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Powering the Future of Electric Aviation

** All authors contributed equally to this memo. The names are listed alphabetically by surname.*

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Abstract

Aviation is one of the largest contributors to climate change on this planet, responsible for nearly 5% of the global warming impact on Earth. As the aviation sector is projected to grow and as new aircraft are introduced, aviation's impact on climate change will only increase. Without sustainable alternatives implemented in the near future, aviation could strongly contribute to making this planet uninhabitable. This paper examines the possibilities of electric aviation and other power sources in reducing the impact of aviation on climate change. Although there are many power sources for aircraft, electricity is the most effective and sustainable power source. Electric aviation, however, is still relatively new, and there are limitations with electric power, such as battery size, energy density, and charging. This paper dives deeper into the applications and factors to consider for the implementation of electric aircraft into the current society, as well as a potential solution to accelerate the process. Specifically, our research finds that hydrogen fuel cells, despite a few limitations, provide the amount of energy necessary to develop capable and sustainable electric aircraft in a manner that may be the most feasible.

Problem Statement

Emissions from the aviation industry are a large contributor to climate change and environmental pollution—the effects of which include global warming, health hazards, and economic decline. Electric aircraft, if implemented, are a practical solution to reducing emissions and the adverse effects that follow. However, electric aircraft have certain limitations that currently prevent them from being implemented into the mainstream, including issues with battery technology, power sources, costs, certification, and infrastructure. We aim to provide solutions to these issues and accelerate the process of establishing electric commercial aircraft within our current society.

Context

Emissions

Aircraft produce emissions that are hazardous to the environment. The most notable result of aircraft emissions is Carbon Dioxide(CO_2), which is often used as an indicator of pollution. Data suggests that aviation-related CO_2 emissions comprise 2% of the Global Greenhouse Gas Emissions.[12] This percentage is expected to increase by 3-4% per year.[1] The source of these emissions is propeller and turbofan engines, found in most aircraft. Both engines produce a high volume of pollutants, and although there are prototypes in development, there are no operational commercial full-electric powered aircraft.

Contrails

Aircraft condensation trails, also known as contrails, are an important factor to consider in aviation. Contrails are easily identifiable behind jet-engine aircraft. Contrails form when exhaust gasses mix with air and liquid water condensation occurs, usually in suitable environments where the humidity becomes high enough or the air temperature becomes low enough. It is estimated that 16% of the atmosphere has sufficient conditions to support contrail formation.[5] Contrails are not dangerous to humans directly, but are linked to climate change by warming the earth.

Climate Change

Climate change is a worldwide problem that is being deeply investigated. As the global temperature increases, it is anticipated that extreme weather events can take place, water and food quality/quantity will be negatively affected, and health hazards will increase.[17] Aviation contributes greatly to this: *"aircraft are estimated to contribute about 3.5 percent of the total radiative forcing (a measure of change in climate) by all human activities and that this percentage, which excludes the effects of possible changes in cirrus clouds, was projected to grow."* [1] Aircraft emissions and contrails are the main parts of aviation that contribute to climate change. Whereas emissions take place both on the ground and in the air, contrails only take place at high altitudes.[5] By reducing emissions and contrails, the impact of aviation on climate change can be diminished.

Costs

Airlines require immense amounts of jet fuel to operate their flights on a daily basis. For example, on a single 10-hour flight, 36,000 gallons of fuel can be consumed.[12] However, jet fuel is expensive, and the price is rising. These rising fuel prices are partially responsible for the rising price of air travel. From January to May 2022, the price per gallon of jet fuel increased from $2.36 to $3.90.[22] Although that amount might seem like a small increase, the thousands of gallons of fuel airlines use results in a large cost difference. The price of fuel does vary when comparing North America to Europe or Asia; however, the increasing trend remains present. Engine manufacturers such as General Electric, Rolls Royce, and Pratt and Whitney seek to reduce the fuel consumption of their engines as time progresses. General Electric, for example, has made a large improvement to their engine to power the new Boeing 777-9. When comparing the fuel efficiency of the GE-9X (jet engine for the Boeing 777-9) to its predecessor, the GE-90-115B (jet engine for the Boeing 777-300ER), the GE-9X has a 10% improvement in fuel consumption.[16] Engine manufacturers also seek to reduce emissions and pollutants produced by engines as time progresses. However, all these benefits come at a cost.

Overview of Electric Aviation

Why Electric Aviation?

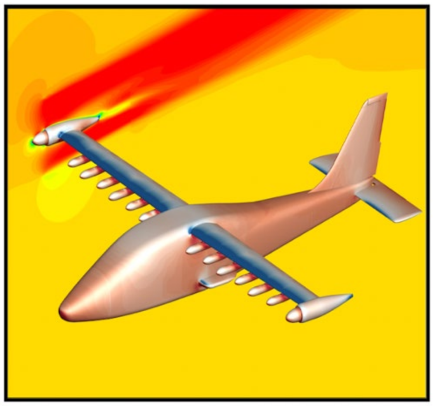
Air travel has been increasing rapidly and is projected to grow in the future; however, emissions from aircraft still remain. Electric aircraft can significantly cut aviation emissions, reduce noise and pollution, and provide cheaper travel.[8] Although commercial electric aircraft are not yet in operation, their development continues, and innovation is surging in the industry. Various companies and organizations such as Wright, Heart Aerospace, NASA, Airflow, and Beta Technologies are striving to produce electric aircraft, most of which are interested in producing regional or short-range aircraft. There are few long-range electric aircraft in development in 2022.

Economics

Electric aircraft will be inexpensive to operate relative to conventional jet engines, which would reduce the cost of flying overall. Fuel costs will decrease as electricity becomes the main power source as opposed to jet fuel. Furthermore, maintenance costs will also be reduced. Heart Aerospace suggests that *"Simple, reliable electric motors reduce maintenance costs by 90% compared to turboprops, and intelligent electronic monitoring reduces inspection needs. Most* *importantly, fuel costs go down by 50-75%."*[9] Reducing maintenance and inspection needs would allow airlines to maximize the potential and capabilities of the aircraft, allowing it to go through more flight cycles and operate conveniently. Although electric aircraft are not as capable as jet-engine aircraft, they will still be able to provide benefits for certain routes and ranges.

Environmental Impact

Electric aircraft will provide substantial environmental benefits by reducing emissions greatly. Reducing emissions will help in the effort to curb aviation's impact on climate change. Furthermore, reducing CO_2 emissions makes aviation cleaner and better for the earth. Heart Aerospace and Wright claim that their planes—the ES-19 and Wright Spirit, respectively—will have zero emissions as well.[14] Although electric aviation may help to reduce current environmental issues overall, certain factors, such as the electricity generation or battery production processes, may present problems. However, these issues can be addressed by ensuring that the methods used for these processes are sustainable and eco-friendly. Moreover, contrail formation is another environmental impact that must be considered. Although electric aircraft do not form contrails, hybrid-electric aircraft and any aircraft that combust fuel will emit particles and thus contribute to contrail formation. Still, these alternatives to traditional jet fuel do lessen contrail formation at lower altitudes, as the temperature threshold is lower (meaning a higher altitude is necessary for contrails to form) if Sustainable Aviation Fuels(SAFs) or liquid hydrogen are used.



Courtesy of NASA

Alternative Aircraft Power Sources

Sustainable Aviation Fuel (SAF)

As part of the effort to curb the use of traditional jet fuel, alternatives like SAFs are being researched. SAFs are a relatively new technology that are being implemented widely at this time (2022). SAFs are biofuels that are derived from alternative renewable sources such as corn grain, oil seeds, algae, fats, gasses, wood mill waste, agricultural and forestry residues, and energy crops.[20] SAFs are effective at reducing the carbon footprint of aviation, further advancing sustainability goals. British Petroleum (BP) claims that "*SAF gives an impressive reduction of up to 80% in carbon emissions over the lifecycle of the fuel compared to traditional jet fuel it replaces, depending on the sustainable feedstock used, production method and the supply* *chain to the airport."* [25] Although SAFs do not eliminate carbon emissions completely, the reduction does make a difference. However, SAFs are costly to produce and thus more expensive than regular jet fuel, which is one of the reasons for the lower demand. BP believes that creating more demand for SAFs in the future could reduce the price and increase their use. On the other hand, an advantage of SAFs is that they can be implemented in all aircraft that are certified for using normal jet fuel. Furthermore, it can be blended up to 50% with traditional jet fuel and then recertified.[25] No changes to the aircraft or infrastructure are needed for the implementation of SAFs. Although using SAFs is both convenient and an improvement in efforts to reduce aviation's impact on climate change, it is not the best long-term solution. Electric aviation can have a larger impact with its ability to create net-zero emissions and reduce contrails. While electric aircraft are being developed, SAFs are a good option to reduce the climate impact of aviation. Because long-range and high-capacity electric aircraft are not being developed, SAFs are a good source for reducing the climate impact of long-range and high-capacity travel.

Hybrid Electric Aircraft (HEA)

While many companies are seeking to create full-electric aircraft, hybrid electric aircraft (HEA) are effective at reducing the impact of aviation on climate change.[26] Hybrid electric aircraft are powered by a combination of batteries and conventional power. Research states that they are capable of reducing both emissions and contrails: *"We compared the HEA to conventional (reference) aircraft with the same characteristics, except for the propulsion system. The analysis showed that the temperature threshold of contrail formation for HEA is lower; therefore, conventional reference aircraft can form contrails at lower flight altitudes, whereas the HEA does not."* [27] Contrail formation, as discussed above, is an important factor in measuring the impact of aviation on climate change. HEAs, due to their ability to reduce both contrails and emissions, are important for reducing the impact of aviation on climate change. Although these aircraft are still in the development and testing state, their capabilities are important for the mission to create sustainable air travel.

Liquid Hydrogen

Hydrogen has long been used as fuel for rockets but has recently come into play for commercial flights. Its high energy density allows for flights of a longer range with the benefit of a reduction in carbon dioxide emissions.[28] However, liquid hydrogen must be stored at subzero temperatures, which requires the improvement of storage technologies, both on the aircraft themselves and at airports. Some developing hydrogen planes employ a hydrogen-hybrid system, in which liquid hydrogen is used as fuel for combustion, and hydrogen fuel cells (which will be discussed in more detail later) are used for complementary electric power.

Electric Aviation: Factors to Consider

Introduction

Although many power sources are available to power aircraft, electricity is a viable eco-friendly solution that is closest to being implemented. There are many companies developing electric aircraft, and there have already been many small-scale prototypes, including the E-Genius and Pipistrel Alpha Electro.[26] These aircraft operated short-distance routes with few passengers, demonstrating that electric aircraft were truly possible. Using electric aircraft for commercial aviation requires many factors to be considered for implementation: air traffic, certification, maintenance, infrastructure, and time frame. Power sources, the main part of the research, will be covered in their own section.

Air Traffic

Due to existing barriers in technology, electric aircraft in the near future will be limited in range and size capabilities. As a result, they are only applicable in regional transport. These electric aircraft differ from existing aircraft in the areas of speed and altitude. Electric aircraft, due to their travel distance and capabilities, will be cruising at lower altitudes than medium and long-range aircraft. They will also be flying at lower speeds than such aircraft. This combination of lower altitude and speed may result in additional oversight, management, and vectoring from air traffic controllers due to the larger difference in speeds between electric aircraft and existing aircraft. For example, if an electric aircraft is approaching a busy airport, it may disrupt the approach pattern because other aircraft will have greater approach speeds than it. Air traffic controllers will have to work to maintain separation between the electric aircraft and existing aircraft. Although this may seem like a minor inconvenience, if there are great amounts of electric aircraft approaching an airport, this could result in delays and traffic management trouble. However, these scenarios may be less likely considering that electric aircraft are expected to cover regional routes and airports not frequented by high speed jet aircraft. Electric aircraft can help reduce congestion at large commercial airports by redirecting passengers to regional airports. For example, passengers could use regional airports in Chicago instead of O'Hare or Midway to get to their destination, as long as the electric aircraft were capable of flying those routes. Electric aircraft would be able to fly to less congested airports and reach more remote areas. Due to their lower seat capacities, they would be able to cover routes with low demand. While there are some minor obstacles with electric aircraft and existing traffic, these are problems that can be handled.

Certification

Due to different infrastructure and different power sources, the certification of electric aircraft will be different. Heart Aerospace, the manufacturer of the ES-19 electric plane, states that their aircraft will be certified to CS-23 standards, which are used to certify traditional commercial aircraft as well.[9] Certification could be simpler for aircraft that are based on previous aircraft models, such as the Wright 1, which is built from the base of the BAe 146. As technology is still developing, certification of electric aircraft is still years away. Heart Aerospace and Wright expect to certify their aircraft after 2025.[14] [9]

Maintenance

Due to differences in infrastructure and technology, electric aircraft require different maintenance procedures than existing aircraft. However, these procedures would be less extensive considering that the aircraft in development are small and intended for small-scale regional use. Heart Aerospace claims that for their ES-19 electric plane "*Simple, reliable electric motors reduce maintenance costs by 90% compared to turboprops, and intelligent electronic monitoring reduces inspection needs.*" [9] With maintenance costs reduced, airlines operating electric planes could provide lower-priced tickets for passengers and reduce the cost of regional flying. Maintenance of electric planes is often simpler due to the electric motor being less complex than traditional jet engines. However, electric aircraft maintenance could turn out costly since a single issue might require that the whole motor be replaced. Companies such as MagniX aim to remedy this issue by designing the motor so that individual parts can be replaced in the case of a fault.[7]

Time Frame

As technology is still in development, the time frame for implementation is not concrete. Some aircraft are projected to be flying in this decade (2020s), whereas others are projected to be flying farther in the future.[14] Electric aircraft will slowly be introduced to regional flying in the late 2020s by multiple companies.[9] Larger and more capable aircraft will not be introduced in this decade because they require more innovation and research. Timeframes are constantly evolving, especially with external factors such as the COVID-19 pandemic.

Electric Aviation: Power

Electricity Sources

The power grid, which consists of power plants, transmission lines, and distribution centers, can be used to obtain electricity. However, this method of generating electricity is not ideal as it can require burning a large amount of fossil fuels, and therefore, highly contribute to greenhouse gasses. Electricity drawn from renewable resources is the best method, as it will result in zero emissions. These renewable resources include solar energy, wind energy, hydropower, geothermal energy, and nuclear energy.

Power Storage

The electricity harnessed from renewable resources can be stored in multiple ways to power the aircraft. The most well-known methods are batteries or fuel cells. Each of these methods has their strengths and weaknesses. These strengths and weaknesses will be compared, and a potential solution will be addressed at the end of this paper.

Battery Technology

Overview

The most commonly used power source for electric aircraft is batteries. Batteries allow for the conversion of electric energy into chemical energy for storage. Lithium-ion batteries are most notable for their relatively high specific energy of up to 265 Wh/kg.[15] However, when compared to the specific energy of aviation fuel (12,000 Wh/kg), lithium-ion batteries are significantly less energy-dense. Due to this difference, one lithium-ion battery alone would not be sufficient enough to power an electric aircraft the size of a conventional jet engine plane. If the number of batteries used was to increase, the weight of the plane overall would also increase, resulting in the reduction of performance with range, speed, and altitude. A large difference between batteries and fuel is that the weight of the aircraft goes down as the fuel is used, allowing for the aircraft to minimize fuel burn and fly longer ranges. This also allows for fuel-powered aircraft to use step-climbs and other procedures to reduce fuel burn and land at a low weight. However, batteries do not lose weight during the flight, and thus the aircraft remains at its takeoff weight. Current battery-powered aircraft cannot meet the capabilities of fuel-powered aircraft; they cannot fly as far, as fast, and as high. There are also other concerns with lithium-ion batteries in addition to weight, including environmental damage, cost, and maintenance. Because batteries are heavy and low-power, they would require frequent charging or replacement. Other types of batteries being investigated for greater advantage are lithium-sulfur, lithium-air, and sodium-ion batteries.

Ethics of Batteries

Although it is difficult to trace the exact resources and exact amount of pollution that production creates, it is known that the production of lithium-ion batteries is not a clean process. As expected, lithium-ion batteries require lithium, a resource that must be extracted from the ground. The extraction of lithium is a lengthy process that is often damaging to the environment and requires high amounts of water, *"approximately 500,000 gallons per metric ton of lithium."* In certain areas, lithium production sites, or mines, have consumed great amounts of water, making the environment dry and unsuitable. For example, *"In Chile's Salar de Atacama, mining activities consumed 65 percent of the region's water, which is having a large impact on local farmers to the point that some communities have to get water elsewhere."* [10] Lithium production sites are also dangerous in that leakages can affect the surrounding areas. *"In May 2016, dead fish were found in the waters of the Liqi River, where a toxic chemical leaked from the Ganzizhou Rongda Lithium mine. Cow and yak carcasses were also found floating downstream, dead from drinking contaminated water. It was the third incident in seven years due to a sharp increase in mining activity, including operations run by China's BYD, one of the world's biggest suppliers of lithium-ion batteries."* [10] This incident may seem uncommon, but it is an example of how chemicals and mining activity are capable of disrupting nature and ruining the environment. Lastly, lithium pollution harms the soil and pollutes the air. Although lithium-ion batteries can provide greener air travel, their production is far from a clean process and is dangerous to the environment.

Battery Charging[6]

With a battery charging system, the battery is fixed in the aircraft, requiring the entire aircraft to be maneuvered to a charging station and essentially "plugged in." Using a system like this, aircraft stands may have to be repurposed to service electric aircraft with charging stations. Another downside to this method is that the turnaround time is dependent on the charging rate of the non-removable battery. The longer the battery takes to charge, the longer the turnaround time, leading to delays and possible congestion.

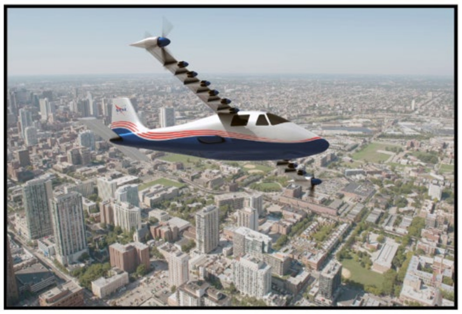
Battery Swapping[6]

Unlike battery charging, the battery can be removed from the aircraft and charged separately before being reattached. This may reduce the turnaround time of an aircraft by enabling the switching of a discharged battery with a fully charged one. Although battery swapping may seem like a smart alternative to immediate charging, it often comes with its own setbacks involving cost and duration. A battery swapping system is more complicated than its counterpart, and the removal and installation of the battery may in itself take up the majority of the turnaround time. Due to the complex nature of the system, it is also more expensive. However, for larger and commercial aircraft, it may be the only viable option for batteries.

Prototypes

Heart Aerospace ES-19 Electric Plane - This aircraft can carry 19 passengers on regional routes. The range of this aircraft is around 250 miles, and Heart Aerospace hopes to certify the aircraft after 2025.[9] This aircraft is an important innovation as it will connect regional cities with low demand. There are multiple airlines/corporations that have shown interest in the aircraft—it will be certified with CS-23 standards and will have low operational and maintenance costs. Heart Aerospace aims to connect more remote areas and provide net zero emission regional travel. This aircraft will be one of the first battery-powered electric aircraft that arises in the electric aircraft market.

NASA X-57 Maxwell - This prototype from NASA serves as a testing mechanism for battery electric aircraft. The aircraft's operational ceiling is 14,000 feet, and it will cruise at a speed of 172 mph when cruising at 8,000 feet. Its takeoff speed is 67 kts, which is low compared to other aircraft, which is a strength.[4] Although the aircraft itself is not extraordinary, it is an important aircraft for testing the capabilities of battery electric power and exploring the possibilities of batteries. This aircraft will not be as beneficial for the regional travel industry since it serves more as a testing prototype, but battery-powered electric aviation will be further tested and investigated through it.



Courtesy of NASA

Eviation Alice - This aircraft is capable of carrying nine passengers in the commuter configuration, which is designed for regional travel. The aircraft can also be configured in the cargo and executive configuration. The aircraft is capable of flying 440 nm in a perfect setting without wind and external factors, and can cruise at a speed of 250 kts. It can also operate at airports with a runway length of 2,600 feet, which is a great feature because the aircraft will be capable of targeting more regional and remote areas.[18] Although its capacity is lower than the

ES-19, it is a good advancement in the battery-powered electric aircraft industry. Small regional airlines, such as those who operate flights between small islands, will be able to use the Alice to connect remote areas and provide cheap and clean transport for passengers.

Implementation

The Alice and ES-19 can be applied to regional travel in the aviation industry. They will be able to provide airlines with emission-free aircraft with low capacities. This will allow airlines to operate sustainable flights to regional airports with low demand. These electric aircraft can reduce the congestion at larger airports and redirect passengers to more local regional airports. Furthermore, some travelers can gain access to travel because these aircraft can be operated in low-demand regions that do not have a large international/intercontinental airport close by. A few problems, however, do arise with these aircraft because of their capabilities. Due to their lower cruise speeds and capabilities, flight times would be increased when compared to traditional aircraft that operate the routes. Furthermore, the approach patterns and traffic management of aircraft may be slightly impacted by these aircraft due to the difference in their capabilities. The air traffic control will have to monitor airspaces and electric aircraft more, but it will not be a major inconvenience. However, the benefits will outweigh the inconveniences with these aircraft.

Comparisons

When comparing the battery electric aircraft to regional aircraft powered by jet fuel, they do lack the capabilities; however, they can still be implemented on the routes. Even though the battery electric aircraft will not be able to match their range, speed, or altitude, they will still be able to cover some routes at a lower capacity and provide sustainable regional travel.

Limitations

In summary, the main limitations of battery electric aircraft are the weight, size, and power. The batteries in the aircraft are heavy and do not lose weight over time, making it more difficult for the aircraft to fly as fast, high, and as far as normal jet-fuel powered aircraft. The batteries are also large and must fit on the aircraft without safety hazards. Furthermore, current batteries (lithium-ion) simply do not have a high enough energy density to power the aircraft, and this resulted in the capabilities of the aircraft being low. While other batteries continue to be researched, presently, batteries are not powerful and light enough to improve the capabilities of the battery-powered electric aircraft.

Summary

When considering all these difficulties with battery technology, it is clear that, in the present day, current battery technology is incapable of powering medium-range and long-range aircraft. Battery technology is a great way to reduce emissions for regional travel, but with current technology, it is simply incapable of powering larger and longer-range aircraft because of its energy density and the limitations discussed. Given the current technology and research, battery technology is not scalable and can only be applied to regional travel. Nevertheless, it can make a good impact on low-demand regional routes and locations. Battery-powered electric aircraft can be useful for local airlines and airlines that want to expand their operations to low-demand areas and reduce their environmental impact. Overall, battery technology is a great advancement and step forward in reducing the impact of aviation on climate change, even if its applications are limited. In the future, with advancements in efficiency and weight, batteries will become a viable option for electric aircraft.

Fuel Cell Technology

Introduction

Fuel cell technology is relatively new, but is being investigated thoroughly. A fuel cell generates electricity for aircraft through a chemical reaction by combining a gaseous fuel, typically hydrogen, with oxygen. Fuel cells require a continuous supply of fuel and air for this chemical reaction to take place. Several aviation companies have researched fuel cells and selected them to power their electric aircraft. There are various types of fuel cells, all with advantages and disadvantages, which are summarized in Table 1 below.

Types of Fuel Cells

Type	**Advantages**	**Disadvantages**
Alkaline (AFC)	• Lower costs • Low temperature/heat	• Sensitive to CO_2 in fuel & air
Phosphoric Acid (PAFC)	• High efficiency • Fuel flexibility	• Low power density
Solid Acid (SAFC)	• High power density • Lower costs	• Slow performance • Long start-up time
Proton-Exchange Membrane (PEMFC)	• Faster start-up time • Fuel flexibility • Easier maintenance • High energy density	• Expensive

Table 1. A chart depicting the various types of fuel cells, along with their advantages and disadvantages.[21]

Hydrogen as Fuel Source

Hydrogen gas is a clean energy source and has no adverse environmental impacts when used, proving to be the best gaseous fuel to power fuel cells. Hydrogen can be produced in various methods and from multiple sources, including natural gas, landfill gas/biogas, petroleum fuels, and electrical energy.[23] The use of electricity in a process called electrolysis is the most ideal method to produce hydrogen as it results in zero greenhouse gas emissions, depending on the source of electricity. Electrolysis involves splitting water molecules into hydrogen and oxygen. If the electricity used for the process is acquired from the power grid or from fossil fuels, then carbon dioxide emissions will be an indirect result of hydrogen production. However, if the electricity is acquired from renewable resources (solar energy, wind energy, hydropower, geothermal energy, nuclear energy, etc.), then there will be no detrimental impacts on the environment. Once the hydrogen gas is produced via electrolysis, it can then be compressed for use within a fuel cell. Within a fuel cell, hydrogen is oxidized to produce electricity for the aircraft. Because this is a chemical reaction that does not involve fuel combustion, there are no carbon dioxide or nitrous oxide emissions produced. However, small amounts of water are released, which can lead to minimal contrail formation.[13] A proton-exchange membrane fuel cell utilizing compressed hydrogen gas has a greater energy density and capacity than a single lithium-ion battery. Therefore, fuel cells are currently able to provide sufficient energy for medium-sized aircraft with relatively long ranges.

Prototypes

ZeroAvia Dornier 228 - ZeroAvia is testing and soon plans to offer the Dornier 228. This 19-seater prototype will use hydrogen fuel cell technology and replace the existing turboprop engines. The hydrogen-electric powertrain aims to decrease aircraft emissions by 90%, decrease operational and maintenance costs by over 60%, and ultimately increase aircraft range by at least 50%.[13] ZeroAvia plans to tackle the logistics of hydrogen-electric powertrains as well. By producing, storing, and transporting the hydrogen required for the fuel cells, they will lay the stepping stones for future infrastructure development.

Wright Spirit - This aircraft, modeled after the BAe 146, is designed to hold 100 seats and uses hydrogen fuel cells to power its four large motors. Wright claims that the Spirit aircraft will provide zero emissions for short-haul, one-hour flights and plans to complete and distribute the aircraft after 2026.[14] During the test and development process, Wright will initially replace one turboprop engine with an electric motor and propeller, and keep the remaining three turboprops. The Wright Spirit will continue replacing turboprop engines with motors until all of the turboprop engines have been replaced by motors. As of 2022, Wright is finalizing motor and inverter development and beginning propulsion fan development. The Wright Spirit promises commercially available ultra lightweight storage, high-power motors, efficient inverters, and integrated propulsors by 2026.

Universal Hydrogen - Universal Hydrogen has developed and is testing a conversion kit for the ATR-72 and De Havilland Canada Dash-8 short-haul aircraft.[24] The conversion kit will replace the turboprop propulsion system with hydrogen-electric fuel cells. The hydrogen fuel cells will facilitate an electric powertrain for propulsion. Relying on the pre-existing network of fuel and cargo handling, Universal Hydrogen expects to be in passenger service by 2025. Additionally, in order to accommodate the aviation emission standards for the Paris Agreement, Universal Hydrogen has conceptualized a hydrogen-powered conversion kit for the widely employed A320 and B737 families.

Summary

Electric aircraft with hydrogen fuel cells are the best option to reduce the impact on climate change overall and for the long term. To quote one of the companies we interviewed, ZeroAvia, “the first, fundamental constraint is that battery-electric, so successful in passenger road vehicles, will not work in commercial aviation, as batteries, even with future predicted energy-density [advances], are simply too heavy. Yet, to truly tackle the climate impact, alternative combustion efforts are not enough. SAF…is not carbon neutral in flight. And hydrogen combustion delivers the carbon savings, but still has [nitrogen oxide] emissions and substantial contrail impact. Electrification is the answer, but it must come from another source. That is why hydrogen fuel cell advancements…are so important.” [13] As more aircraft are developed in the industry, hydrogen fuel cells will prove to be both better for the environment and for the development of larger, more capable electric aircraft as they are able to bypass the limitations that battery technologies pose on electric aviation. Further on in this paper is a proposed course of action to begin converting the aviation industry into integrating hydrogen fuel cell technology in everyday use.

Proposal

Hydrogen Production & Transportation

For hydrogen production, the ideal method would be via the process of electrolysis, which would be run by electricity produced from on-site renewable resources, such as solar power from non-reflective panels (to avoid solar panel glare for pilots). The water used in the process will come from nearby water sources, including freshwater rivers and lakes. This hydrogen production will take place on-site at airports. The infrastructure needed includes an electrolyzer, a compressor, and a refueling truck. The electrolyzer will produce gaseous hydrogen. The compressor will then increase the pressure of the hydrogen by reducing its volume for storage, and the refueling truck will transport the compressed hydrogen to the electric airplane. Another option for transportation would be to install a landside-to-airside pipeline that carries the compressed gaseous hydrogen in a modular tank system. This system allows for the retrofitting of planes already in use. The tanks of hydrogen would be loaded onto an airplane in a manner similar to cargo, strapped down, and connected securely to the aircraft. After the destination is reached, a new tank will replace the depleted tank, which would then be sent back to be refilled at the hydrogen production facility at the airport. This system enables hydrogen to be used throughout all areas of the flight, maximizing efficiency, reducing the overall weight, and improving payload and range.[23]

Certification & Costs

However, because the energy density of hydrogen gas is less than that of jet fuel, the number of seats and size of the fuselage must be reduced. Because these aircraft would be retrofitted, certification of the aircraft would take much less time than if the aircraft were built from scratch. In addition, the cost of maintaining a hydrogen-electric propulsion system would be significantly lower since fuel cells and electric motors have fewer moving parts than traditional combustion engines. There is a lower possibility of damage being done to the system, and there is a longer time between overhaul. The lower operational expense, along with a smaller cabin, significantly reduces the Cost Per Available Seat Mile (CASM), ensuring greater profitability and efficiency. (CASM can be obtained by dividing the operational costs of the airline by the number of available seat miles.)[2]

Hydrogen-Electric Propulsion System

Once the fuel cells are integrated within the aircraft, generators/alternators will power the Auxiliary Power Unit (APU) system of the aircraft. Proton-exchange membrane fuel cells will be used, and the electricity that is generated from them will power the motors. The motors will have propellers, which will then provide thrust for the aircraft as they spin at different speeds in relation to the throttle.

Addressing Limitations

Cost is one of the biggest issues with the implementation of hydrogen fuel cells. However, the cost of fuel cells and hydrogen will decrease due to increased performance, production, and durability. For example, the cost of Proton-Exchange Membrane (PEM) fuel cells decreased by 60% from 2006 to 2018.[11] As the usage of hydrogen fuel cells in aviation rises, the costs will continue to lower. The aviation industry is also heavily dependent on jet fuel, and there is little infrastructure currently to support our solution. Although the amount of infrastructure needed may require a sizable investment initially, the decreased cost of fuel cell operation and increased number of paying passengers due to lower fares will pay for the infrastructure in the long term.

In terms of safety risks, hydrogen can be extremely flammable, and the fuel cells produce heat emissions that may disrupt airplane functionality. However, well-developed safety protocols and execution will ensure safety. In fact, current tests have shown that hydrogen can be produced, stored, and dispensed securely.[19] In addition, the amount of heat produced may not be a significant issue, depending on where the fuel cells are stored and where the heat is released. However, if heat is indeed an issue, heat exchangers can be utilized to neutralize the heat output by the cells. Along with the heat, fuel cells produce some water, although in minimal quantities, so contrail production will remain low. The main issue, however, is that although hydrogen fuel cells are more advantageous than batteries due to their greater energy density, they still do not have the capacity to power a commercial 100-passenger flight over a long range. For the time being, this issue can be addressed by implementing hydrogen hybrid-electric aircraft, which contain both an electric motor powered by electricity generated via hydrogen fuel cells, as well as a combustion engine that burns liquid hydrogen fuel. As a way to begin converting the aviation industry, we recommend that hydrogen hybrid-electric power may be used temporarily until fuel cell technology improves. Table 2 below provides a final comparison between the discussed fuel sources.

Power Source	**Contrails**	**Scalability**	**Emissions (CO_2)**	**Emissions (NO_x)**
SAF	Produced	Good	Produced (minimal)	Produced
Hydrogen Combustion	Produced	Good	None	Produced
Battery Electric	None	Poor	None	None
Hydrogen Hybrid-Electric	Produced (minimal)	Good	None	Produced (minimal)
Hydrogen Fuel Cells	Produced (minimal)	Good	None	None

Table 2. A chart depicting each possible method to power electric aircraft. Information regarding contrail production, scalability, and carbon and nitrous oxide emissions is provided to demonstrate a final comparison.[13]

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