Reducing the adverse effects of noise by developing electric aircraft benefits the health and safety of the passengers and the health and safety of cabin crews, pilots, and people living near the airports.

2.3. Reducing emissions

Most importantly, electric aircraft operate in a much cleaner way that aims to reduce carbon emissions. As is well known, greenhouse gas emissions deeply threaten society’s health and the environment. They are the gases that contribute to the rise of global warming as they trap sunlight in the Earth’s ozone layer. Offering a potential solution, electric aircraft using electric propulsion and systems are estimated to decrease CO_2 emissions by 49-88% compared to traditional fossil fuel aircraft [10]. For example, when compared to a conventional aircraft taxing system, the usage of an Electric Green Taxiing System (EGTS), which uses electricity to power aircraft during taxiing, may lower CO_2 emissions by 61%, NOx emissions by 51%, unburned HC by 62%, and CO emissions by 73% [11]. Although the case study doesn’t potentially represent all the phases of an aircraft’s pathway, the data given above shows a clear idea that using electric operating systems on aircraft, even just in the taxing phase, may reduce emissions by a significant amount. As a result of the current limits of the number of electric aircraft available, a full test comparison between the traditional aircraft and the electric aircraft at different phases is virtually impossible. Yet, it is undeniable that electric aircraft with high efficiency and cleaner operations systems are capable of averting the negative consequences of climate change by cutting emissions.

3. Technologies to implement in the electrical aviation industry

To develop a fully-functional electrical aviation, its components or parts must be considered heavily.

3.1. Battery technology

First, battery technology is the most significant as it stores the electric energy to power the engine, control system, and gear system. The average lithium-ion batteries are capable of storing energy from 100 Wh/kg to 265 Wh/kg (0.36 MJ/kg to 0.95 MJ/kg) [12]. However, to make electric planes take off to the sky and perform long-distance flights, lithium batteries' energy density must increase to at least 500Wh/kg (1.8MJ/kg) [13]. The battery company Amprius has just developed lithium battery packs with high performance of 500 Wh/kg or 1300 Wh/L at 25 degrees Celsius [14]. What's more, these batteries operating with maximum discharge rates are able to provide 200% run time compared to graphite cells under ½ the wright [14]. Future electric automobiles and the aircraft industry will likely adopt these new-generation cells by 2025. These leave big promises and developments for the future of electric batteries.

3.2. Electric motor technology

The second crucial technology is the electric motor. This device receives electric input from the battery to generate a strong electromagnet. This strong electromagnet then interacts with the stator (North & South), which causes a spinning motion. This mechanism converts electrical power into mechanical power to provide thrust to run the electric aircraft. As many jet engines still use the process of internal combustion to run, electric motors inside current aircraft are limited to generating electricity for avionics systems, lighting, and in-flight entertainment. Thus, their specific power output (1-5 kW/kg) is significantly lower than gas turbines [15]. To increase the specific power of electric motors to be comparable with jet engines, researchers and engineers have proposed adding high-temperature superconducting materials to an electric motor. The solution and processes are quite simple. The ohmic resistance can be decreased by superconductivity at specific low temperatures, increasing the magnitude of the armature's electric field [15]. This increases the frequency interaction between the rotor and the armature, boosting the spinning motion performance [15]. Thus, the specific power output will likely rise around 10 kW/kg, comparable to a traditional internal combustion gas turbine [15]. Further details will be discussed in Section 5.

3.3. Airframe technology

As there has been rising interest in electric aircraft over the years due to the prevalence of electric vehicles, many researchers and scientists have investigated the most suitable airframe design technology for the electric aviation industry to achieve maximum efficiency and flight times. The airframe technology currently splits toward two main concepts: distributed propulsion system (DPS) and boundary layer ingestion (BLI) [15]. The DPS acquires many small electric motors on the edge of the wing to provide the thrust instead of using two large engines like in traditional planes [15]. This configuration successfully brings in more airflow through a smaller surface, causing the lift force to rise significantly by boosting air circulation and air-dynamic pressure [15]. In this way, downstream airflow is cut down, increasing propeller efficiency and decreasing drag [15]. An analysis of the X-57 aircraft prototype with distributed electric propulsion airframe technology shows that it can cut the engine's needed power by 20% [16]. This not only allows improvement in efficiency but also better thrust generation and flight control of the whole aircraft.

Similar findings come from NASA-funded research of the prototype Liebeck with a turboelectric propulsion system, which shows 27% less fuel burned, 15% less take-off weight, 12% less empty weight, and 27% more total thrust [17]. The second type of airframe utilizes the BLI concept. The engines are placed on the top back of the aircraft's fuselage, absorbing part of the slower boundary layer air. Hence, the engines reach higher efficiency as they ingest part of the drag, meaning they do less work. Nowadays, The E-thrust jet is a prototype that combines both of these ideas. It has a single-turbine engine at the back of the fuselage that powers a generator to charge a battery pack on board and six electric motors that drive propellers along the trailing edge of the wings [16]. This configuration offers the advantage of enhancing efficiency through increasing lift and decreasing drag.

4. Key requirements and challenges of developing electric systems in aircraft

4.1. Energy density

Despite the various technologies above to facilitate electric aircraft development, there are many challenges for scientists to overcome in the future. One major problem is the lithium batteries' low energy density. Although lithium batteries have high efficiency in converting electric power to work output, the most advanced energy density is around 0.9 MJ/kg compared to jet fuels such as JP-8 and Jet A-1, with an energy density of 43 MJ/kg [18,19]. In other words, 50 kilograms of batteries must be installed on the aircraft to deliver the same energy as 1 kilogram of jet fuel. The A320-200 civil medium aircraft carrying 150 passengers has an open empty weight of 42,100kg [20]. Its maximum take-off weight is 78,000 kg and uses the Jet-A1 fuel of density 0.8 kg/L [20,21]. Entering all the calculations, its maximum payload for passengers, crew, and cargo is 16,600 kg, leaving 12,472 kg for fuel. The aircraft stores about 536,296 MJ of input fuel energy to fly to another destination. Accounting for an efficiency of 33% for traditional turbines, 176,977 MJ of work energy is produced to generate the thrust required.

Lithium batteries with a high efficiency of 90% will need 196,642 MJ of electric energy input to operate the plane successfully. However, accounting for 0.9 MJ/kg low energy density, 218,490 kg of weight needed to be occupied for electric energy storage, which exceeds the fuel or weight capacity by 206,018 kg. This overtakes the fuel tank of traditional jets by 17 times. Energy storage for current batteries becomes a big challenge as they increase the weight that prevents huge electric aircraft from taking off. Even if aircraft are able to successfully take off, their flight performances are limited to the amount of time they can travel before the batteries run out of energy. Along these lines, more research should be done on enhancing the energy density of these advanced lithium batteries.

4.2. Cost

Additionally, another significant challenge is cost. The main costs associated with electric civil aircraft are batteries, maintenance, and infrastructure. Provided that the average cost of today's lithium-ion batteries is $150 /kWh, Figure 1 shows the break-even electricity prices with battery-specific energy and battery cost compared to jet fuels in an A320/B737 aircraft [22]. This represents that the only economically competitive configuration is the $100 /kWh battery with a specific 800 kWh/kg energy density. Hence, jet A1 fuel is still more economically competitive and viable for most scenarios than electric batteries.

Nonetheless, the price of electric LIBs can decline in the future due to the rise of specific power they produce, which may increase their economic effectiveness. Another cost factor is maintenance. Since batteries have a limited lifetime due to their charge and discharge rates, they must be replaced within roughly 1000 cycles. The maintenance cost for an internal combustion jet A320neo is about $960 /flight hour [23]. On the contrary, the maintenance cost for AEA is estimated to be $1170 /flight hour with battery-specific energy of 1200 kWh/kg and cost of $100/kWh and $1500 /flight hour with battery-specific energy of 800 kWh/kg with a cost of $200 /kWh [23]. The data shows that electric aircraft's maintenance cost is significantly higher than traditional aircraft. There are two reasons for this result. First, LIBs have potential safety hazards that make them flammable easily. Secondly, lithium batteries have short life cycles that make them operate less efficiently in range after some time. So, they are more likely to be required to be maintained more often and possibly be replaced after a few years. Finally, since electric aircraft use electricity to fly, they need more charging stations infrastructures in the airport. While most aircraft typically run on fuel, many current airports lack the necessary charging station infrastructures to widely adopt all-electric aircraft. While the typical charging EV stations cost around $700 - $1800, implementing electric infrastructure in the airport may be much higher [24]. This is one economic barrier before the wide adoption of electric aircraft in the commercial aviation industry.

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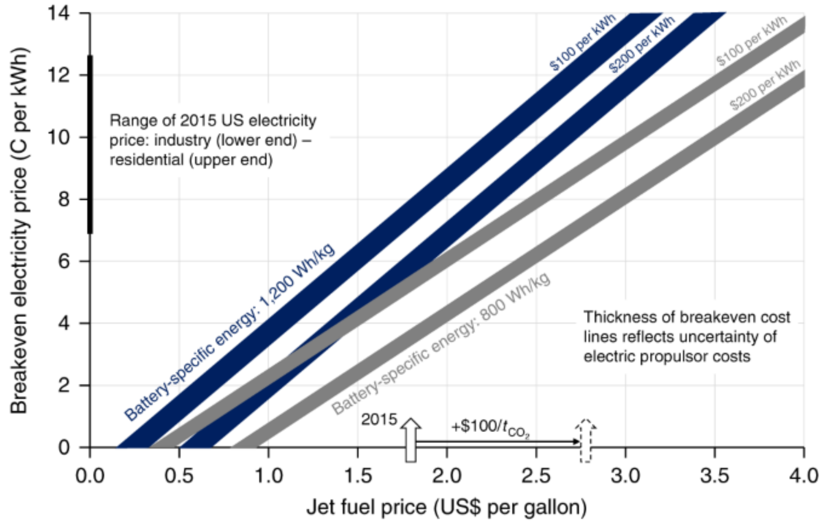

Figure 1. Break-even electricity price for a first-generation all-electric aircraft [23].

4.3. Power distribution

At last, power distribution is another issue faced in developing MEA and AEA. As more engineers and scientists try to replace hydraulic, pneumatic, and mechanical systems with electric systems to increase efficiency and reduce maintenance, the demands for electric power generation are likely to boost by a huge amount [25]. Electric generators with higher power outputs are vital as electrical power actuators demand transient power quickly [25]. However, this is extremely likely to make the electric system heavier and more expensive for power distribution [25]. This is because higher power output requires more power input, and a small increase in energy storage directly increases the weight of the battery. Moreover, the increasing frequency of high-power output may lead to safety issues like overheating for the batteries [25]. This is why efficient and lightweight stable electronics are crucial for maintaining high efficiency and stability for power distribution. In the meantime, the B787, the first commercial more-electric aircraft, has successfully implemented a safe lithium battery power system [25]. Its electric generators are able to replace traditional pneumatic, mechanical, and hydraulic systems.

5. Current systems to move toward an MEA or AEA

5.1. LIBs

The battery system is essential for MEA or AEA to function safely and reliably. The lithium-ion battery, nickel cd battery, and lead acid battery are the options for powering the MEA aircraft X. Several criteria for the battery involve consistent power output, lightweight, and long lifetime. Table 1 compares each battery's chemistries, such as nominal cell voltage, battery cost, energy density, cycle life, operating temperature…etc. With 135 Wh/kg, general LIBs have the maximum specific energy density compared with others of 65 and 40 Wh/kg. Likewise, the volumetric energy density of three batteries is 70, 105 and 200 Wh/L. Since the Li-ion battery is the largest, it carries the most energy under the same size, making them lighter than the others. In addition, the specific power of these types of electric generators is 450, 1000 and 2000 W/kg, as shown in the graph of Figure 2. Similarly, lithium batteries have the highest power densities, suggesting they can deliver the most energy or power output for the engine to create thrust quickly.

The advantages of lithium batteries give rise to tremendous opportunities for developing MEA. Adopting a lithium battery system will reduce aircraft weight and reduce costs. Li-ion battery systems reduce weight by 154.5 kg, saving US$96,780 per aircraft [26]. Lithium battery technology, accompanied by an effective battery management system, performs in many beneficial ways, such as increasing energy storage and providing high power output. They are the power sources not only for the engines but also for the flight systems and control systems. Due to their superior qualities and attributes, LIBs will gradually replace Ni-Cd batteries in commercial aircraft in the near future.

Table 1. Summary of diverse battery chemistries [26].

Serial no.	Criteria	Li-ion	Ni-Cd	Pb-acid
1	Nominal cell voltage, V	3.20	1.20	2.00
2	Typical battery cost in US$, V, Ah, Wh	207(12, 21, 252)	100(12, 20, 240)	67(12, 20, 240)
3	Cost per Wh in US$	0.82	0.42	0.28
4	Cycle life(no.)	3000	1500	250
5	Cost per cycle in US$	0.069	0.067	0.268
6	Cost per Wh per cycle in US4	0.00027	0.00028	0.00112
7	Specific energy density, Wh/kg	135	65	40
8	Operating temperature, Celsius	-20 to 60	-30 to 60	-20 to 60
9	Self-discharge/month	2-3%	4-6%	15-20%
10	Overcharge tolerance	very low	moderate	high
11	maintenance	Not required	1-2 months	3-6 months

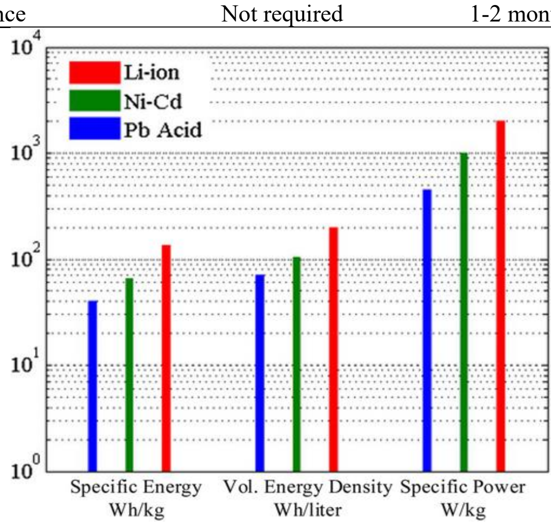

Figure 2. Performance evaluation of Li-ion, Ni–Cd and Pb-acid batteries [26].

5.2. Mechanical electrical actuator

The electric actuator system is another important advancement to move toward more electric aircraft. Actuators manipulate flight controller or regulator systems like the elevator, rudder, flaps, and landing gears [27]. Conventional actuators are mostly powered by hydraulics systems which may contain several disadvantages, including high maintenance cost and less temperature tolerance [27]. This is why researchers have shifted their direction to developing electric actuator systems. Electric actuators bring numerous advantages by enhancing reliability and safety due to the lack of flammable fluids and structures [27].

Moreover, the aircraft's weight and volume are saved without a complex transmission system [27]. Nowadays, two electric actuators stand out, namely electro-hydrostatic actuator (EHA) and electromechanics actuator (EMA) [27]. The EHA uses the hydrohalic pump and the cylinder to drive certain mechanisms, while the EMA adopts a gearbox to control the driven load, as shown in Figure 3. A study comprehensively tests the EHA and EMA by examining three parameters: the performance at room temperature, vacuum environment, and iron bird [27]. The results indicate EMA system has higher reliability and lower maintenance cost than the EHA system [27]. While the EMA system is likely to become the new generation actuator system, its performance can be improved when integrated with other mechanisms. For instance, implementing the fault-tolerant servo motor and the mechanical transmission structure allows the EMA to perform at its best with the combination of the hybrid actuator configuration [27]. Research improvement areas are still directed toward jamming-free systems and condition-monitoring testing mechanisms [27]. However, success in certain tests still does not make it mature enough; the most realistic approach would be to combine the EMA and hydraulic actuator system (HAS). Nevertheless, the arrival of the EMA system in controlling horizontal stabilizers and thrust reverser is a huge step toward developing more electric and all-electric aircraft [27].

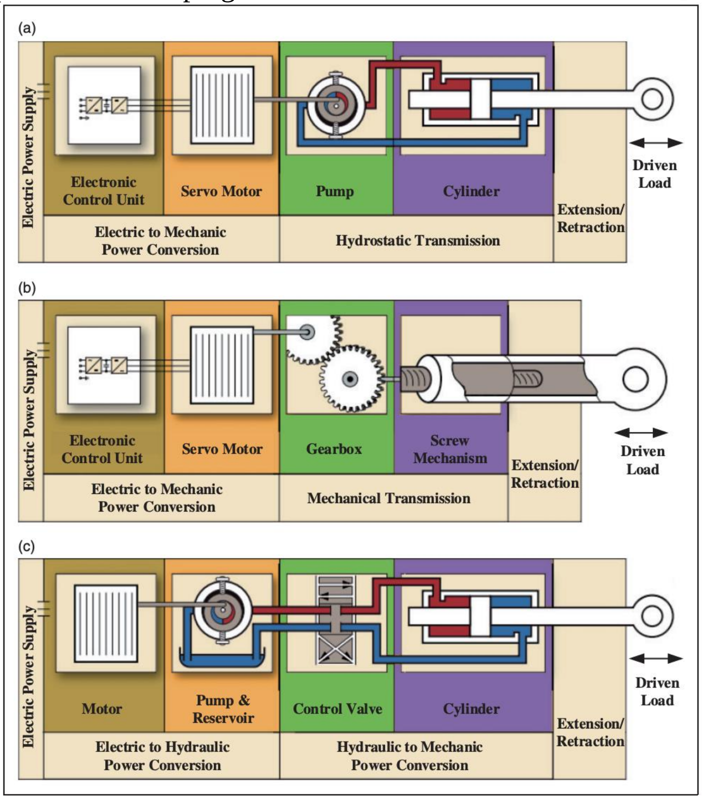

Figure 3. Power-by-wire actuators and HAS composition. (a) EHA, (b) EMA, and (c) HSA [27].

5.3. Superconducting motors

The superconducting motor applies the concept of superconductivity, which successfully reduces the ohmic resistance in spinning motion. To set it up, superconductive coils are located to replace the previous stator and rooting windings, as shown in Figure 4. This boosts the armature's electric field, which drives the interactions or force between the magnets and the armature [15]. Based on this mechanism, angular momentum can increase, allowing the motor to spin much quicker. For example, a group of researchers demonstrates that the superconductive coil on aerospace applications allows an increase in specific power of up to 10kW/kg, equal to a traditional aircraft's internal combustion engine [28]. Likewise, a study concluded that implementing superconductive materials in aviation will likely cause the specific power to rise to 40kW/kg at 99% efficiency [29]. However, the study does mention that it would take at least 20-25 years before the first superconductive motor is assembled and built [29]. Superconducting motors may sound like a promising technology, but its disadvantage must also be considered. Given the fact that they operate at high temperatures, the safety issues of implementing them must also be considered. These require more heat-resistant materials like composite matrix ceramics and possibly a strong cooling system that may add to the weight of the motor. The superconducting motor promises high specific power output to generate thrust for the electric aircraft. In contrast, it would take decades for the first superconducting motors to come. Its technology and applications are promising for the electric aviation industry.

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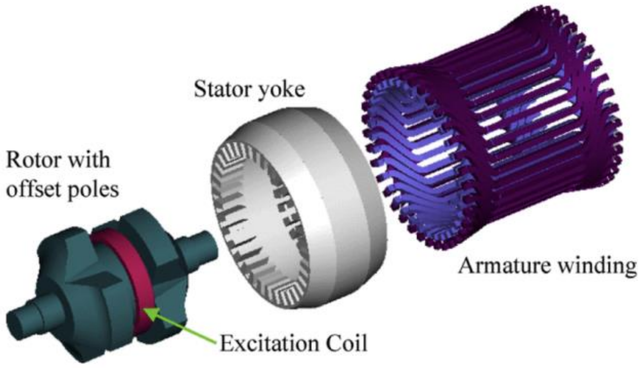

Figure 4. Structural scheme of HTS motor [15].

6. Conclusion

In 2022, Alice's first fully electric passenger plane had just completed its first flight. Lasting roughly 8 minutes in the sky, this plane carries 9 passengers with 2 aircrews. Its significant advantages lie in the fact that they are cost-efficient due to the exclusion of mechanical and hydraulic systems, and they can reduce emissions fully by 100%. Hence, more time and research are needed for engineers to develop fully electric aircraft to travel longer paths. Alice's first successful test flight did prove the capability of electric aircraft. Going back, the electric aircraft creates numerous benefits of reducing emissions and improving efficiency. While AEA may not be running soon, modern airplanes, including B787 and A350, have already adopted more electric systems in flight control actuation, landing gear control, icing protection, and inflight entertainment. The concepts of more electric and all-electric aircraft are more promising industries that will come faster. Currently, the main challenges that prevent large-scale electric aircraft from entering existence are low energy density and power distribution. There are various directions that researchers could investigate, for example, LIBs, superconducting motors, and electric mechanical actuators. Hence, more research efforts should be dedicated to improving the battery, electric motor, and airframe technology, like boosting efficiency and power output and driving lift dynamics to enhance electric aircraft's capabilities, performances, and viabilities.

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