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Electrification of Aviation: Environmental Impacts, Limitations, and Performance

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ABSTRACT: The aviation sector continues to use unsustainable fuels, which significantly impact CO_2 emissions at a rate considered unhealthy for our planet. Solutions towards a greener society, such as the electrification of aviation, have been widely discussed in recent years, yet no significant action has been taken. The main objective of this paper is to discuss the electrification of aviation, including the environmental impacts, limitations, and performance. Within this paper, the literature was compared in terms of its publication date from 2018 to 2025. In the aviation sector, the main and current strategies to electrify aircraft, challenges with long-distance flights, the environmental impact from a life-cycle perspective, performance of different types of batteries, and the energy efficiency of electric aircraft compared to fuel-powered aircraft will be discussed. The impacts, limitations, and performance in electrifying aircraft are important, as current progress can be compared with future projections to achieve the electrification of aviation to a commercial level.

KEYWORDS: Aviation, Aircraft Propulsion, Aviation Electrification, Electric Aircraft, Energy-Efficient Batteries.

Introduction

Aviation currently accounts for around 2% of total CO_2 emissions globally, as shown in Figure 1; however, this is expected to increase significantly as the population grows and global air traffic demand increases.[1] In recent years, the aviation industry has faced increasing pressure to reduce its environmental impact, as outlined in Flightpath 2050, which targets a 75% reduction in CO_2 emissions per passenger kilometre and a 90% reduction in NO_x emissions relative to the technology level of 2000.[2] A promising solution to this involves electrifying aircraft with electric or hybrid-electric configurations, which has become significant in mitigating greenhouse gas emissions, bringing advantages regarding mass, impact, fuel consumption etc.[3] This paper reviews the field of electrifying aviation with a focus on its impacts, limitations, challenges and performance aspects, and concludes with an evaluation of how early electrification can be achieved. The discussion begins by exploring the main and current strategies involved in electrifying aircraft.

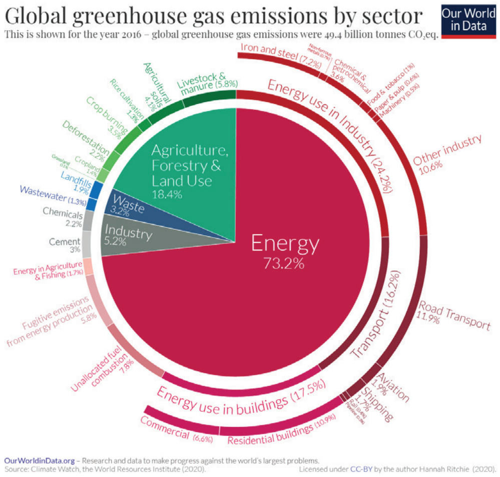

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Figure 1: Global greenhouse gas emissions by sector.[1]

Electrifying aviation is important in today's world as it acts as a great stepping stone towards a greener society. The world is moving towards a more sustainable future — switching from fossil fuels that emit greenhouse gases to renewable energy, such as electrifying transport in cars. This means that air travel can be seen as the next big step in this mission for a cleaner planet. Research on electrifying aircraft has been fairly new. Most reviews within this topic have primarily focused on propulsion system architectures and energy management without integrating environmental impacts from a life-cycle perspective or providing comparisons of performance factors such as efficiency, range, and cost.[2–4] This paper aims to assess these topics presented and evaluate when the electrification of aviation at a commercial scale can be achieved. Attempts at bringing this concept to life have been implemented by a few companies, such as Airbus, Siemens, and Rolls-Royce's E-Fan X, a hybrid-electric propulsion system.[4] The first flight of an electric aircraft was achieved in 1973 by the Austrian manufacturer H. Brditschka with the aircraft MB-E1, which lasted about 10 minutes.[4] Generally speaking, the biggest limitations to flying electrically are the battery and the duration of the flight. This is why the primary challenges and limitations of long-distance electric flights will be covered.

Examining the literature on this topic reveals issues such as the range, battery weight, environmental cost of battery production, and whether it can become a commercial reality, so the environmental impact of plane batteries from a life-cycle perspective will be addressed. These challenges motivate further research, allowing newer technologies to be developed to achieve this goal. Currently, fuel-powered aircraft are still the primary method of air travel, as no all-electric or even hybrid-electric aircraft are able to replace them due to a lack of electric motor efficiency and battery energy density. Fuel-powered aircraft are known to be powered by kerosene, a fossil fuel,

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which releases greenhouse gases in the form of carbon dioxide that is harmful to the environment as it traps radiation emitted by the earth coming from the sun into the atmosphere, increasing global temperatures and climate change.[5] This also results in the extinction of many animal and plant species, forest fires, melting of ice, and the rise of sea levels. This is why aircraft electrification stands as a promising pathway to decarbonise the aviation sector and achieve a cleaner and more sustainable mode of transport to protect our planet.

This paper reviews the current situation and progress of electrifying aviation by analysing existing strategies, the challenges of long-distance all-electric flights, and the environmental and performance impact of electric air travel from a life cycle assessment perspective, and the efficiency of battery-powered aircraft compared to traditional fuel-powered aircraft. This paper aims to assess whether electric aviation can become a reliable mode of transport in the coming years.

Additionally, the performance of batteries in terms of their density and efficiency will be compared to that of a conventional fuel-powered aircraft. All-electric and hybrid-electric propulsion systems will be analysed, followed by an evaluation of which system performs best. The environmental impact of aircraft batteries will be assessed, as they produce no direct greenhouse gas emissions during operation, but can contribute significantly during manufacturing.[6] Different types of batteries that are most optimal for an aircraft will also be considered by examining various batteries made from a range of materials, and the energy efficiency and cost of electric aircraft compared to traditional fuel-powered aircraft will be explored.

■ Current strategies to electrify aviation

Several strategies to reduce carbon emissions through electrification have been explored by the aviation industry. This section will dive into the main and current strategies to electrify aviation.

Hybrid-electric aircraft:

The first method is a hybrid-electric aircraft, which is much more appropriate with current technologies. A hybrid-electric system uses both a jet engine powered by fuel and electric motors as the main sources of propulsion. There are two types of hybrid-electric aircraft: series and parallel. In series hybrid-electric aircraft, propellers are powered only by electric motors, where the electrical power is supplied from a jet engine-powered generator or battery. This allows for a low amount of mechanical power transfer between the jet engine and the electric motor, which increases the reliability and efficiency of the system.[7]

In parallel hybrid-electric aircraft, propellers are rotated either by a jet engine or by an electric motor, which is charged by a battery. Electrical power coming from an electric battery is used to supply power to the propeller, and a mechanical system is used to switch between the jet engine and the electric motor. This is done to optimise emissions and energy consumption during the flight.[7,8] In situations where high thrust is needed, both the jet engine and the electric motor can be used, such as take-off, or just the electric motor alone when low thrust is needed, such as cruising.[8] The parallel configuration requires fewer components than the series configuration, allowing for weight saving; however, the operation and control are complex due to the mechanical systems involved in integrating the jet engine with the electric motor. Examples of hybrid-electric aircraft include the collaboration between Airbus, Rolls-Royce, and Siemens with the E Fan X, containing two electric motors, a Rolls-Royce engine, and a lithium-ion battery pack that was first proposed in 2017 but later cancelled in 2023.[8,9] Ampaire takes the body of the Cessna 337 and turns it into a hybrid-electric aircraft, the Electric EEL, which is flying today. Ampaire also claims that fuel costs would be saved by 50-70%.[10] Zunum Aero was a startup aircraft manufacturer that cooperated with Boeing and JetBlue to propose a 12-passenger hybrid-electric aircraft being able to achieve top speeds of 550 km/h.[4]

All-electric aircraft:

The other method to electrify aviation is all-electric aircraft. These are solely powered by batteries as their energy source for propulsion, which drives an electric motor and rotates the propeller. All-electric aircraft are known to have higher efficiencies compared to combustion engines.[10] Additionally, it is known to be the only method of electrifying aviation to be able to achieve zero CO_2 emissions. It is also able to significantly reduce noise pollution compared to fossil fuel-powered aircraft. However, the batteries of all-electric aircraft have a very low specific energy and energy density. This results in a heavy battery in order to balance the energy density fit for modern flight requirements. These batteries also consume much more energy, which results in significantly shorter flight ranges. This could also be because of the fact that the batteries of all-electric aircraft can not be recharged during the flight, unlike hybrid-electric aircraft, as the battery is the only energy source for the aircraft, meaning that maximum range would depend on the single battery charge on the ground.[10]

The range of flights also depends on the payload of the aircraft, such as the number of seats/passengers and the weight of the baggage.[9] Furthermore, examples of all-electric aircraft include the Lilium Jet manufactured by Lilium GmbH, Germany. They proposed an all-electric five-seater aircraft with 36 fans that allowed for vertical take off and landing (VTOL) and a range of 300 km for regional commuting to be used as an air taxi service. Eviation Aircraft Ltd, Israel, has produced Alice, another all-electric aircraft seating nine passengers with a range of 1000 km and three electric motors producing a power of 900 kW.[3] NASA's first attempt at making an all-electric aircraft includes the X-57 Maxwell. This all-electric aircraft was designed as an experimental aircraft containing 14 propellers that increase the lift, allowing the aircraft to remain efficient, as the aircraft offers a 20% reduction in required engine power.[10]

Although it is believed that battery-driven architectures, such as hybrid-electric and all-electric systems, can significantly reduce aviation-related emissions, these emissions released all depend on the source of electricity used in charging the batteries. If non-renewable sources of energy are used to

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charge the batteries, such as fossil fuels, the effect of electric aircraft on the environment will not be different. Using renewable sources of energy to charge aircraft batteries would result in close to zero emissions released into the atmosphere. Achieving the carbon-neutral goals in the aviation industry will depend on the progress and investment in sustainable energy generation. This leads on to the challenges involved with electric aircraft being able to achieve long-distance flights.

Challenges of all-electric, long-distance flights

All-electric flights are possible with current technologies, but only with smaller aircraft and short-distance flights. A hybrid-electric aircraft is another alternative, although it still contributes to the release of CO_2 emissions into the atmosphere. This section will highlight the primary challenges and limitations of all-electric, long-distance flights.

Performance:

The main technologies involved in the challenges of the electrification of aviation all have to do with the batteries of the aircraft. The most important categories of these challenges are performance and safety. Regarding performance, according to María Zamarreño Suárez *et al.*,[11] a mean specific energy, which is the amount of energy stored in a battery within a given mass, of 600 Wh/kg-pack is required to power a regional aircraft with a range of up to 500 NM (926 km) carrying 30-75 passengers. For a narrow-body aircraft with a range of 1000 NM (1852 km), a mean specific energy of 820 Wh/kg-pack is required, and a 1280 Wh/kg-pack is required to power a wide-body aircraft with a range of more than 2000 NM (3704 km) for 200-400 passengers. Past studies have determined that the minimum battery pack specific energy or energy density for an aeroplane the size of an Airbus A320 required to fly is 800 Wh/kg.[11] This result comes from a comparison of the weight factor and the efficiency of propulsion systems between electric motors and jet engines.[8,9] It could be concluded that the specific energy of the batteries remains as a significant limiting factor in achieving fully functioning all-electric planes, as only small regional aircraft would be able to go into action with today's technologies. This means that further research needs to be done until batteries capable of satisfying these figures are developed.[2]

Energy density:

Furthermore, energy density also stands as a key parameter under the performance aspect, which is one of the other challenges of long-distance flights. Energy density is the amount of energy stored in a battery within a given volume. It should be high for batteries in all-electric aircraft so that they can carry a large payload and fly long distances. Currently, the most commonly used type of battery in the aviation industry is the lithium-ion battery due to its high energy density, charging efficiency, and potential use in the future.[11] They have become increasingly popular due to their successful usage in portable electronic devices and in the automobile industry.[10] While the energy density of jet fuel is around 12000 Wh/kg, the energy density of lithium-ion batteries is around 250 Wh/kg, which is around 48 times less than the jet fuel equivalent.[10,11] However, the maximum value for lithium-ion batteries in the future is expected to increase to 400 - 500 Wh/kg at the cell level,[11] Uber-Elevate stated that lithium-ion batteries capable of reaching energy densities of 400 Wh/kg and above are needed for all-electric flight. Nonetheless, lithium-ion batteries are known to overheat at high voltages, which can end in battery damage and system failure in an aircraft.[10] While the fuel-to-wheel efficiency of an internal combustion engine is around 28%, an electric motor is around 90%. This means that lithium-ion batteries having such a difference between jet fuel in energy density would be able to compensate for the gap to need a minimum energy density of 600 Wh/kg, an advancement in electric motor design for high power applications, and efficient aerodynamic design.[10] According to Adu-Gyamfi and Good, by looking into the possibility of CO_2 emission reduction by using electric propulsion, they identified that 92% of the current global fleet in the world would not be able to take off using current battery technology due to the increased weight that it would have.[10] This means that without significant advancements being made in lithium-ion battery technologies, all-electric flights at even the regional level would not be possible. A comparison between current battery technologies and aircraft energy requirements can be seen in Table 1.

Table 1: Comparison of aircraft energy requirements and current battery technologies.

Category	Specific Energy/Energy Density (Wh/kg)	Notes
Jet Fuel	12000	Around 48x higher than Li-ion batteries
Required for Regional Aircraft	600	Up to 500 NM (926 km) range, 30–75 passengers
Required for Narrow-Body Aircraft	820	1000 NM (1852 km) range. Comparable to Airbus A320 class (min. 800 Wh/kg needed)
Required for Wide-Body Aircraft	1280	More than 2000 NM (3704 km) range, 200–400 passengers
Current Li-ion Batteries	250	Overheating risk at high voltages
Projected Future Li-ion Batteries	400-500	Uber Elevate states that 400 Wh/kg or more is needed for all-electric flight
Required for All-Electric Flight	600	Requires improved electric motor efficiency (≈90%) and aerodynamic optimisation

Safety:

Regarding the safety aspect of these challenges, the battery pack of an aircraft would need to be equipped with special casing and housing materials for the battery to operate at an optimum. However, this means that the weight of the battery would increase as these materials do not generate power but are just used for safety. To prevent overheating problems with the battery, additional cooling systems would need to be equipped to the battery pack to prevent this from happening, as it could lead to degradation of the battery structure and could lead to battery failure, which would also add weight to the battery. On the other hand, the battery would usually be operating in the air, at very low temperatures, which might affect the functioning of the battery at an optimum rate, as the kinetic energy would be significantly lower. The electrolyte within the battery could also end up freezing at low temperatures. Additionally, batteries that would be used in all-electric aircraft should have very long life cycles if they are to be used sustainably at a large scale and be economically appropriate. Unfortunately, the most powerful types of batteries in terms of their specific energy (i.e., lithium-ion batteries) often have the most common life cycle problems. The charging times of batteries also need to be as short as possible so that more flights can take off and be efficient.[11] This means that further research needs to be done to solve these issues and also create a design of a battery pack that can operate efficiently without being too heavy and negatively impacting the aircraft.

In summary, the electrification of aviation is currently limited by battery technologies regarding specific energy and energy density, and safety issues preventing all-electric, long-distance flights. Lithium-ion batteries, currently the most used and energy-dense batteries, have a much lower energy density than jet fuel, face overheating and weight issues from safety regulations, and operate inefficiently in low temperatures. These limitations force electric aviation into small regional aircraft, meaning that, without a breakthrough in battery design, long-distance commercial flights do not seem likely to be a reality in the future. Although there is a clear technological gap, ongoing research and hybrid systems may help future possibilities to make this a reality.

■ Environmental impact from a life-cycle perspective

When considering the batteries of electric aircraft, their environmental impact needs to be examined as well. In this section, the environmental impact of a plane battery from a life-cycle perspective will be presented.

As the single aircraft component of an electric aircraft with the highest lifetime emissions is the battery,[6] the environmental impact it has will be explored from a life-cycle perspective.

Results show that battery production increases GHG emissions, which are compensated for during flight operation. According to Pinheiro Melo *et al.*,[12] a reduction of 45% of the environmental impact compared to fuel-powered aircraft was observed. If renewable energy resources (RES) are used for the electricity used during operation, then the reduction in the environmental impact may be around 95%. However, a direct comparison is not suitable because the range of electric aircraft is reduced by half compared with fuel-powered aircraft due to the batteries' weight. Regarding environmental impacts of climate change (CC), Terrestrial Acidification (TA), Human Toxicity (HT), freshwater eutrophication (FE), photochemical oxidant formation (POF) and mineral resource depletion (MRD), the Lithium Iron Phosphate (LFP) and Lithium-Sulfur Battery (LSB) tend to perform better than the Lithium Nickel Manganese Cobalt Oxide (NMC) and Lithium Nickel Cobalt Aluminium Oxide (NCA). LFP performs better in TA, HT, FE, and MRD categories, whereas LSB performs better in CC and POF. NMC-111, NMC-442, and NMC-532 variants are all the worst performers in each category except NMC-811 in the category TA, in which it is the worst performer. Regarding CC impacts, the cathode's electrode paste is the largest contributor across all battery types, at around 30% for LSBs and 45-61% for LIBs, which is mainly due to the use of the N-methyl-2-pyrrolidone (NMP) solvent and large quantities of LFP, NCA, or NMC materials. Regarding MRD, the primary source of impact in LSBs and LFP-based LIBs is the current collector of the anode at around 35%, while in NMC and NCA LIBs, it comes from the nickel, cobalt, and manganese in the cathode materials, which range from 63-71%.[13] The relative performance of each battery across the key environmental indicators is summarised in Table 2.

Table 2: Performance of battery chemistries across environmental indicators.

Battery Type	**CC**	**TA**	**HT**	**FE**	**POF**	**MRD**
LFP	—	Best	Best	Best	—	Best
LSB	Best	—	—	—	Best	—
NMC-111 / 442 / 532	Worst	Worst	Worst	Worst	Worst	Worst
NMC-811	—	Worst	—	—	—	—
NCA	Poor	Poor	Poor	Poor	Poor	Poor

Best = best-performing chemistry in the category; Worst = worst-performing chemistry in the category; — = neither the best nor the worst.

The main battery recycling techniques currently utilise acids or extreme temperatures. Batteries must be sustainable throughout their life cycle to ensure their usage is a sustainable propulsion system, including the stages after their disposal from aircraft. Although using batteries is clean and free of emissions, they might contain toxic or polluting materials. This is why batteries need to be reused in other industries or recycled once they are no longer fit to be used in electric aviation, ensuring a sustainable life cycle.[11]

81% of aviation emissions come from passenger travel, and 19% from freight.[1] According to Adu-Gyamfi and Good,[10] clean energy generation takes up 38% of the global energy mix. This means that electric aircraft will become more than 30% cleaner over the stages of their life cycle while using the current energy generation mix levels. In conventional aircraft, the main sources of power generation come from the Auxiliary Power Unit (APU) and the turbo shaft. Secondary power systems are also important for the operation of the aircraft, where mechanical, hydraulic, and pneumatic power is combined. The total energy consumption of these systems forms around 5% of the total fuel burnt during the operation of the flight.[14]

In conclusion, aircraft batteries are the largest lifetime sources of emissions for electric aviation, with the production stage contributing significantly to climate change and resource depletion. LFPs and LSBs were shown to outperform NMCs and NCAs. Ensuring a sustainable life cycle through effective recycling or reuse is important, as battery materials can be polluting or toxic. As clean energy in the global energy mix increases, this will lead to the overall life cycle impact of electric aircraft improving. It could also be concluded that because battery usage in electric aircraft is still in the early stages of development, there have not been many LCAs conducted on aircraft batteries, compared to electric car batteries, for example, due to the differences in technologies.

The performance of different types of batteries

After looking at the environmental impact of a battery from its life cycle, the performance can also be considered. This section will discuss the efficiency and performance of different types of batteries made from a range of materials.

In both all-electric and hybrid-electric aircraft configurations, battery power is stored electrochemically within the cell.[11] This means that energy within a battery is stored in chemicals, converting it into electricity with controlled chemical reactions. The battery types that will be discussed in this section include: lithium-ion batteries, solid-state batteries, and lithium-sulfur batteries.

Lithium-ion batteries:

Lithium-ion batteries are currently the most used batteries, ranging from portable electronic devices to the automotive industry, due to their high specific energy and energy density compared to other batteries currently on the market. Li-ion batteries are also known to have higher cell voltages of up to 3.6 V, which is three times greater than other battery technologies such as nickel-cadmium (Ni-Cd) and nickel-metal-hydride (Ni-MH). This allows them to produce a large amount of current for high-power applications. Even though Li-ion batteries have a significantly lower specific energy than that of jet fuel (250 Wh/kg compared to 12000 Wh/kg),[10] attempts into increasing their specific energy requires a further increase in the energy density of the anode and cathode material, consequently, the electrochemical stability window of current electrolytes in the battery does not allow an increase in cathode voltage above ~4.3 V. Additionally, they are known to overheat after exceeding specific voltages, which can cause harm to the battery and lead to battery failure. This means that further research needs to be done to make them safer, but also to achieve higher capacities to be able to compete with jet fuel.[10] Lithium-ion batteries also have the lowest reduction potential out of all the elements, which is a measure of the tendency to gain or lose electrons, and therefore be reduced or oxidized.[11]

Solid-state batteries:

Solid-state batteries are a promising alternative to achieving higher energy densities, which remain a major limitation with lithium-ion batteries. They use a solid lithium electrolyte, which provides high conductivity at room temperature along with high processing flexibility and stability, a lithium metal anode, with the highest theoretical capacity of 3860 mAh g^{-1} and lowest potential of -3.04 V,[10] and finally a sulfur or oxygen cathode.[11] This allows for a shorter charging time, higher energy density, and increased safety, putting solid-state batteries ahead of Li-ion batteries in terms of future battery technologies. In 2020, NASA obtained results of a solid-state battery with a carbon-sulfur cathode reaching an energy density of 1100 Wh/kg. In 2021, Quantum Scape also obtained results of a ten-layer solid-state battery achieving 390-500 Wh/kg energy density. This battery was able to charge from 0 to 80% of its capacity in 15 minutes while achieving 800 cycles to meet the current automobile standard. However, the real challenge in solid-state batteries is developing methods for mass production.[10]

Lithium-sulfur batteries:

Lithium-sulfur batteries are also another alternative, as they, too, are capable of reaching high energy densities. Li-S batteries are made up of a lithium metal anode and a sulfur-based cathode and can theoretically reach energy densities up to 2600 Wh/kg, which would make them the most promising option for energy storage and aviation applications, as they would have more than double the energy density of jet fuel. Sulfur is also a cheap and abundant element, is not toxic, and is relatively light, so it acts as a suitable material for weight-sensitive applications such as aviation. Nevertheless, sulfur is non-conductive, so it requires additional conductive materials in its electrodes, which leads to slower electron migration, limited utilisation of active substance, and poor reaction kinetics. Sulfur also expands in volume to approximately 80% during discharge, which can cause active components to detach and lose electrical connection. This limits Li-S batteries to a low discharge rate of 0.2C and a short life cycle between 180 and 300 cycles. To combat this issue, a graphene-oxide cathode was developed, and the life cycle was improved to 500 cycles. Applications of Li-S batteries in the aviation industry include the Airbus Zephyr aircraft, which made the longest endurance flight of 14 days, and Oxis Energy and Bye Aerospace, making a 500 Wh/kg Li-S battery, which offered a reduction in battery weight by half.[10] Li-S batteries have a future specific energy goal of 500 Wh/kg to achieve large-scale commercialisation.[11] Table 3 shows a summarised comparison of the three batteries discussed.

Table 3: Comparison of promising battery technologies for aviation.

Battery Type	Battery Technology	Theoretical Energy Density (Wh/kg)	Advantages	Disadvantages
Lithium-ion	Anode, cathode, separator, electrolyte, high cell voltages	250	Most used battery type, cell voltages are 3x stronger than other battery technologies	Can overheat, exceeding specific voltages, leading to battery failure
Solid-state	Solid lithium electrolyte, lithium metal anode, sulfur or oxygen cathode	1100	Potential for high energy densities	Methods for mass production are required
Lithium-sulfur	Lithium metal anode, sulfur-based cathode	2600	Most promising option for aviation applications, sulfur is cheap	Short life cycle

Since fuel-powered hybrid aircraft have to provide 150-300 kW of battery power per tonne of the aircraft's mass to allow for an all-electric take off,[9] this poses a need for additional research to be done to develop more powerful batteries to be used at the commercial level. Lithium-ion batteries currently serve as the most powerful and energy-dense battery; however, solid-state and Li-S batteries offer much better performance in theory, but face big engineering challenges to compete with Li-ion batteries.

Energy efficiency and cost compared to fuel-powered aircraft

Discussing the performance of different types of batteries would lead to their energy efficiency and cost being assessed as well. This can be compared to conventional fuel-powered aircraft, which are discussed in this section.

Electric aircraft configurations, specifically all-electric aircraft configurations, are known to have very high energy efficiency systems.[2,3] All-electric and hybrid-electric aircraft are projected to operate at 85-90% efficiency, as well as be 20-40% more efficient than fuel-powered aircraft. Looking into hybrid-electric aircraft, they contain an Auxiliary Power Unit (APU), typical in fuel-powered aircraft, which generates electrical energy for the aircraft during ground operations when the engine is turned off. The APU has an efficiency of less than 20% and emits CO_2, NO_x, and noise pollution.[4] Continuing with hybrid-electric aircraft solutions, they are known to use battery storage and electric motors to increase efficiency and decrease weight by using thrust and power generation together and by providing thrust during certain periods, allowing different components to be optimised to cruising speeds.[15] In real-world applications, the Clean Sky 2 NOVAIR project has a battery efficiency of 95% and an electric machine (EM) efficiency of 98%.[2] NASA's Pegasus is a parallel hybrid-electric aircraft with 48 seats that is planned to go into operation in 2030. With distributed electric propulsion (DEP) as its propulsion architecture, it is proposed to have a battery density ranging from 750-1000 Wh/kg, with up to 40% energy efficiency improvement. When considering efficiency, the efficiency of charging the batteries should be considered as well. According to Scholz *et al.*, the efficiency of charging the batteries is 90%.[16] This would allow for faster charging times.

One of the biggest reasons and motivations for electrifying aircraft stands with the fact that they have low operational and maintenance costs.[16] While the price of Jet-A kerosene is 0.72 US$/L,[10] the average price of renewable energy coming from wind power is $0.016 per kW h.[7] This proves that the cost of electricity coming from renewable sources is much cheaper than jet fuel, by a factor of 45. A real-life example showing this would be AeroTEC and magniX's electrified version of the Cessna Caravan 208B that had been modified to carry nine people. It flew for 30 minutes, during which the cost to fly was just $6. If standard jet fuel were used, then the same flight would have ranged from $300-400.[17] Looking into the infrastructure cost, once electric aircraft are implemented into airports, one 120 kW charging station in an airport would be able to cover 88% of airports that operate with 70-seater aircraft. Airports with the highest number of flights would need around 4-8 120kW charging stations. As a result, the investment costs for the majority of airports would be between 15,000 EUR and 50,000 EUR, as for the airports with the highest number of flights would cost around 200,000 EUR.9 Shifting towards electric aircraft over conventional fuel-powered aircraft would improve the life cycle cost and lower the average overall operational and maintenance costs compared to using kerosene to power aircraft and pollute the environment.

Electric and hybrid-electric aircraft demonstrate significant advantages in both energy efficiency and operating costs compared to fuel-powered aircraft. With battery efficiencies known to reach up to 95%, and operational costs being low due to the cost of renewable energy, these technologies offer a promising motivation to switch to electric aircraft. Real-world examples such as the electrified Cessna Caravan indicate the low operational costs, displaying the economic and environmental benefits that electrification of aviation possesses.

Conclusion

This paper aimed to address the current situation and progress of electrifying aviation by demonstrating that it will become a reliable mode of transport within the coming years. This can only become a reality on a commercial level with breakthroughs in battery technologies, but with the current rate of humanity's projections, I believe that it will become a reality within the next 15 years.

This was done by exploring the environmental impacts, challenges, limitations, and performance of electric aviation, proving its potential as a cleaner alternative to conventional aviation. Firstly, the current strategies to electrify aviation were discussed, showing that the amount of emissions released depends heavily on the electricity source used to charge the batteries. The challenges and limitations of all-electric, long-distance aircraft were then examined, with the major limitation being the low energy density of current batteries and the safety issues associated with them. The environmental impact of a plane battery from a life cycle perspective was outlined next, concluding that LFPs and LSBs are the most environmentally favourable options. The performance of different battery types was then compared, with solid-state and Li-S batteries offering far better theoretical performance than Li-ion batteries, although they still face significant engineering challenges. Lastly, the energy efficiency and cost of flying electric aircraft were analysed in comparison to conventional fuel-powered aircraft. It was found that electric aircraft are much cheaper to operate compared to fuel-powered aircraft due to electricity being cheaper than fuel, and that electric motors are much more efficient than jet engines; however, today's batteries are not dense enough to fly long-distance commercial flights, which is a major limitation. This means that further research for newer technologies to be developed to achieve long-distance electric flights and future innovations in battery technology would need to be accomplished to compete with the energy density of kerosene.

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