The viability of the all-electric aircraft in commercial aviation

by

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B.S., Kansas State University, 2020

A REPORT

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Aviation
College of Technology and Aviation

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2023

Approved by:

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Abstract

This report addresses the viability of all-electric aircraft systems in the commercial aviation industry. The industry is driving the need for these types of systems to accomplish the goals of reducing emissions and noise, while increasing overall system efficiency. This effort, however, brings along many unique challenges that are novel to engineers and require a different design perspective than conventional combustion engine aircraft. The works of multiple researchers are brought together in this study to analyze all the challenges engineers currently face with system weight, performance, and integration into the commercial aviation market. The results of multiple computer models ranging from short-range commuter aircraft to larger airline designs are compared and referenced in the discussion of electric aircraft viability. The safety and redundancy of all-electric designs are also analyzed to determine the risk factor behind aircraft relying solely on electrical power. The purpose of this report is to analyze and critique the concept of all-electric propulsion systems for commercial operations to determine whether these aircraft have the potential to meet industry goals of reducing emissions and noise while also increasing the safety and efficiency of the whole system.

Keywords: Electrification, aircraft propulsion, propulsion systems, commercial aircraft, safety, multifunctionality

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SECTION I.

Introduction

Greenhouse gases continue to threaten the health of the planet while its human inhabitants race to slow our impact and minimize our carbon footprint. This challenge has driven multiple industries to invest billions of dollars and countless man-hours into novel technologies and research into uncharted territories. While many sectors are involved in the effort, the most notable in recent years has been the achievements of the auto industry. While Tesla may be the biggest name in the electric vehicle market, many major players, such as Ford, General Motors, Toyota, and Rivian have stepped up to match the efforts of Elon Musk and his Tesla. Even the prominent European manufacturer Mercedes-Benz has committed to developing only electric cars from 2025 onward and will have a combustion-engine-free lineup by 2030 (Mercedes-Benz Group Media, 2021). This commitment, and those comparable efforts from other industry leaders, will undoubtedly reduce the auto industry's carbon footprint, which is the largest contributor to greenhouse gas emissions in the United States.

As previously mentioned, many shareholders have invested money, assets, and personnel into the development of novel technologies to meet environmental goals. The aviation industry is no stranger to these endeavors as many companies are designing and certifying new electric motors and all-electric aircraft for short-range missions carrying six or less passengers. However, there seems to be a lack of similar designs targeting the commercial aviation sector. Modern aircraft with narrow body designs, such as the Boeing 737, and wide body designs, such as the Boeing 787, currently fulfill the typical commercial mission. Although, these narrow body and wide-body fleets account for roughly 43% and 33% of aviation greenhouse gas emissions, respectively. This threat to the global carbon footprint is compounded by the 4-5% annual growth in commercial air travel (Barzkar & Ghassemi, 2020). So, what's holding manufacturers back from eliminating this threat with new technology and designs capable of meeting the same environmental goals as those key players in the automotive and light aircraft markets?

The following report serves as an investigative study into the challenges facing the development of all-electric aircraft for commercial missions. The need for this research is summarized well by Gohardani et al. (2011) who state, "The intricate challenges of meeting future environmental goals in commercial aviation require a cross-disciplinary effort that focuses on feasible propulsion systems, reduced fuel consumption, aviation safety and reliability, noise reduction, and optimized aircraft design to achieve desirable flight attributes."

While much of the recent literature addresses each of the above criteria individually, very few recent works combine those criteria and analyze the combined challenges to address the overall viability of an all-electric aircraft to serve commercial aviation. **Section II** of this study dives into the history of electric aircraft research to understand how it has progressed over the last few decades. The remaining sections then address the individual design and regulatory challenges facing aircraft manufacturers before the final sections of this study discuss and analyze the end viability of an all-electric aircraft to accomplish commercial missions. The problem is summarized by Jones et al. (2021) who state:

The efficient development of viable designs for the electrical power systems for all sizes and variations of these aircraft is immensely challenging due to the low technology readiness level (TRL) of systems and technologies, lack of pre-existing, commercially operating systems and relevant industry standards, and the relatively short time frames for the development of these systems.

SECTION II.

History of Electric Aircraft

Before diving in to examine the various challenges facing the development of electric aircraft systems, this section will briefly look back at the history of electric aircraft to better understand how the concept has grown throughout the last roughly 50 years. Many assume that electric aircraft systems are relatively new technology due to the recent growth of companies designing aircraft for Urban Air Mobility (UAM), also called air taxis, that can pick you up at your office or home and fly you across town or to the nearest airport to get on a commercial flight. However, these systems trace back to the 1970s when the National Aeronautics and Space Administration (NASA) began researching all-electric aircraft technology and engineering concepts of their own.

Most electric aircraft designs today implement batteries with rapid charging capabilities as the power source for the propulsive motor. NASA, however, powered its initial concepts with solar-panel technology, beginning with the Sunrise I solar-powered airplane, which first flew on November 4, 1974. This method of generating electrical power had its limits, not being able to operate at night or in cloudy conditions but served as proof of concept for an electric-powered airplane. Sunrise II followed shortly after and displayed the potential to reach higher altitudes, benefiting from improved aerodynamics compared to its predecessor (Gohardani et al., 2011).

Then, the first manned flight of a solar-powered aircraft occurred on April 7, 1980, pushing NASA's research forward into the development of the Solar Challenger aircraft. The Solar Challenger, with its 46.5ft wingspan and over 16 thousand solar cells, was designed to withstand increased turbulence levels and was driven by an electric motor and propeller. To demonstrate the aircraft's efficiency, the Solar Challenger completed a manned long-distance flight from Paris to London on July 7, 1981 (Gohardani et al., 2011).

Figure 1. NASA Centurion solar-powered aircraft. By Tschida, T. (1998).

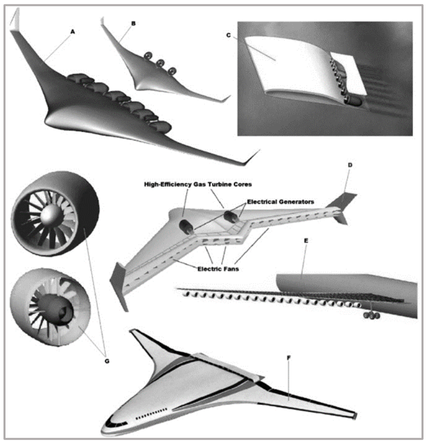

Figure 2. NASA distributed propulsion concepts. From Gohardani et al. (2011).

The continued success of NASA and its all-electric solar-powered aircraft culminated in the Centurion, shown in **Figure 1**. The Centurion evolved the usability of solar-powered aircraft technology by proving that it could stay airborne for weeks at a time, collecting scientific data and images with its telecommunications relay platforms. All the Centurion's systems, including the multiple electric motors, communications systems, and avionics, were powered by the aircraft's solar cells. However, it was also equipped with a backup lithium battery, capable of providing an additional two to five hours of flight time after dark (Gohardani et al., 2011).

Even with these incredible achievements, NASA's solar-powered technology was only a fraction of the research conducted in the way of all-electric aircraft. Their work paved the way for the future we see today with electric aircraft designs pushing the boundaries of aviation technological advancement. NASA continues its research today, as shown in **Figure 2**, with all-electric aircraft and distributed propulsion technology designed for the commercial aviation market. Only time will tell the impact this shift from internal combustion engines to distributed electric propulsion systems will have on our goal of reducing the aviation industry's carbon output.

SECTION III.

Efficiency and Range

The design and implementation of electric propulsion technology in aircraft has engineers facing many new and unique challenges. The remaining sections of this paper address each of these challenges through the research and studies of various industry professionals and subject matter experts. This section addresses the specific challenge of efficiency and range of a fully electrified aircraft compared to a typical internal combustion engine aircraft. Each of the studies referenced in this section analyze a proposed fully electric version of the De Havilland Canada Dash 8, which is a short-range commuter aircraft typically used for regional flights with up to 90 passengers.

There are multiple benefits to electrifying aircraft of this size, including reduced emissions, higher reliability, lower maintenance and operating costs, and reduced noise. Although, you often don't hear any benefits to this technology along the lines of performance and endurance. That's because those statistics aren't great. According to simulations ran by Kozakiewicz & Grzegorczyk (2021), applying electric propulsion to existing aircraft today, without any other modifications, would reduce the flight range of those aircraft by approximately six times. A similar conclusion was found by Ebersberger et al. (2022) who state that it poses a large challenge to achieve a full-electric concept of a short-range aircraft, like the De Havilland Canada Dash 8, that provides feasible flight range.

The statements from the above reports suggest that the range of electric aircraft is significantly less than that of the conventional combustion engine aircraft. The statistics from computer simulations run by Kammermann et al. (2020) support these comments. According to the report, the maximum range of the conventional (internal combustion) propulsion system is 2000km, while the maximum range of the fully electric propulsion system is only 427.5km. Additionally, this simulation showed that the studied model with the electric propulsion system does not allow for the payload capacity to carry as many passengers as the conventional version. Therefore, from an operational perspective, this would require more overall flights or a larger fleet of aircraft to meet air travel demands.

The conclusions made by these researchers are further supported by the works of Kozakiewicz & Grzegorczyk (2021). Their computer simulation model was constructed from a Dornier 328, another short-range regional commuter aircraft, which replaced the conventional turboprop engines with electric motors powered by batteries with a 180 Wh/kg energy density and had the same resultant mass as the conventional version. The results showed that the flight range of the conventional turboprop aircraft was 1200km, while the electric propulsion model reached just over 200km. Kozakiewicz & Grzegorczyk (2021) suggested the following modifications for the electric version to match the range of the conventional model:

- Reduction of aerodynamic drag by 20%.
- Increase wingspan by 50% to reduce induced drag.
- Reduction of the aircraft's structural mass by 20%.
- Increase the battery energy density to 500 Wh/kg.

Current lithium-ion battery technology gives the highest energy density with today's technology, and batteries are still the most feasible solution for energy storage. However, battery energy density ratings, that Kozakiewicz & Grzegorczyk (2021) determined will be required to meet flight range goals have not yet been technologically achieved. The most promising solution to this problem results from hybrid-electric models showing drastically improved flight range statistics and will be discussed further in **Section VII** of this paper. The challenge of battery energy density will also be discussed in the next section regarding aircraft weight.

SECTION IV.

Aircraft Weight

One challenge facing all aircraft designs, whether electrically propelled, conventional internal combustion, or a hybrid design, is weight. In general, a fixed-wing aircraft must develop enough speed to produce the lifting force required to offset the aircraft's weight to get airborne, accelerate, climb, etc. Other than gliders that utilize the assistance of tow aircraft, this speed must be obtained via propulsive power output from the engine(s). The heavier an aircraft is, the more propulsive power is required to achieve the performance for takeoff, acceleration, and gaining altitude. Modern military fighter aircraft, as well as civilian aerobatic aircraft, have extremely high power-to-weight ratios, allowing them to perform grueling maneuvers that would cause most aircraft to fall out of the sky.

Arguably, the challenge of overcoming weight has more of an impact on electric aircraft than it does on conventional aircraft. This is due to 40% of a conventional combustion aircraft's weight being fuel, which is burned during flight (Barzkar & Ghassemi, 2020). Therefore, the longer the aircraft flies, the more its weight is reduced, requiring less propulsive energy to stay airborne. Since less lift is required to offset weight, the aircraft can burn less fuel at the same airspeed, due to less required power, or burn the same amount of fuel at a faster speed and cover more ground. To put it simply, as a combustion aircraft flies, its potential range and endurance continuously improve.

This is not the case for electric aircraft that do not lose weight (in fuel) as they fly, meaning they land at the same weight as when they took off and must carry the full weight of the propulsion system throughout the flight. Due to this reason, the electric motor and other various components must be as light as possible, while being mechanically capable of sustaining high power output through the duration of the flight. The heaviest contributor to the electric propulsion system is the battery, as shown in **Figure 3**, therefore it must have a high power to weight ratio, typically measured in Watt-hours per kilogram (Wh/kg), to be a viable power source for the system.

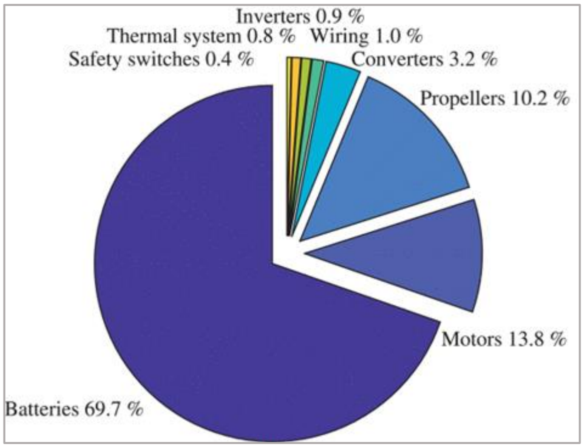

Figure 3. Proposed weight distribution of an electric propulsion system. From Ebersberger et al. (2022).

Ebersberger et al. (2022) compare the propulsion system weights of a conventional King Air 200 turboprop aircraft to one retrofit with an electric propulsion system. The weight of the conventional system, accounting for the fuel, fuel tanks, propellors, and two turboprop engines, is roughly 2200kg. Comparatively, the weight of the fully electric propulsion system, including the electric motors, propellors, batteries, and various components, is approximately 1956kg. While the weight of the electric version is almost 250kg lighter, the weight of the fuel alone in the conventional system is 1600kg, which would be consumed during the flight, reducing the overall weight of the turboprop system.

Aside from their majority share of the total system weight, the main drawback to batteries with today's technology is their low energy density. According to Kozakiewicz & Grzegorczyk (2021), the highest energy density batteries that are currently available today are rated from 150-250 Wh/kg, with Tesla's 21-70 battery being a high-performing outlier with an advertised rating of 250-320 Wh/kg. Lithium-ion batteries are the most preferred for electric aircraft applications due to their availability and cost, but even the best have a specific energy of only 250 Wh/kg, which is vastly overshadowed by the 12,000 Wh/kg rating of jet fuel (Wheeler et al., 2021). Now, relate these numbers to **Section III** where Kozakiewicz & Grzegorczyk (2021) referenced the need to increase battery-specific energy to 500 Wh/kg to achieve the same range results as a conventional turboprop propulsion aircraft.

While the batteries available today don't offer promising results for weight, flight range, or power-to-weight (energy density) ratings, battery technology continues to improve over time in more than just the aviation sector. As stated by Kammermann et al. (2020), lithium-ion batteries being developed for use soon could have around 400-600 Wh/kg energy densities. Research is being done in developing lithium-sulfur batteries that have a higher energy density than lithium-ion, however, they currently have much shorter life cycles, requiring frequent replenishment. Nevertheless, the overarching challenge is that even if battery technology achieves 500 Wh/kg, the energy density of the most advanced batteries will still be 25 times less than that of liquid fuels and 50 times lower than hydrogen (Kozakiewicz & Grzegorczyk, 2021).

SECTION V.

Lithium Batteries

Unfortunately, weight and energy density ratios aren't the only factors threatening the future of batteries in electric aircraft. More issues arise in the material used in these batteries, lithium, which currently holds the most promise for use in all types of electric vehicles. This material is growing so rapidly in popularity, that many analysts consider it the new “white gold,” according to research by Tabelin et al. (2021). This statement was proven in 2019 when over sixty percent of the total lithium produced was used in the manufacture of lithium-ion batteries. Their research estimates that this number will grow to more than ninety percent of global lithium consumption by the year 2025 (Tabelin et al., 2021).

The hesitation to use lithium in electric vehicles, regardless of its potential, stems from its environmental impact and the overall danger it poses. According to a letter by Wanger (2011), the world’s second largest lithium reserve, located in Bolivia in a large salt pan, contains about 5.4 million tons of lithium ore. This location remains untouched due to its natural beauty and status as a major tourist attraction and source of income for the locals. If this reserve were to be mined, the impact wouldn’t only devastate the local economy, but also potentially pollute the water supply for this population in the mining process (Wanger, 2011). Even after the mining process, lithium still poses a threat to people, as cited in reports by the Federal Aviation Administration (FAA) as the cause of 256 aircraft incidents involving damaged lithium batteries causing smoke, fire, or explosions (Tabelin et al., 2021).

Although credible threats, these issues don’t challenge the future of lithium batteries near as much as the exponential demand matched by limited resources. By 2025, the demand for lithium in battery applications will reach 174,000 tons (Tabelin et al., 2021). By 2050, the annual lithium demand for electric vehicles in the U.S. alone is predicted to reach 55,000 tons (Wanger, 2011). However, the projected supply of lithium does not match the increasing demand, as currently operating mines are only estimated to increase production by two percent to five percent in the next few years. According to these projections, global lithium reserves are predicted to be depleted as early as 2038 (Tabelin et al., 2021). **Figure 4** below depicts the growth of lithium demand and visualizes the point where demand may soon exceed the availability of global reserves and resources.

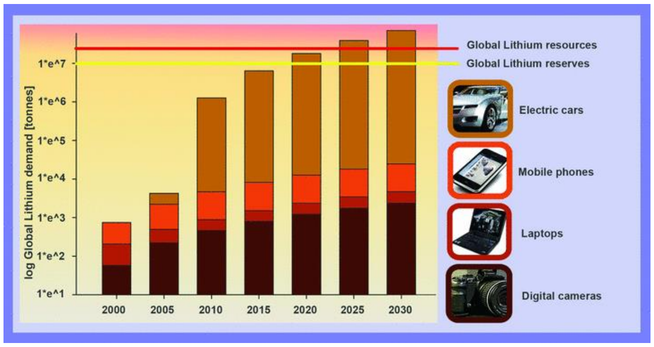

Figure 4. Global Lithium demand for Lithium-ion batteries and available global resources. From Wagner (2011).

A favorable solution to this problem is the establishment of lithium recycling facilities to reduce the reliance and consumption of global resources. However, some research shows that it may already be too late, and even if one hundred percent of all lithium batteries today were recycled, this could not prevent the depletion of global resources. **Figure 5** shows that even the one hundred percent recycle rate would only have a twenty-five percent reduction in predicted lithium consumption by the year 2030 (Wagner, 2011).

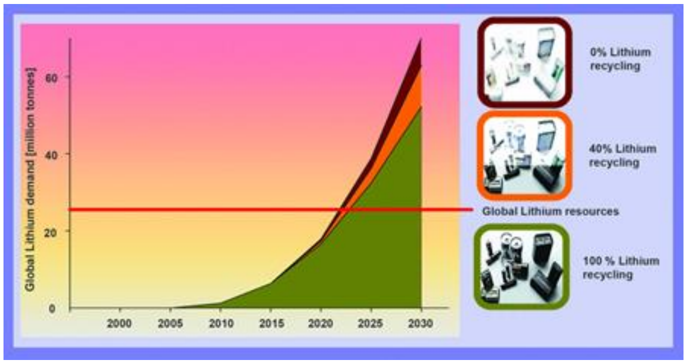

Figure 5. Effect of Lithium recycling on global Lithium demand. From Wagner (2011).

SECTION VI.

Incorporating Multifunctionality

Due to the weight challenges discussed in **Section IV**, developing multifunctionality in new aircraft designs is increasingly beneficial, especially for fully electric aircraft. Multifunctionality, to put it simply, is the ability of a component on the aircraft to serve more than one purpose. This reduces the overall number of components necessary for the full operation of the aircraft, which can result in a reduction of the aircraft's total weight. **Figure 6** shows an example of multifunctionality in the Solar Impulse II solar-powered aircraft, which incorporated solar cells into the wing, fuselage, and tail surfaces. The Solar Impulse II accomplished a spectacular flight around the globe in 2016 (Kozakiewicz & Grzegorczyk, 2021).

Figure 6. Solar Impulse II solar-powered aircraft. From Kozakiewicz & Grzegorczyk (2021).

Similarly, the research of Jones et al. (2021) discusses a multifunctionality concept relating to the structure and materials used to build future electric aircraft. The technology would incorporate structural, thermal, and electrical properties into the exterior structure, reducing the need for heavy wires and cable harnesses for the electrical system. The report discusses two main methods of storing energy in the skin, either through bonding thin capacitors or batteries to the exterior surface or embedding batteries in a honeycomb structure on the interior of the skin structure. There is also a benefit to utilizing both techniques to achieve higher energy output with dual structural energy storage functionality. **Figure 7** shows a potential make-up of a structural laminated battery matrix system.

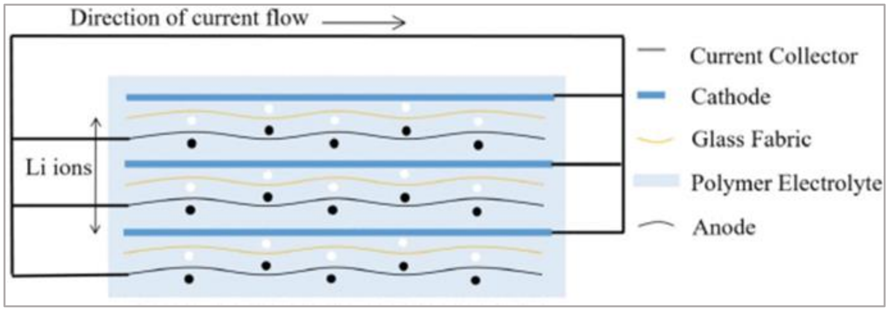

Figure 7. Structural battery with laminated structure. From Jones et al. (2021).

However, there are multiple challenges with incorporating batteries or capacitors into the skin of the aircraft. Jones et al. (2021) describe one of these challenges being the physical degradation of the battery. Normal degradation occurs due to the swelling and contracting of the carbon fibers during repeated charging and discharging of the battery. While research into this technology is ongoing, it has been demonstrated that coating the carbon fibers in lithium fluoride nanocrystals can reduce swelling.

Another challenge is the thermal management of the structural battery system to prevent the equipment from overheating or the composite skin from thermal degradation. If the resin is heated to its glass transition temperature, the resin will soften, and the composite will lose its structural integrity and could break. If the resin exceeds this temperature, the composite could reach the point where it starts to decompose and loses all structural strength and stiffness. Either case would cause significant damage to the aircraft or result in a catastrophic failure in flight. Some structures have been previously developed with thermal management for use in space satellites with electronics embedded in the honeycomb core of the structure. In these cases, copper or composite heat straps bonded to the exterior of the structure have been used to conduct heat away from the electrical source (Jones et al., 2021).

Further challenges arise in developing the carbon fiber reinforced polymer (CFRP) that will contain the structural batteries, without reducing the mechanical performance of the aircraft skin. Finding the right balance between good electrical performance and mechanical strength for the resin matrix will be detrimental to the success of this technology. This also includes developing methods for testing the mechanical integrity of the CFRP for absorbing a mechanical load, and for manufacturing the panels themselves at a large scale with repeatable and dependable quality (Jones et al., 2021).

Even facing all these challenges with battery degradation, thermal management, and mechanical performance, a multifunctional aircraft skin with embedded electrical energy storage capabilities will help solve the problem of overall system weight and move electric aircraft propulsion closer to realization. Additionally, Jones et al. (2021) concludes, a fully capable all-electric aircraft does not have to be the immediate product of this technology. Work can be done to gradually develop multifunctionality from a more electric aircraft, or a hybrid design, to an all-electric version once the structural battery technology is fully developed. More electric, hybrid, and all-electric aircraft concepts will be discussed further in **Section IX** of this paper.

SECTION VII.

Fault Management

Although the challenges and potential faults with electric aircraft technology discussed in the previous section were based on theoretical equipment designs, there are various weak points that still need to be discussed regarding already realized technology in use today in electric vehicles. While equipment faults are no stranger to conventional combustion aircraft either, multiple levels of redundancy are intentionally built into those systems to prevent catastrophic failure or loss of the aircraft if something were to go wrong. For instance, if the battery were to fail on a piston engine aircraft, there is a backup battery capable of handling the electrical load of all essential equipment, which will occur automatically without pilot input. There is also an additional backup battery installed in the secondary avionics if an electrical power loss or system fault causes the primary avionics to fail. Redundancy is also built into the propulsion system, which is designed to continue running in the event of an electrical system failure, resulting from an electrical fire, battery failure, or alternator failure. Dual engine-driven magnetos are designed to provide the electrical source required by the ignition system, and each of the magnetos can independently run the engine if one were to fail.

This same devotion to redundancy needs to be engineered into electric propulsion systems to demonstrate a level of safety at least equal to that of combustion aircraft for this technology to be a viable alternative. A reliable fault management system would need to be capable of preventing a total electrical power loss to the propulsion system and other equipment essential to the safety of flight. There would also need to be a way to manually control the distribution of electrical power to individual system components and to monitor the voltage, amperage, and power flow through those components to safely manage the electrical system in an abnormal or emergent scenario. According to Flynn et al. (2019), if one of the main wingtip thrusters failed on the NASA X-57 Maxwell electric aircraft concept (**Figure 8**), there would not be enough rudder authority available to overcome the yawing forces on the aircraft. Therefore, to maintain directional controllability of the aircraft, the pilot would need the ability to decrease the power output in the opposite wingtip thruster, and/or divert electrical power to the smaller booster thrusters on the wing with the failed engine, which would normally be shut down in cruise flight. This ability would be even more crucial in the takeoff and landing phases of flight, which are typically at lower air speeds, and can result in an uncontrollable longitudinal roll at low altitude with little room and time to recover. This is one of the highest dangers threatening modern twin-piston aircraft, resulting in the loss of aircraft every year.

Figure 8. NASA X-57 Maxwell electric aircraft concept.
From Gent (2023).

An additional threat to both combustion and electric propulsion aircraft is lightning strikes. However, the difference in the level of this threat lies in the materials used in the exterior structure of the aircraft. Ebersberger et al. (2022) describes the conductivity of the metal skin on conventional aircraft, which is designed to protect the internal electronics by conducting the electric charge away from the essential equipment. Electric aircraft designs instead incorporate composite materials, such as carbon fiber, in the aircraft body. These materials have much lower conductivity than metal, therefore require additional features to protect the electrical system from a lightning strike. Not only should the critical electrical components be engineered with overvoltage protection, but areas with a high probability of a lightning strike, such as the wing tips and propulsive motors, should have metal mesh or foil built into the composite body material. This would create a highly conductive path for the electrical charge to travel, possibly culminating at discharge lines on the trailing edge of the wing.

The fault management system engineered for an all-electric aircraft will also need the ability to dissipate the thermal heat resulting from a potential overvoltage, battery fault, environmental extremes, or excessive electrical load. Aside from small avionics fans, cooling systems on aircraft are primarily designed for engine cooling or atmospheric systems for passenger comfort. This prioritization would need to shift in electric aircraft designs with much of the cooling system keeping the batteries and electrical components within temperature tolerances. Ebersberger et al. (2022) discusses the temperature range that a typical aviation battery experiences throughout a flight. Batteries, which are usually stored in compartments that are not climate controlled, can experience ambient temperatures swinging from −70°C at higher cruising altitudes to +50°C at airports in hot regions. Typically, colder temperatures reduce a battery’s capacity, while hotter temperatures can reduce a battery’s total life cycle.

In the worst cases, the added stress on a battery in a high-temperature environment can lead to thermal runaway, especially during takeoff when the power demand is high on the electrical system. According to Ebersberger et al. (2022), thermal runaway occurs when excessive heat energy cannot be dissipated quickly enough, resulting in the ignition of the battery cells and the production of toxic gas. Electrical vehicle fires are especially difficult to extinguish, as Barnes (2021) reports, a burning combustion engine car requires 500-1000 gallons of water to extinguish, while an electric car fire requires 30,000-40,000 gallons. Electric vehicle battery packs are also known to reignite after several hours and even burn when submerged in water. Therefore, a thermal management system is critical in electric aircraft to prevent catastrophic battery failure and a potential fire in flight. Luckily, fire detection devices, extinguishing agents, and fire isolation zones are required to meet aircraft certification parameters (Ebersberger et al., 2022).

SECTION VIII.

Maintenance Challenges

In addition to the challenges of fault management in flight, are the challenges of preventing those faults through effective aircraft maintenance. Since electric propulsion systems are a new and innovative technology that has yet to be fully implemented in aviation at an operational level, there are few maintenance technicians with the training and expertise to work on these systems. Furthermore, there is little knowledge in the industry regarding the maintenance requirements that electric aircraft will face, and the types of maintenance issues that will arise as equipment wears and ages. To get ahead of this challenge, Naru & German (2018) compiled a list of feedback from maintenance professionals regarding the issues that they estimate will emerge in the wake of aircraft electrification. The following is the list of their findings:

- High-speed bearings inside the electric motor cores will need to be monitored and replaced at regular intervals.
- Contaminants, abrasion, and vibration can cause damage to windings, requiring the electric motor to be removed and overhauled.
- Thermal damage to wires and insulating components would need to be strictly monitored.
- High-power batteries will necessitate special training for inspection and repair protocols.
- Connector damage on batteries is expected, including damage from the battery being dropped during installation or removal.
- Electric motors may not be serviceable in the field, requiring removal and shipment to dedicated repair shops.

The high safety record of the commercial aviation industry is due to the multiple levels of redundancy designed into modern combustion engine aircraft. Electrification of aircraft propulsion systems will not be feasible unless this same level of reliability and safety can be integrated into electric aircraft systems. The integration of a fault management system will be essential for the detection of faults and must provide a solution for managing the cooling of the electrical system and for the distribution of electrical energy throughout individual components. Additional research is also needed regarding the unique maintenance challenges that will arise in an electric aircraft fleet. A systematic stepping-stone approach may be required to develop electric aircraft technology from a hybrid model to an eventual all-electric design, which will be discussed further in the next section.

SECTION IX.

All-Electric vs. More Electric

While it seems that aircraft manufacturers and government agencies are racing to launch their version of an aircraft with an electrical propulsion system to meet the demands of an electrified aviation market, one may wonder if this is the right approach in essence of safety and technological responsibility. Instead, maybe the evolution of electric aircraft should slow down and take baby steps toward the end goal of eliminating the need for liquid fuels. This thought is not unusual, as researchers have contributed considerable effort into the development of hybrid designs, versus a fully electric model. This section analyzes this research to contrast the all-electric and more electric, or hybrid, proposals.

A large-sized all-electric concept, intended for commercial passenger-carrying missions, has yet to be realized. Although, there are some models in service today implementing more electric concept architectures. For instance, the Boeing 787 and its competitor Airbus A380 both utilize electrical power to actuate systems that have been historically driven via pneumatic bleed air from the engines, or through fluid hydraulic pressure pumps. As depicted in **Figure 9**, some of these systems now implementing electrical power in these aircraft include flight control surface actuation, ice protection, electrically actuated brakes, and cabin environmental systems. It is estimated that by converting these aircraft and replacing multiple subsystems with more electric technology, the total weight of the aircraft can decrease by ten percent, making them more economical in flight (Gohardani et al., 2011).

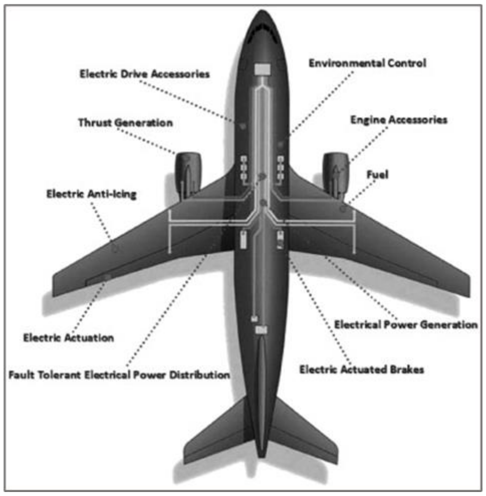

Figure 9. Modern aircraft electric subsystems.
From Gohardani et al. (2011).

Modern conventional aircraft, other than the B-787 and A-380 previously discussed, distribute the power output from the engine(s) into four primary elements. Those elements are mechanical, electrical, hydraulic, and pneumatic energy to operate the various systems onboard the aircraft. The major energy consumers other than thrust generation are avionics systems (electrical), flight control and landing gear actuators (hydraulic), and environmental control and ice protection (pneumatic). In some advanced concepts of more electric aircraft, such as NASA's STARC-ABL in **Figure 10(a)**, the primary output of the combustion engines are through generators and power energy converters, which distribute electrical energy to the aircraft’s various subsystems and its primary electric propulsive motor. Comparatively, all-electric models, such as ESAero’s Eco-150 in **Figure 10(b)** and NASA’s N3-X in **Figure 10(c)**, utilize evenly distributed propulsion systems made up of numerous small electric motors to provide all electrical power and propulsion for the aircraft’s operation (Barzkar & Ghassemi, 2020). Additionally, **Figure 11** depicts an all-electric version of a Beechcraft King Air 200 with its various electrical subsystems in the aircraft architecture.

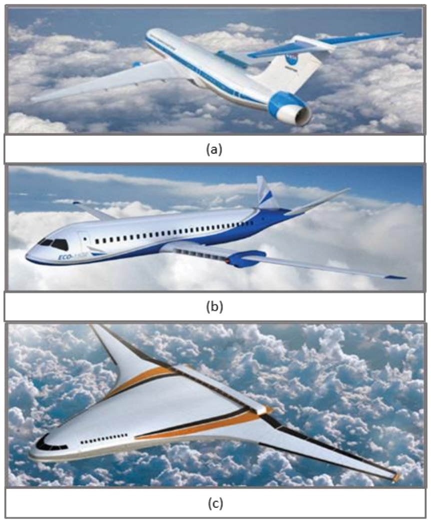

Figure 10. Examples of proposed More Electric and All Electric aircraft concepts. From Barzkar & Ghassemi (2020).

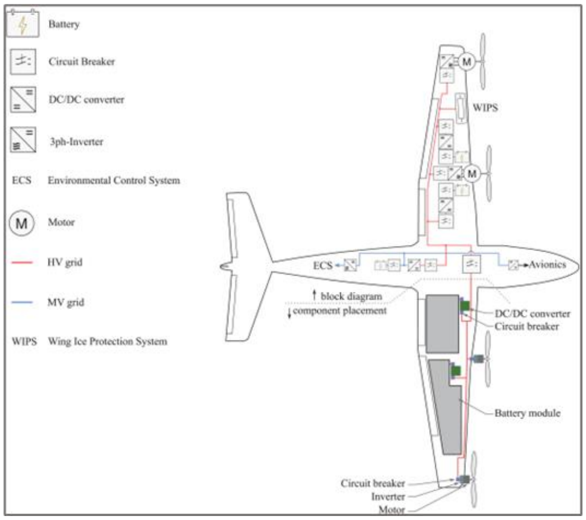

Figure 11. All Electric aircraft modeled after Beechcraft King Air 200 series. From Ebersberger et al. (2022)

Creating a large-capacity, all-electric commuter vehicle that can carry numerous passengers is currently impractical due to the limitations of existing battery technology explained in **Section IV** and **Section V**. Aerospace Engineer Gokcin Cinar from the University of Michigan points out that jet fuel outperforms batteries by holding 50 times more energy per unit of mass. To illustrate, a single pound of fuel can generate the same amount of energy as 50 pounds of batteries. Cinar emphasizes this point by using the Boeing 737 as an example. To achieve full electrification of this aircraft, one would need to occupy all available passenger and cargo spaces with modern batteries. In such a configuration, the all-electric 737 would only be able to provide just under an hour of flight endurance (Cinar, 2022).

There are essentially three versions of electric propulsion system architecture that are the frontrunners in electric aircraft design. First, is the hybrid-electric structure, as the schematic in **Figure 12(a)** outlines, where a conventional turboprop engine is combined in parallel with an electric motor powered by batteries. Alternatively, the electric motor(s) could be powered in series via either batteries or a voltage generator. The second electric propulsion architecture in **Figure 12(b)** instead operates in a turbo-electric structure where the conventional engine provides the electrical supply for the main propulsive electric motors. Finally, the last schematic in **Figure 12(c)** depicts an all-electric design where the battery acts as the sole power source for the propulsion system, eliminating the need for a conventional combustion engine in aircraft architecture (Kozakiewicz & Grzegorczyk, 2021).

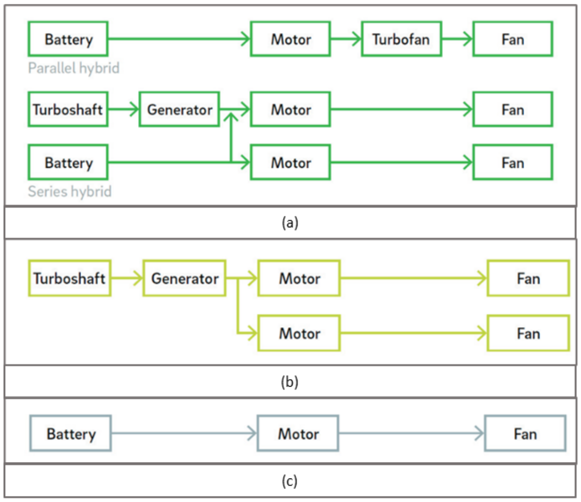

Figure 12. Diagrams of electric propulsion architectures.
From Kozakiewicz & Grzegorczyk (2021).

The most promising of these three architectures for commercial operations is the turbo-electric structure in **Figure 12(b)**. In some designs, the turbine engine in this configuration acts more as an auxiliary power unit to generate the electricity to charge the batteries, rather than to provide thrust or propulsive power. With fully charged batteries, the aircraft could maneuver around the airport environment solely under electrical power, reducing the local carbon emissions at airports. The turbine engine, acting primarily as a generator in this case, could then be activated as a power assist during takeoff, acceleration, or other phases of flight to maintain sufficient power output for aircraft performance. **Figure 13** depicts a hybrid-electric regional aircraft from Heart Aerospace, capable of carrying 30 passengers, and is expected to be in service by 2028. United Airlines and Air Canada have both placed the initial orders for this aircraft, and 50-70 passenger variants are expected to be developed soon after (Cinar, 2022).

Figure 13. Heart Aerospace Hybrid-Electric concept.
From Cinar (2022).

Commercial aviation is making the shift toward more electric aircraft technology to harness the benefits of reduced weight, resulting in increased energy savings. Several transport-category aircraft studied by Decerio & Hall (2022) show a potential reduction in fuel consumption ranging from two percent to sixty percent depending on the size of the aircraft and the flight range. Hybrid-electric propulsion systems, such as those discussed above, have the highest energy-saving potential with short-range missions, making smaller commuter aircraft the ideal targets for electrical propulsion architecture. Hybrid-electric and turbo-electric systems, similar to the ones depicted in **Figure 14** and **Figure 15**, can increase the fuel economy of these smaller aircraft, while also benefiting from reduced weight and higher payload capacity. As the world continues to push for clean energy and reduced emissions, advances in electric propulsion technology may become a viable alternative for larger commercial aircraft, thus reducing the aviation industry's considerable share of the carbon footprint.

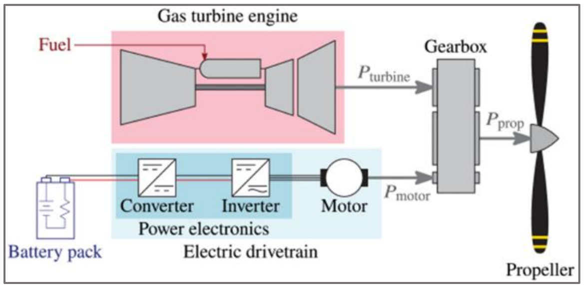

Figure 14. Hybrid-electric propulsion configuration. From Decerio & Hall (2022).

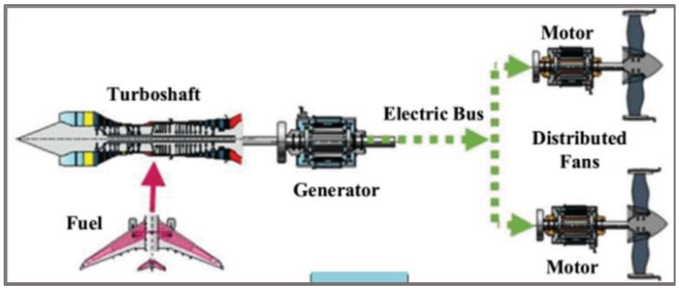

Figure 15. Turbo-electric propulsion configuration. From Barzkar & Ghassemi (2020).

SECTION X.

Regulation and Certification

The final area to introduce is that of the regulation and certification requirements for novel aircraft or engine designs. Unexclusive to electric aircraft, all new developments that aircraft manufacturers make must meet current regulatory standards or find unique ways to comply with those standards using a novel approach. This is typically accomplished through a Special Condition, Equivalent Level of Safety (ELOS), a Means of Compliance (MoC), or a Supplemental Type Certificate (STC) for updates to a preexisting model. Regardless of these multiple avenues, one of the biggest hurdles preventing manufacturers from simply innovating, building, and selling, are these regulatory and certification processes that take large amounts of time and money to overcome.

The organization that regulates and approves these processes, while assisting manufacturers in safely implementing novel designs and technologies, is the Federal Aviation Administration (FAA). In order to better understand and capture the certification challenges facing electric aircraft in this report, I conducted an interview with Tim Smyth, retired Eastern Regional Aircraft Certification Office Branch (ACOB) Manager for the FAA. During Tim's 31-year career with the FAA, he gained experience overseeing small airplane propeller/airframe/engine STCs, leading small airplane/engine certification projects, and implementing and revising regulatory and advisory certification standards and FAA policies. This experience made Tim a subject matter expert and a must have interview for my research (T. Smyth, personal communication, October 31, 2023).

Regarding electric aircraft specific experience, Tim managed teams who worked on certification basis development and policy efforts to support certification programs for electric-powered projects by MOOG and Bye Aerospace. When asked about any foreseen challenges regarding the regulation of electric aircraft for commercial use, Tim responded, "with any new technology there are technical challenges to identify and overcome," and, "some of the efforts in all-electric aircraft have not been done before." Tim further suggested that "commercial use applications for any new aircraft category/technology as comprehensive as introducing a new propulsion system, require a broad coordination and review effort with multiple groups within the FAA to establish clear safety impact understandings with the associated new operational and maintenance needs" (T. Smyth, personal communication, October 31, 2023).

However, he then added that new regulatory efforts are already published or are currently being drafted to establish the regulatory safety requirements for integrating this new technology into the National Airspace System (NAS). A lot of learning will occur during this integration and the key to its success will be working together to identify and address the unique issues and needs presented by this technology. Regulations and certification standards will need to be continuously revised to address and mitigate the safety impacts these aircraft will have on the existing transportation system (T. Smyth, personal communication, October 31, 2023).

SECTION XI.

Summary

The purpose of this paper has been to compile the findings of multiple areas of research into electric propulsion systems for aircraft and to analyze those findings to consider electric aircraft as a viable replacement for modern internal combustion models. There are numerous benefits to electrifying aircraft, however, the primary driver behind the development of the technology has been the reduction of carbon emissions. Commercial air transportation generates over 900,000 tons of CO2 each year, contributing two and a half percent to the global carbon footprint (Kozakiewicz & Grzegorczyk, 2021). While advancements in combustion engines have greatly increased their efficiency and reduced their carbon output, the growth of air travel alone has resulted in a steady increase in the total contribution to greenhouse gases, as depicted in **Figure 15**. Thus, the motivation to eliminate combustion engines has taken the engineering forefront.

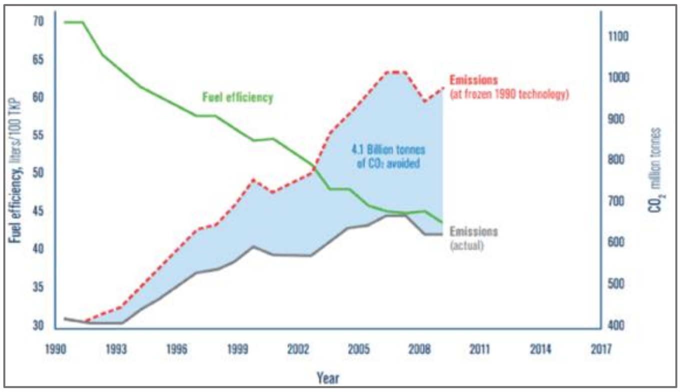

Figure 15. Commercial airline emissions since 1990: Forecast if maintaining 1990 technology (Red), Actual with modern technology improvements (Grey), Fuel efficiency (Green.) From Wheeler et al. (2021).

However, the transition to an all-electric fleet cannot happen overnight, due to the numerous challenges, which have engineers vying for novel solutions. One of these challenges, discussed in **Section III**, is the efficiency and range performance of an electric propulsive unit versus a modern combustion engine. While both aircraft types are limited by weight, a combustion aircraft gets lighter as it burns fuel, thus becoming more efficient and increasing its range while it flies. This is not the case for electric aircraft that will takeoff and land at the same weight.

Current battery technology is incapable of providing sufficient power to achieve the same range results as liquid fuel, as addressed in **Section IV**. Therefore, the realization of an all-electric commuter aircraft will not come to fruition with the necessary endurance until battery technology advances to higher energy density (Wh/kg) ratios. Luckily, aircraft manufacturers continue to drive this progression, as the Pipistrel Velis Electro demonstrates, with the world's first electric motor (see **Figure 16**) certified for general aviation operations. The light aircraft currently boasts a 50-minute flight endurance with a one-hour rapid charge time (Kozakiewicz & Grzegorczyk, 2021).

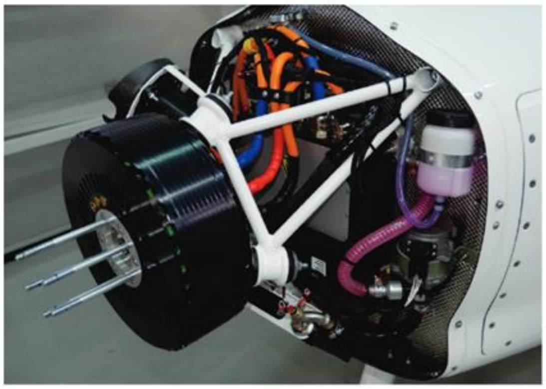

Figure 16. E-811 motor developed by Pipistrel.
From Kozakiewicz & Grzegorczyk (2021).

Developments in battery technologies to support all-electric aircraft operations rely heavily on the availability of Lithium as discussed in **Section V**. However, with current demand on Lithium and current consumption rates, we are likely to face a shortage of Lithium, bringing both economic and environmental consequences. Therefore, there is an immediate need to initiate Lithium recycling efforts to reduce the economic costs and environmental impacts of natural resource exploitation. Since the scarcity of Lithium resources cannot be prevented with recycling alone, there is also a need to research and develop other types of alternative energy. Some promising research is currently being conducted on metal-air batteries, bioelectric batteries (using glucose for example), and hydrogen fuel-cell technology (Wanger, 2011).

The problems of efficiency, flight range, and weight contributions of an electric propulsion system, necessitate the multifunctionality of aircraft components. **Section VI** addressed this engineering mentality with the example of laminating batteries in the structural composite aircraft skin. Until the power density of batteries improves, designing components to serve multiple functions will help reduce the overall number of components onboard the aircraft, thus reducing the weight and increasing the total flight range. Thinking outside the box in the engineering phase of electric aircraft design will be crucial to the success of the technology and its potential to replace modern combustion-driven commuters.

One of the more crucial design elements in all aircraft is the implementation of a capable fault management system. This is even more pertinent in electric aircraft, as **Section VII** derives, with the use of lithium-ion batteries as the power source. Onboard fires resulting from an electrical fault or thermal runaway of a battery would result in the catastrophic loss of the affected aircraft. Similar fires in electric cars have required excessive amounts of water and time to extinguish, and that's with relatively available and rapid emergency response. If a fire emergency were to occur on an electric commuter aircraft at a high cruising altitude, possibly over mountainous terrain or open water, it would take a considerable amount of time for the aircraft to descend and land, all while racing the voracious flames. Safety should be the number one priority in electric propulsion system architecture, which should also provide a reliable and redundant fault management system capable of isolating individual components and redistributing electrical power.

Additionally, more effort and research need to be allocated toward the unique maintenance challenges that technicians will face when electrification takes place, especially in the commercial aviation sector. The Federal Aviation Administration regulates air carriers with strict standards that are mostly the result of lessons learned from equipment faults leading to air accidents. Unfortunately, incorporating majorly novel technology in an industry that has been primarily centered around combustion engines since the birth of the airplane, leaves more of the lessons learned ahead of us, than behind us. Taking the time to consult with maintenance professionals to predict impending technical challenges will also be crucial in the early engineering phase of electric propulsion design. It only takes one catastrophic air accident to lose consumer and passenger trust, which is vital to the success of aircraft electrification.

Taking a stepping-stone approach to the implementation of electric propulsion may be the answer to its success. Rather than an immediate transition to an all-electric fleet, **Section IX** considers more-electric or hybrid architectures. In a turbo-electric system, a gas-driven turbine provides an electrical source, usually through a generator-rectifier, which is capable of driving the primary propulsive electric motor(s) and underlying subsystems onboard the aircraft. This approach greatly reduces the typical fuel burn and carbon emissions of a gas-only model, without sacrificing performance criteria such as flight range. The utilization of these hybrid systems before the launch of all-electric models would move the industry in a satisfactory direction, while allowing time to further develop electric propulsion and battery technology.

Lastly, **Section X** presented the challenges regarding the regulatory and certification side of designing novel aircraft and propulsion systems. While every new development in aviation encounters these same hurdles, extra emphasis must be placed on electric aircraft certification standards to reduce the safety impact these aircraft will have as they enter the National Airspace System. According to Tim Smyth, “technology breakthroughs are required to achieve a level of performance (and safety) to make electric powered aircraft commercially viable.” He also concludes that “new regulatory certification safety requirements need to be finalized and published” by the Federal Aviation Administration, “to allow a level playing field for all interested to participate.” Currently, many of the big aerospace companies are involved in this effort to obtain government regulatory authorities’ commitment and support for electric aircraft technology as a new transportation system (T. Smyth, personal communication, October 31, 2023).

Altogether, the challenges facing electric aircraft technology are daunting to say the least. The goals of eliminating combustion aircraft and implementing systems that develop and run off clean energy are achievable but must be approached with safety and reliability at the forefront. To conclude that these systems aren’t viable would be like saying 50 years ago that nobody would ever be able to walk around with a computer in their pocket. The inevitability of aircraft electrification once battery technology allows for it is clear. Therefore, there is a mounting need for research into batteries, primarily in lithium refinery and recycling, and expanding energy density capacities.

SECTION XII.

Conclusion

The pressure to combat greenhouse gas emissions is being felt worldwide and is no stranger to the aviation industry. While the electrification of cars is well on its way, considerable research into challenges unique to electrifying aircraft is being performed to determine the architecture needed for a safe and reliable electric fleet. Some designs have seen successful implementation into the general aviation market, such as the Pipistrel Velos Electro discussed in the previous section. Others are making headway in the Urban Air Mobility movement with eVTOL (electric vertical takeoff and landing) air taxis.

Companies like Joby Aviation, Volocopter, and Archer Aviation have begun the race toward FAA certification. Each of their prototypes are targeting the ridesharing market, intent on carrying a handful of passengers a short distance around cities or toward nearby airports. Some models can travel up to 200mph and at distances of up to 150 miles, while others boast capacities for up to six passengers once fully autonomous flight is allowed. These eVTOL aircraft would serve as a quieter, more economical, and more sustainable replacement for modern helicopters (Velazquez, 2023).

Soon, we will see the same developments and success in commercial aviation operations implementing distributed propulsion architectures and electric propulsion in varying degrees. While eVTOL companies have built successful electric aircraft models, this paper highlights the need for additional research to accomplish the same engineering feats in larger commercial carriers. It was determined in **Section V** and **Section XI** that lithium batteries cannot be counted on as a sustainable power source due to the inevitable exhaustion of resources. However, other alternative energy projects are underway in the realm of hydrogen powered engines, which were not discussed in this paper, but should be considered for their use in commercial aircraft. The need for additional research is also highlighted in **Section VIII** regarding predicted maintenance challenges and a solution for training a large community of mechanics in a completely novel technology.

Only time will tell when a fully electric commercial airliner comes to fruition and flies silently over our heads. To reach this era in aviation will take a collaborative effort between subject matter experts in numerous fields to determine a safe and sustainable path toward zero emissions. The challenge of engineering an electric commercial aircraft highlighted by this paper should serve as a motivator, rather than a deterrent, toward our common goal of sustainability. The responsibility lies on the shoulders of the entire human race to find a way to reduce the global carbon footprint and to pass the keys to a healthy planet over to future generations.

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