

Pathways to Sustainable Aviation through Electric Aircraft and Emerging Technologies

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Abstract. The aviation industry is a major contributor to global emissions, noise pollution, and energy inefficiency, driving the need for sustainable solutions. Electric aircraft have emerged as a promising alternative, offering potential benefits such as reduced emissions, lower noise levels, and improved energy efficiency. This paper explores the advantages of electric aircraft, focusing on noise reduction, emission cuts, and enhanced energy efficiency, while also addressing the current limitations of battery technology, such as low specific energy and reserve requirements. Despite these challenges, startups are actively developing new battery technologies, such as solid-state and pouch cells, to overcome these barriers. Additionally, the paper examines alternative sustainable technologies, including hydrogen fuel and biofuels, which could complement electric aircraft in achieving low-emission aviation. The report concludes that although widespread adoption of electric aircraft may not be immediate, advancements in technology and integrated solutions will likely drive the aviation industry's transition to a more sustainable future.

Keywords: Materials science, electric vehicles, electric aviation.

1. Introduction

The traditional aviation industry has had significant adverse environmental impacts through various mechanisms. Firstly, it generates substantial emissions from the combustion of unsustainable fossil fuels, contributing approximately 2.5% of global emissions. These emissions, including gases such as NO₂, CO, and atmospheric particulates, exacerbate global warming and pose direct toxicity risks to human health. Klöwer et al. estimate that aviation contributes approximately 4% to human-induced global warming, surpassing the total emissions of most individual countries [1]. Furthermore, the consequences of these emissions are severe. Yim et al. modeled that aircraft emissions result in approximately 16,000 premature deaths globally each year, with PM_{2.5} identified as the primary factor, accounting for 87% of all cases [2]. The negative effects of these emissions are disproportionately distributed, with economically disadvantaged populations bearing a greater burden. This disparity is supported by the findings of Henry et al. and Rissman et al. Henry et al. demonstrated that economically disadvantaged students are disproportionately affected by airport emissions in California [3]. Similarly, Rissman et al. analyzed PM_{2.5} levels at Hartsfield-Jackson Atlanta International Airport and revealed a strong positive correlation between concentrations of aircraft-generated particulate matter and the percentage of minority populations [4].

Secondly, noise pollution from aircraft contributes to adverse health effects for both humans and wildlife. Basner et al. highlighted that aircraft noise negatively impacts human well-being, children's cognitive abilities, and sleep quality [5]. Correia et al. corroborated that exposure to aircraft noise is associated with an increased risk of heart disease and stroke, based on a study of 6 million adults aged 65 years or older, showing a statistically significant relationship [6]. Moreover, van Kempen and Babisch found that noise pollution from aviation extends its impact to hypertension, underscoring the various mechanisms through which noise pollution adversely affects human health [7].

The environmental and health impacts of traditional aviation underscore the urgent need for a more sustainable and renewable aviation industry. This necessity drives the exploration of alternatives, with electric aircraft emerging as a particularly promising solution. Therefore, this report will assess (a) the benefits of electric aircraft and (b) the feasibility and future prospects of electric aircraft. For (a), the report will focus on the environmental and energy efficiency benefits of electric aircraft. The (b),

the paper will argue that while electric aircraft may not become widespread in the short term, they are likely to represent the future trend in aviation.

2. The Benefits of Electric Aircraft

As highlighted in the introduction, the traditional aviation industry faces several critical challenges, including excessive noise levels, pollution, and low energy efficiency. Electric aircraft present potential solutions to all three issues. This section explores the key mechanisms by which electric aircraft can address these challenges.

The first major improvement offered by electric aircraft is noise reduction. Parker and Song conducted a study comparing the average peak sound levels of three traditional aircraft with those of an electric aircraft. Their findings, depicted in Figure 1, show that the electric aircraft produced significantly lower noise levels, peaking at just 65 dB—well below the threshold for hearing damage. For context, sustained exposure to noise levels above 70 dB can cause hearing impairment, while noise levels above 120 dB can lead to immediate harm. Similar results were reported by Magnix, a company specializing in electric and traditional aircraft development. Their research revealed that during takeoff, electric aircraft produced noise levels 20 dBA lower than conventional aircraft, which corresponds to a 100-fold reduction in noise energy. Overall, noise levels were reduced by 16-22 dBA [8].

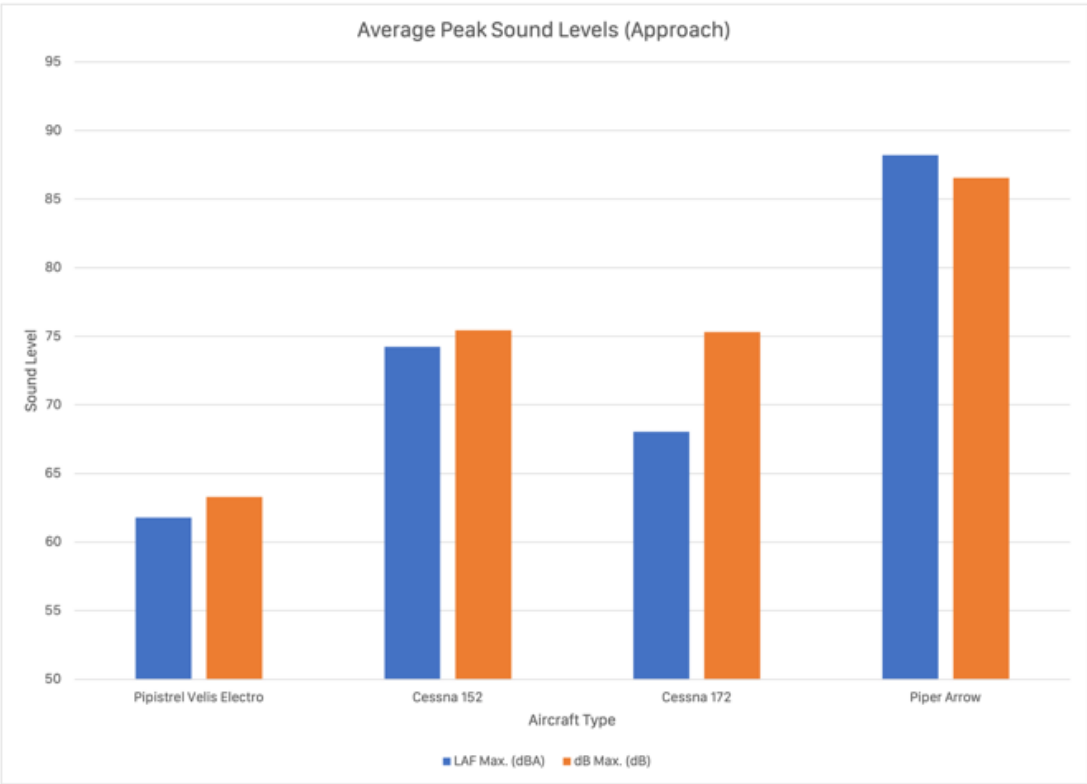


Figure 1. Average peak sound levels of different types of aircrafts (Picture/image credit: Original)

The second area of improvement is the reduction of emissions. Mukhopadhyay and Graver found that electric aircraft can reduce CO₂ emissions by 49% to 88%, a significant reduction compared to traditional aircraft [9]. A separate study conducted at Chalmers University of Technology estimated that small electric aircraft would reduce climate impact by 60% over a quarter of their expected lifespan [10]. This reduction is largely due to the use of electricity rather than non-renewable fuels, which not only contribute to global warming through atmospheric chemical reactions but are also toxic to the environment.

The third area of improvement lies in energy efficiency. Internal combustion engines in traditional vehicles typically operate with an efficiency of 17% to 21%, as much of the energy is lost as heat. In

contrast, electric vehicles, including aircraft, can convert approximately 77% of their input energy into useful output, making them nearly three times as efficient. This efficiency advantage is similarly reflected in the aviation sector. Mukhopadhyay and Graver noted that electric aircraft are 2.1 to 3.9 times more efficient than their conventional counterparts [11]. Two key factors contribute to this superior efficiency: first, electric motors boast a high power-to-weight ratio, largely due to their use of high-induction soft metal alloys and advanced motor stacks; second, electric motors utilize turbines to convert electricity into propulsive force, which tend to be more efficient than piston engines. Moreover, when compared to alternative renewable options such as hydrogen and synthetic fuels, which achieve only 20% to 30% efficiency, electric batteries stand out with efficiencies around 70%. These substantial benefits—reduced emissions and increased energy efficiency—emphasize the need for the aviation industry to transition from non-renewable fuels to electric power.

3. The Feasibility and Future of Electric Aircraft

The first major limitation is the low specific energy of current battery technologies. Specific energy, defined as the energy stored per unit mass of the battery pack (measured in watt-hours per kilogram), is a critical metric for evaluating battery performance. As Mukhopadaya and Graver highlight, existing battery technologies currently enable electric aircraft to carry only nine passengers over a distance of 140 km, which is insufficient for practical commercial use or to replace traditional fossil fuel-powered aircraft [12]. Their model estimates that just 9% of the commuter passenger market could be served by current electric technologies. The core issue lies in the low specific energy of existing batteries; the current standard of 250 Wh/kg must be doubled to support aircraft capable of carrying 90 passengers over 280 km. Achieving this improvement would represent a substantial advancement, potentially increasing market coverage to two-thirds.

This challenge is further compounded by the need for reserve energy. Aircraft are required to carry sufficient backup energy to sustain an additional 30 minutes of flight in emergencies and to travel an extra 60 miles to an alternative airport. Crownhart notes that these reserve requirements reduce the effective flight range from 160 miles to approximately 30 miles [13]. Such a short range significantly limits the commercial viability of electric aircraft under current technological conditions.

Another key challenge is the mass of batteries relative to their lithium content. Hemmerdinger notes that only 3% of the total mass of a battery is composed of lithium [14]. This means that material advancements are necessary to either develop lighter batteries or batteries capable of carrying more lithium to increase energy output. Mukhopadhyay explains that reducing the empty mass fraction of the aircraft is essential for extending flight range. Reducing non-essential aircraft mass would allow more space to be allocated to batteries. In quantitative terms, reducing the empty mass fraction by 30% could quadruple the market coverage for commuter aircraft [15].

Additional challenges arise from the higher operational costs associated with electric aircraft, primarily due to the expense of maintenance and frequent battery replacements. Avogadro and Redondi estimate that operating costs for electric aircraft could be 20% higher than those of conventional aircraft, which may reduce consumer interest in choosing electric flights [16]. Given these technological and economic challenges, Crownhart projects that electric aircraft will contribute only a 1% reduction in aviation emissions by 2050 [17].

Despite these challenges, innovative startups are working to advance battery technology. Jeff Engler, founder and CEO of Wright Electric, predicts that molten batteries, which can incorporate a higher fraction of lithium, could significantly enhance both energy density and specific energy in batteries. Additionally, pouch cells are being developed as an alternative to the conventional cylindrical cells used by companies such as Tesla. A battery expert and the founder of Cuberg explain that while cylindrical cells can achieve a maximum specific energy of 270 Wh/kg, they are not compatible with lithium metal anodes. In contrast, pouch cells offer higher energy densities than their cylindrical counterparts. Amprius, for example, has successfully developed batteries with energy densities reaching 500 Wh/kg. Although industry experts agree that the technology is still maturing,

these incremental advancements from startups provide promising prospects for the long-term development of electric aircraft [18].

4. Suggestions for Future Low-Emission Aircraft and Advancements in Technology

This section suggests the areas of improvement in aviation technologies, with a special focus on electric aircraft, hydrogen fuel, and biofuels, and their impacts on emissions, noise, and energy efficiency. Electric aircraft hold significant potential to reduce aviation's environmental impact, but advancements in material science are critical for their success. One of the primary areas for improvement is the development of better batteries with higher energy densities. Solid-state batteries, which offer higher energy density, faster charging times, and enhanced safety compared to traditional lithium-ion batteries, are considered a promising avenue. However, as Mukhopadhyay and Graver highlight, current battery technologies fall short of supporting long-range commercial flights [19]. Advancements in battery materials, such as lithium-sulfur or lithium-metal batteries, could help overcome this limitation. Furthermore, lightweight materials, including carbon fiber composites and advanced alloys, are essential to reduce aircraft weight and improve energy efficiency. By integrating these materials, electric aircraft could achieve a higher power-to-weight ratio, extending flight range and reducing energy consumption.

Beyond energy density, battery durability and recycling are also critical areas of focus. To enhance the lifecycle of electric aircraft batteries, innovations in battery management systems (BMS) are necessary. These systems optimize battery usage and mitigate degradation over time, improving both performance and environmental sustainability. Finally, advancements in battery recycling technologies are vital to ensure the long-term viability of electric aircraft, as the large-scale production and disposal of batteries pose environmental challenges.

Hydrogen fuel offers another promising path for reducing aviation emissions, but its widespread adoption faces several technical and logistical barriers. The development of green hydrogen, which is produced via renewable energy sources like wind or solar, is crucial for ensuring that hydrogen-powered aircraft deliver true environmental benefits. Currently, the vast majority of hydrogen is produced from natural gas through steam methane reforming, a process that emits significant CO₂. To fully realize the potential of hydrogen as a zero-emission fuel, the expansion of green hydrogen production infrastructure is essential. Additionally, advancements in hydrogen storage and distribution technologies are required to overcome the challenges posed by hydrogen's low energy density and the difficulties in storing it as a liquid at cryogenic temperatures or as a compressed gas.

Moreover, the efficiency of hydrogen fuel cells, which convert hydrogen into electricity to power aircraft engines, must be improved. This can be achieved by enhancing catalyst materials, such as by incorporating more efficient and durable catalysts made from platinum or advanced carbon materials. Increasing the efficiency of fuel cells will not only improve energy output but also reduce the overall cost of hydrogen-powered aviation. According to Mukhopadhyay and Graver, overcoming these barriers would enable hydrogen-powered aircraft to serve a larger portion of the aviation market, particularly in the context of long-haul flights, where battery-electric aircraft face limitations due to weight and energy density constraints [20].

Biofuels present a complementary solution to decarbonizing the aviation industry, especially in the near term. Sustainable aviation fuels (SAFs), derived from biomass sources such as agricultural waste, algae, and even municipal solid waste, can be used in existing aircraft with minimal modifications. This makes them an attractive option for reducing emissions while new technologies are being developed. The International Air Transport Association (IATA) has set a goal for the aviation industry to achieve net-zero carbon emissions by 2050, and biofuels are expected to play a crucial role in meeting this target. However, the production of biofuels at scale faces challenges related to land use, water consumption, and the potential competition with food crops.

To address these concerns, research into second- and third-generation biofuels is ongoing. These biofuels are produced from non-food biomass, such as algae or agricultural residues, reducing the environmental and ethical concerns associated with first-generation biofuels. In addition, technological advancements in bio-refining processes are needed to increase the efficiency of converting biomass into fuel, thereby lowering costs and reducing resource consumption. As Mukhopadaya and Graver note, while biofuels alone may not be sufficient to decarbonize aviation entirely, they represent a practical solution for reducing emissions in the short- to medium-term [20].

Integrated Technologies and Future Outlook: The path to low-emission aviation will likely require a combination of technologies. Hybrid aircraft, which combine electric propulsion with biofuel or hydrogen-powered engines, offer a flexible solution that could bridge the gap between current technologies and future advancements. Such aircraft could utilize electric propulsion for shorter distances or takeoff and landing, while relying on biofuels or hydrogen for longer flights. This hybrid approach would allow the aviation industry to reduce its reliance on fossil fuels while maintaining the range and payload capabilities required for commercial operations.

In addition to technological advancements, policy and regulatory frameworks will play a crucial role in accelerating the adoption of low-emission aircraft. Governments and international organizations must invest in research and development, provide subsidies for green technologies, and establish stringent emissions targets for the aviation industry. Additionally, carbon pricing mechanisms could incentivize airlines to adopt cleaner technologies and offset their emissions.

Ultimately, achieving a sustainable aviation future will require a holistic approach that combines advancements in electric aircraft, hydrogen fuel, biofuels, and hybrid systems. These technologies, together with supportive policies and infrastructure investments, can help the aviation industry reduce its environmental impact and transition toward a greener future.

5. Conclusion

This paper presents two key findings. First, transitioning to electric aircraft offers significant societal benefits, including reducing global warming by lowering toxic gas emissions, mitigating health issues related to high noise levels, and conserving energy through improved efficiency. Second, current technologies are not yet equipped to support a rapid shift to electric aviation, primarily due to limitations in battery-specific energy, the need for reserve energy, and inefficient use of space within aircraft. Despite these obstacles, startups globally are actively working on innovative solutions to address these constraints. The report concludes with optimism that, as technologies mature, the aviation industry will gradually adopt electric aircraft in the long term.

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