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Establishing a Pathway to Greener Aviation

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Abstract

The burning and production of jet fuel in both commercial and regional planes at a high volume releases extreme levels of carbon emission as of its current state[1]. This paper analyzes the implementation and benefits of three sustainable alternatives to traditional jet fuel: sustainable aviation fuel (SAF), hydrogen fuel cells, and electric batteries. A roadmap to show progress in reducing the carbon footprint of aviation is then proposed.

The first phase of the roadmap involves the evolution of technology, validation, and testing of SAF-powered planes and the preliminary development of hydrogen production and propulsion and battery technology and the development of electric propulsion technologies. The second phase illustrates the widespread implementation of all three fuel sources where electric aviation will be enforced in short-range travel (30 min-3 hrs), medium-range aircraft (3-6 hrs) will use hydrogen fuel cells, and long-range (6+ hrs) airliners will utilize SAF. The third and final phase will enact the use of SAF and electric batteries for long-range applications while hydrogen fuel cells will dominate short- and medium-range aircraft.

This roadmap, in combination with proper legislative action and corporate cooperation paired with public awareness, can help eliminate the usage of jet fuel in the aviation industry and replace it with three more sustainable and clean fuel sources.

Problem Statement

The production of jet fuel on commercial and regional airlines is a large contributor to climate change and the release of carbon dioxide (CO_2) emissions. With the emergence of this new “era of global boiling,”[1] it is imperative to seek the implementation of sustainable alternatives replacing traditional jet fuel. Sustainable aviation fuel (SAF), hydrogen fuel cells, and electric batteries, more specifically, are innovations that can reduce carbon emissions and put flying on a greener path.

Introduction

Aviation has been placed under intense scrutiny as a result of its negative effects on humans and the environment. The production of jet fuel from airlines cost exorbitant amounts of money and additionally impact the releasing of CO_2 emissions, climate change, and health issues. As a result, these effects have driven public officials to mitigate the impact of aviation through legislation.

Emissions

Greenhouse gas emissions from aviation strengthen the greenhouse effect, greatly contributing to climate change. Specifically, aviation contributes to about 2% of the world’s carbon emissions[2], which at first glance, may not seem like a huge issue, however, aviation is highly challenging to decarbonize, unlike other industries like road traffic and power. Some of these prime greenhouse gasses resulting from the production of jet fuel include carbon dioxide, nitrogen oxide, contrails, and particulate matter.

Carbon dioxide, or CO_2, is a chemical compound composed of two oxygen atoms bonded with a single carbon atom which affects the temperature[3]. In other words, less CO_2 makes the earth cold while more CO_2 makes it warmer through the greenhouse effect. Essentially, the sun sends energy and heat to the earth’s surface which normally emits some back into space, but CO_2 gets in the way of some of that by trapping and re-emitting that heat into the earth. Without CO_2, energy would be sent into space very easily, however, the surface of the earth would be frozen. But as more CO_2 is added to the atmosphere, it traps more of that heat going into the earth. On top of that, flying also emits nitrogen oxide, or NO_X, chemicals which heat the planet even further. NO_X are a mixture of gasses, which, like CO_2, absorb long wavelength radiation to trap heat radiating from Earth, and thereby contributing to global warming. In addition, condensation trails, or contrails, which are line-shaped clouds produced by aircraft exhaust, also trap the heat from the sun onto the Earth's surface[4]. Lastly, particulate matter, also known as PM, are particles found in the air such as dust, dirt, and smoke, which act as a pollutant that primarily contributes to human health issues. Overall, these factors pertaining to aviation greatly contribute to the release of CO_2 emissions and as a result the increase in the greenhouse effect[5].

Climate Change

Climate change is a long-term change in temperature over a long period of time. Earth's climate has constantly been changing over the course of thousands of years, long before humans. However, the average temperature has been drastically increasing at an unprecedented rate. Specifically, heat-trapping gasses have already warmed the planet by 1.5°C and 2°C above pre-industrial levels, which is expected to increase throughout the 21st century. In fact, as this warming effect continues to grow, the intensity of droughts, heat, and rainfall will also escalate[6]. This heat-trapping gas, or the greenhouse effect, keeps the planet warm like a big blanket wrapped over Earth. The change of Earth's temperature by one or two degrees affects the health of plants and animals, largely as a result of human activities. More specifically, the burning of fossil fuels to power cars, power factories, etc., causes the irreversible effect of altering the natural greenhouse. Emissions from aviation and the burning of fossil fuels to produce jet fuel are prime contributors to climate change. Nonetheless, by minimizing aircraft emissions with the replacement of sustainable fuel, the influence of aviation on climate change can be alleviated.

Health Effects

Air pollution exposure caused by aviation not only affects the environment but acts as a threat to human health and prosperity too. Public health officials linked the exposure of particulate matter, noise, and air pollution from airplane exhaust to cancer, respiratory, and cardiovascular diseases such as heart disease, lung disease, and asthma, as well as lower school performances among children. These effects are especially common among residents in the vicinity of an airport and are more harmful to children under five, elderly above the age of 65, and lower socioeconomic groups. In fact, a study shows that people living near Seattle airports and under flight paths are more likely to be people of color with lower incomes and have more exposure to the diseases mentioned prior compared to residents who do not live in the area of an airport[7].

Costs

Fuel plays a prominent role in aviation which can be troubling, especially when the airline prices constantly fluctuate. For example, the U.S. National average of one gallon of jet fuel was $6.59 in June of 2023, down 13 cents from the averages in May 2023 and down $1.38 per gallon from June 2022. Nonetheless, the largest reduction in jet fuel price was found in New England, with prices down 37 cents a gallon from May figures. Despite these small reductions in fuel prices, jet fuel is becoming more expensive and continues to rise in price. In fact, the research found that the Western Pacific Region held the largest price, at an average of $7.35 for each gallon[8]. This constant irregular change of jet fuel prices is caused by various dependencies of other countries such as Russia which act as a great source of energy and oil put into jet fuel. These soaring fuel prices trouble the development of airlines because it raises the price of air travel, as travelers are compelled to cover the cost of fuel through higher ticket prices.

Current Legislation

Legislation plays a vital role in addressing aviation emissions, in order to mitigate the environmental impact of air travel and fight climate change, the significance of these efforts must be recognized. In order to curb its environmental footprint, the aviation sector must take comprehensive and coordinated measures to reduce emissions. As aviation continues to expand as a result of global connectivity and economic growth, it becomes increasingly important to move towards environmental responsibility practices. As such, addressing aviation emissions is becoming increasingly important for policymakers, environmental change makers, and the general aviation industry. Legislation plays a vital role in guiding and regulating aviation, having the power to reduce its overall environmental footprint. Two examples of such legislation are the Clean Air Act, and the Kyoto Protocol; both notable pieces of legislation in relation to addressing emissions and climate change.

***Clean Air Act*[9]** - The Clean Air Act, implemented in 1970 with subsequent revisions; mostly in 1990, stands as a pivotal legislative measure that outlines the Environmental Protection Agencies' pivotal role in regulating emissions, including national ambient air quality standards. By setting precise standards for pollutants such as carbon dioxide, sulfur dioxide, nitrogen dioxide, and more, the Clean Air Act plays a part in safeguarding public health and environmental well-being. It demands cooperation between federal, state, and local entities to devise strategies and regulations for emission control, air quality management, and pollution reduction. Furthermore, the Clean Air Act fosters innovation and drives technological advancements by compelling industries to invest in research into greener and eco-friendly alternatives.

***Kyoto Protocol*[10]** - The Kyoto Protocol was an international treaty adopted in 1997 in Kyoto, Japan, with the primary objective of addressing the growing concerns of climate change by targeting the reduction of emissions and greenhouse gasses in the atmosphere. It marked significant milestones in combating climate change by setting binding emissions targets on a global scale. In total, 192 countries participated in the Kyoto Protocol, showing a widespread and global desire to curb climate change. However, the effectiveness of this protocol was hindered by several factors, most notably the lack of participation from major emitters such as the United States and China, limiting its overall impact. The Kyoto Protocol concluded in 2012, in which it was extended with the Doha Amendment; this amendment extended the commitment period to 2020 for participating countries and established new emission reduction targets for the time period. However, the Doha Amendment was replaced in 2015 with the Paris Climate Agreement.

***2021 US Aviation Climate Action Plan*[11]** - The 2021 US Aviation Climate Action Plan introduces a comprehensive framework aimed at mitigating the environmental impact of aviation while promoting sustainable practices. Focused on reducing greenhouse gasses, enhancing fuel efficiency, and fostering innovation over time; this plan outlines ambitious objectives such as emission reduction targets, promotion of electric aircraft, and strengthening of international partnerships. This plan comprehensively addresses the issue at hand by introducing a clear, achievable, and ambitious framework in order to be effective in implementing and developing these changes and advancements to work towards a goal of net zero aviation emissions by the year 2050. The US Aviation Climate Action Plan aligns with global efforts to combat climate change and reflects broader international commitments to sustainability. Considering that aviation continues to play a crucial role in modern society, this plan takes on even greater importance, reflecting a profound understanding of its own environmental impact. The plan emphasizes reducing greenhouse gas emissions and improving fuel efficiency in order to achieve a low-carbon future. This forward-looking approach, which includes promoting electric aircraft and international collaboration, contributes to the collective ambition to improve the environmental sustainability and resilience of the aviation sector. The long-term vision of the plan, aiming for net-zero aviation emissions by 2050, positions the United States as a trailblazer in the global pursuit of sustainable air travel.

Insufficiencies

Despite current legislation and policy efforts aimed at curbing the environmental impact of the aviation industry, these initiatives still do not address the wide scope needed to make a significant impact on emissions. While acknowledging the significant role that legislation plays, it is becoming increasingly evident that a more coordinated and profound approach is needed to properly address climate change. Current legislation may become insufficient because of high costs related to technology adoption, limited public awareness, and legislation's voluntary nature.

Int. J Aviation Management[12] – Adoption of more sustainable practices is often hindered by high costs and regulatory complexities, overall limiting growth in the field of sustainability. These factors collectively hinder the integration of eco-friendly alternatives, therefore impeding the growth of more environmentally conscious solutions within the aviation sector. A critical reevaluation of economic models and regulatory framework is essential to incentivize the transition towards greener aviation. Collaborative efforts among aviation companies, government, and research institutions can help streamline regulations, promote research into cost-effective alternatives, and foster innovation to mitigate financial barriers.

Handbook of Environmental Policy[13] – There is an overall lack of education when it comes to the significant impact of aviation emissions on the environment, despite the substantial environmental impact of these emissions, public awareness remains inadequate. This lack of awareness translates to less pressure on policymakers to enact stricter regulations and stimulate demand for greener aviation alternatives. Aviation contributes significantly to greenhouse gas emissions and climate change, and educational efforts about its environmental consequences are crucial to empower individuals and communities to advocate for change. Increasing public understanding about the impact of aviation emissions can amplify demands for sustainable aviation practices, foster technological development, and encourage industry-wide shifts towards more environmentally friendly operations.

Current incentive programs aimed at reducing aviation emissions often rely on voluntary participation from airlines. This approach can create a gap in reduction efforts, as some airlines may choose not to engage, emphasizing the importance of establishing stronger regulations to ensure consistent and widespread emission reduction practices. While voluntary participation can foster innovation and accommodate varying circumstances, it is not efficient to achieve the necessary level of emission reduction across the entire aviation industry. In-depth regulations, backed by comprehensive research and international cooperation are crucial to set a baseline that all airlines must adhere to. Such regulations could include emission caps, technology adoption requirements, and carbon pricing mechanisms. Currently, there are numerous airlines who have proposed such plans individually and serve as groundbreakers in roadmapping to reduce emissions. One of such airlines includes Delta[14] who has notably published a detailed roadmap including current statistics as well as milestones and timely goals. Other notable airlines who have proposed sustainability roadmaps include United Airlines[15] and American Airlines[16], who both have proposed timely goals and milestones concerning their impact on environmental sustainability, all similarly set to achieve net-zero emissions by 2050.

Alternate Power Sources

In order to reduce the dependency on and emissions of fossil fuels, the development of many alternative propulsion power sources such as SAF (Sustainable Aviation Fuel), hydrogen, and electricity is currently ongoing. This section will examine the uses of the fuel, current projects, growth, and their limitations.

SAF (Sustainable Aviation Fuel)

Introduction

SAF or Sustainable Aviation Fuel is a strong candidate in the effort to reduce emissions and ultimately make aviation a net-zero operation. Unlike standard jet fuel which is extracted from fossils and deposits in the earth, SAFs are made from old biological mass, making it a renewable and environmentally friendly alternative[9]. Even though it is burned, SAF has a low net environmental impact because when the fuel was produced, CO_2 had to be taken out of the atmosphere, creating a cycle that replenishes itself over time and does not draw from a finite resource supply like jet fuel. Additionally, aircraft do not need to be redesigned for SAF use nor do the pilots need additional training[17].

Currently, SAF is derived from sources such as biomass, waste oils, sewage, and many other renewable feedstocks. This allows for relatively cheap production and can help clean up many dirty environments that are littered with biomass such as decaying forests or sewers[17].

Projects

Increased awareness regarding climate change and the need to curb aviation emissions have led SAF adoption to grow greatly in recent years. Various organizations have already started incorporating SAF into their daily operations.

Airbus[18] - In the fall of 2021, Airbus, a major airliner manufacturing company, worked with CFM International, a renowned jet engine producer, to deploy an A319neo with 100% SAF capabilities. Additionally, Airbus has equipped its aircraft with engines that allow 50% blend capabilities with jet fuel. They are trying to raise this to 100% by 2023.

Commercial Airliners[19] - Alaska Airlines, American Airlines, British Airways, Finnair, Japan Airlines, and Qatar Airways announced plans to purchase up to 200 million gallons of ethanol-based SAF per year over five years from renewable fuels producer Gevo.

Growth

The future outlook for SAF is promising. As technology advances and economies of scale are achieved, it is expected that the price of SAF will come down and its usefulness will grow. In fact, the International Air Transport Association (IATA) noted that with the right policy support, SAF could make up to 2% of all aviation fuel by the middle of the 2020s and the price of SAF could be equal to jet fuel by around 2037[20]. However, as of now, the cost of SAF is around $1.1 per Liter which is more than double the current average rate of jet fuel which is around $0.5 per Liter.

Limitations

Despite SAF's great environmental benefit and growing capabilities, it still holds many limitations which simply cannot be fully overcome with more research and development. One of these is the emissions produced during transportation and other parts of the production cycle. These make it so SAF is not fully net-zero and still creates 20% of the emissions that jet fuel produces as of now. Also, as demand for biological material rises for SAF production, feedstocks will need to grow and harvest in a more sustainable and climate-friendly way, As of the present, the total global production capacity for Sustainable Aviation Fuel (SAF) is estimated to be approximately 0.8 billion gallons and is projected to increase significantly and reach two billion gallons by 2027. This growth is driven by specialized producers actively expanding their production capabilities, and new entrants are expected to join the SAF market, further contributing to the increase in production capacity[21]. The emissions may go down, however until all factors of SAF production, delivery, and use are net-zero, then SAF cannot be called full net-zero.

Additionally, the use of SAF does not prevent the adverse health effects of exposure to particulate matter from airplane exhaust or noise. These exposures have been linked to cancer and lower school performance among children living near airports and areas with high air traffic[22].

Hydrogen

Introduction

Hydrogen is a promising alternative fuel source that, with proper development, can provide clean and renewable energy for application in aviation. Effective production and implementation of hydrogen as a fuel within the context of aviation will ideally eliminate all carbon emissions, both during flight and throughout the process of production; hence, the value of hydrogen as a step along the Pathway to Greener Aviation is evident. Hydrogen power may be incorporated into aircraft as a power supply for a hydrogen fuel cell or for direct combustion. The former option is preferable, as while hydrogen combustion notably does not produce CO_2, its emissions include NO_x particles and increased amounts of water vapor. Comparatively, hydrogen as used in fuel cells is a zero-emission energy source, optimal within the ongoing climate crisis, and suitable for improving the sustainability of aviation[27].

In order to ensure the successful development and deployment of hydrogen aircraft, these standards of sustainability must be extended to the production of hydrogen itself. There are three primary methods of hydrogen production, referred to as gray, blue, and green hydrogen. Gray hydrogen is the least preferable of these three, with its production process involving the derivation of hydrogen from natural gas, generating CO_2 as a byproduct. Blue hydrogen presents an improvement upon this method by capturing the CO_2 byproduct during a steam reforming process, reducing negative environmental impact. Green hydrogen, however, is the ideal process of hydrogen production, utilizing renewable sources of energy such as electricity, wind, or solar photovoltaic to derive hydrogen from water through electrolysis[28].

The storage of hydrogen during transportation, refueling, and flight is an additional logistical aspect that requires particular consideration for this alternative fuel source. Hydrogen may be stored as a liquid within cryogenic systems or as a pressurized gas; given hydrogen has a smaller volume as a liquid, it is most likely that liquid hydrogen will be applied in aviation as opposed to gaseous. Nonetheless, even liquid hydrogen poses constraints for efficient storage, as liquid hydrogen's volumetric energy density is approximately four times less than that of traditional jet fuel, and consequently demands approximately four times as much storage space[29].

Current State

In its current state, hydrogen as an aviation fuel source is still within the stages of early development, due to some of the specific needs and concerns which are presented above. Hydrogen aircraft and infrastructure for hydrogen production and distribution are still yet to mature, though ongoing progress is underway to tap the full potential that lies therein. Airbus is one such company that is taking an active role in the development of hydrogen in aviation. Airbus reports taking the initiative to develop infrastructure for the supply of liquid hydrogen, projected to take place from the present (2023) to 2030[30]. Additionally, the Airbus ZEROe project is presently exploring three design concepts for hydrogen aircraft, projected for release by 2035. Current reports and estimates suggest that hydrogen power could be viable for commercial passenger aircraft on flights up to 3,000 km (short-range) by 2035 and 7,000 km (medium-range) by 2040, indicating the expected technological progress which will be made over the coming decades[31].

Growth

Discussion of growth areas for hydrogen primarily concerns the development of cost-effective hydrogen production and design for sufficient storage. Production of green hydrogen is not currently cost-effective, resulting in only about 1% of hydrogen being produced through this method. As hydrogen infrastructure is established and strengthened, the International Energy Agency (IEA) predicts that the costs of producing green hydrogen through renewable electricity could fall roughly 30% by 2030, a promising statistic for the future economic prospects of hydrogen aviation[32]. This progress can be supported through legislative action providing economic incentives to utilize environmentally conscious fuel sources such as hydrogen, or else the imposition of taxes on traditional jet fuel. The previously discussed storage constraints which liquid hydrogen presents also serve as a focus and direction for growth. Conventional aircraft would not be able to feasibly accommodate hydrogen storage needs, requiring the retrofitting of currently functional aircraft or the design of new models. Hydrogen aircraft on long-haul flights would require an enlarged fuselage for storage or a blended wing design, which would produce a triangular shape. Such new designs would likely improve fuel efficiency and aerodynamics as an additional benefit besides arranging for hydrogen storage[33].

Limitations

The limitations of hydrogen in aviation are arguably equivalent to the areas of growth, as the directions for growth explained above outline the actions that must be taken to overcome the challenges which hydrogen poses: namely, concerns of storage demands and economic viability. These are both lasting issues that arise from the composition of hydrogen itself and are accordingly inherent to the energy source, obstacles that prevent the immediate application of hydrogen as an aviation fuel. These obstacles will require further development and continual innovation to address and overcome.

Electricity

Introduction

Electric-powered vehicles are a flourishing industry in 2023. Electric cars have become very popular with about three million Americans owning one. If planes were to start running off batteries, not only would that mean a full emission-free flight, but in the long run it could actually be cheaper. Batteries are an investment, but once acquired, the batteries are reusable and upkeep is minimal. In addition, electric motors are quieter, which lowers community noise during takeoff and landing[34].

Current state

Currently, electric-powered aircraft are being developed. An aerospace company called Heart Aerospace, which has been leading the movement toward electric aviation, has been developing an electric regional airliner called the ES-30. The ES-30 is a battery-powered aircraft that utilizes four electric motors, and hybrid turbo generators which serves as a backup during the battery-electric flight. The plane will carry 30 passengers and can travel 200 kilometers on fully electric power and 400 kilometers on hybrid power[36]. Diamond Aircraft Industries has also been working on an electric plane. This plane, called the eAircraft, is fully electric with countless amount of testing hours and research. It can fly for 90 minutes and costs up to 40% less to operate than a piston aircraft[35].

Growth

Flight length and range using batteries is predicted to improve over the coming years, and leading to fewer limitations. In the mid-2030s the range is predicted to be 300 kilometers for electric and 500 kilometers for hybrid, and in the late 2030s 400 kilometers for electric and 600 kilometers for hybrid. Currently, there are zero emissions at airports for electric-powered aircraft on routes up to 200 kilometers[37]. As the battery evolves this number will increase.

Limitations

The biggest limitation of electric planes is the weight of the batteries. Batteries are very bulky and weigh a lot which impacts the range of the aircraft so they will not provide enough energy for an efficient and prolonged flight. Another weight-related issue is that batteries do not combust[38]. With jet fuel, SAF, and hydrogen, during the flight, the fuel is released causing less weight in the plane at the end of the flight. However, with batteries, they are just as heavy at the end of the flight as they were in the beginning.

Just like any other aviation fuel, battery storage is a significant consideration. When a battery is in storage, it self-discharges or gradually loses charge even when the battery is not being used. The state of charge decays with time and the rate of decay is greatly affected by the storage temperature. The higher the temperature, the faster the battery loses its charge, making a cooler place to be stored, better. As a battery loses its charge, the sulfate level in its plates increases causing it to take longer to charge and last shorter[39].

Hybrid Electric Aircraft (HEA)

Hybrid electric aircraft, HEA, is a step towards electric planes that consists of both fuel and batteries being used to power the plane. They are expected to take around 30 to 50 minutes to charge for a plane with a 250-mile range, and there is also an idea being tested about charging batteries during the flight. A HEA works by using electric motors to help with takeoff and landing and the traditional engines supply power during cruising. This allows the traditional engines to not work at full power. A big reason why hybrid planes have not taken off as much as other hybrid vehicles is because planes are much more sensitive to weight[40]. HEA are more of a stepping stone to electric planes because in order for hybrid planes to work, the range for batteries needs to increase, and if it increases then the more logical option would be to go to electric planes. In addition, a HEA reduces emissions by 5%, whereas fully electric planes reduce emissions almost completely[41].

Energy Density and Specific Energy

Energy Density - Energy density is the amount of energy stored in a certain amount of volume or mass of a substance. Understanding the energy density of fuel in aviation is critical because of the strict limitations on weight, volume, and aerodynamics needed for efficient and cost-friendly flight. Therefore, the higher energy density a fuel has, the more energy it carries in a certain weight or volume, enabling longer and more efficient flights.

Specific Energy - Often confused with energy density, specific energy is the energy content per unit mass of a substance. Specific energy is crucial in aviation because it directly impacts the performance and range of aircraft. Higher specific energy means that a lighter aircraft can carry the same amount of energy, enabling more efficient flight.

Analysis

For high-speed and long-range aviation, finding the optimal fuel with the best energy density and specific energy ratings is key. Below is a breakdown of one of the most energy-dense batteries currently on the market compared to a standard UL Power 520IS Engine running on gas power.

When compared to a gas-powered engine, an electric motor shows itself to have a higher efficiency (see Table 1); meaning that it loses less energy to sound, heat, and vibration. However, the battery’s specific energy is lower and when multiplied by the motor efficiency, it is shown that the specific energy used for propulsion or “effective specific energy” is higher for gasoline than a battery, revealing that using gas would be the lightest option as of now.

Table 1. The process to calculate the effective specific energy for gas-powered and battery platforms

Factors	**UL Power 520IS Engine (gas powered)[23]**	**Amprius 500 Wh/kg Battery Platform paired with a standard motor[24]**
Motor Efficiency	~30%[23]	~85% (Optimal)[25]
Specific Energy	12,700 Wh/Kg[26]	500 Wh/Kg[24]
Effective Specific Energy	**3,810 Wh/Kg**	**425 Wh/Kg**
Image Credit: UL Power (Image 1), Amprius (Image 2)		

Taking this a step further, the weight of the equivalent of a 100-kilogram fuel tank of gas in batteries can be calculated.

$$3{,}810Wh/KG \times 100KGFuelTank = 381{,}000Wh$$

By multiplying the effective specific energy of the engine by a 100-kilogram fuel tank, it is revealed that 381,000 Wh of energy would be used to drive the aircraft forward.

$$381{,}000Wh \div 425Wh/Kg = \sim 896.4Kg$$

Dividing this total by the effective specific energy of the AMPRIUS battery shows that, in order to store the same amount of usable energy as a 100 kilogram gas tank, a battery made with today’s technology would need to be around 896.4 Kg, close to 9 times the weight of the gas tank.

Outcome

Many propulsion systems are in need of more development and research. Electricity, like described in the analysis above, is one of them. These fuel sources need more time for development and research in order to become viable for many classes of aviation. Understanding these complexities is important for drafting a feasible and realistic plan for alternative fuel implementation.

Roadmap Proposal

Figure 1 shows a roadmap that is split into three phases. Each phase is based on a set amount of years to build or improve on green aviation technology. The first phase lasts from the present day until 2028 and will focus on the implementation of SAF-powered planes and the further development of renewable energy and battery technologies. The second phase lasts from 2028 to 2040 and will revolve around the administration of all three technologies in the industry at varying levels. The third phase lasts from 2040 to 2060 and beyond, revolving around the improvement and upkeep of SAF, hydrogen, and battery technologies. The goals of each phase are summarized in Table 2.

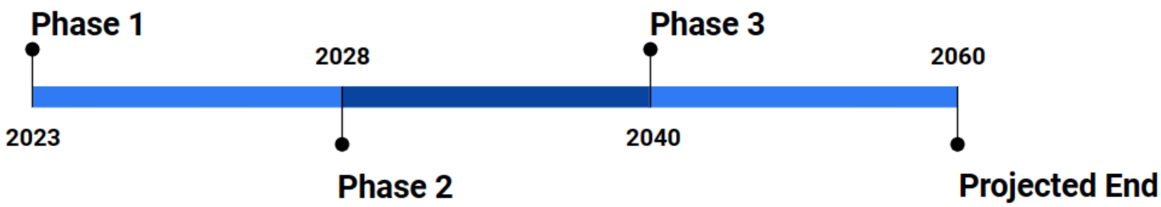

Figure 1. Roadmap

To complete this roadmap, two major assumptions have been made in order to simplify the process of data collection and research. Primarily, all statistics and research are based on the United States to create a standard to base calculations and plan ahead. Secondly, corporate and government cooperation has been assumed in order to simplify the process of outsourcing the technology and infrastructure necessary to complete the roadmap.

Phase 1

The first phase of the roadmap to greener aviation will take place from the present day until the year 2028. There are four main goals to be accomplished during this time period, all of which will greatly contribute to the development of the three aforementioned technologies and set the stage in order to execute the remaining two phases of the roadmap.

The first goal is a legislative action to introduce new laws and taxes for high-emission fuels. The tax mentioned would be a “Cap-and-Trade” system[42]. Under this system, each airline gets a “carbon allowance” based on their historical rate of emissions. This represents their right to emit a certain amount of greenhouse gases and other high-emission gases. If the airline has a surplus allowance, due to higher usage of SAF versus traditional jet fuel, they could choose to sell it to other airlines. This model allows for increased incentives to reduce emissions and creates a market to make money if the airline is able to operate greener.

The second goal is to continue the development of SAF for commercial applications. This will be accomplished by developing new ways to acquire SAF in a sustainable manner, lowering the cost of SAF, and increasing production[43]. To acquire SAF in a more sustainable manner it is proposed to use waste sewage, organic cooking oils, agricultural residues, municipal waste, and other biomass products. By finding more sustainable sources of SAF, it is possible to increase its production and more quickly phase out gas. Lastly, the slow phasing out of gas will gradually decrease the cost of SAF.

The third and fourth goals relate to the growth of battery technology and renewable energy sources[44]. To rapidly expand in the battery technology field, a federal policy framework must be created that encourages the growth of battery technology through a reward system. This framework will highlight clean-energy-related job opportunities along with their impact on climate change. In terms of renewable electricity, it is important to incentivize corporations to create sustainability teams (which are dedicated teams to influence policies and set goals to promote sustainability).

Phase 2

The second phase of the roadmap takes place from the years 2028 to 2040. During this time period, the two main goals are to introduce hydrogen fuel cells as a mainstream alternative fuel source and to continue the promotion of SAF in the aviation industry. With the advent of both of these accomplishments, the use of traditional jet fuel in the aviation industry will be eradicated. Electric-powered battery engines will be used for short-range flights, hydrogen fuel cells will be implemented in medium-range aviation, and SAF will dominate long-range applications.

The first goal is to introduce hydrogen fuel cells into aviation. In its current state, hydrogen will require a drastic change in the infrastructure of fueling, docking, and on-flight storage to be able to be used properly and safely[45]. The completion of this task will allow hydrogen to quickly and easily enter the aviation industry because the necessary hardware will already be in place.

The second goal will be in regard to the legislative and economic aspects of hydrogen introduction. Primarily, one of the main strategies to promote hydrogen over jet fuel will be to place a tax on kerosene (one of the major components of jet fuel)[46]. By doing this, jet fuel will become noticeably more expensive and hydrogen will be viewed as a stronger and more viable alternative. Another economic benefit of the usage of hydrogen is the predicted thirty percent reduction in hydrogen production costs by 2030 due to its production using renewable electricity[47].

The third goal will be to make hydrogen the primary choice for medium-range flights (ranges of 3,000 and 7,000 kilometers) by 2040. This will be accomplished by completing the aforementioned tasks, namely the taxing of kerosene and a decrease in hydrogen production costs.

Finally, the fourth and final goal will be in regard to the continued development of SAF. At this point in the lifetime of SAF, it is expected that it will already be viewed as a reliable alternative to jet fuel because of the measures taken in Phase 1 in the developmental stages of SAF. As of the present day, it is expected that SAF has a projected growth to reach three billion gallons of SAF usage per year by 2030[48]. This, combined with the annual growth rate of SAF usage of sixty percent by 2033 will prove that SAF is a major competitor to leading jet fuels[49].

Phase 3

The third and final phase of the roadmap to greener aviation takes place from 2040 to 2060 and beyond. At this stage of the timeline, SAF and electricity are implemented as energy sources for long-range aviation, while hydrogen is utilized for short- and medium-range applications. This phase can be considered a resolution and goal of the prior decades ' developments and is itself a period of significant growth that carries us forward into the distant future.

Building upon the action points of previous phases, SAF infrastructure should be well developed and mature by this time. The U.S. Department of Alternative Fuels Data Center has placed a yearly SAF consumption goal of 35 billion gallons by 2050; in comparison to the 2030 yearly SAF consumption goal of 3 billion gallons, this demonstrates the exponential growth of SAF applications[48]. Within Phase 3, the SAF industry may be strengthened and expanded through a focus on international production. SAF manufacturing must take place in proximity to the feedstock supply; internationally produced SAF would ensure access to refueling for international flights, thus broadening the reach of SAF aircraft. An additional incentive for this initiative is the economic independence that local SAF production can bring to nations. SAF feedstocks should be globally available, meaning nations can be self-reliant in the production of SAF.

Electric aviation is projected to observe great progress within Phase 3, as the continual development of battery technology works toward the eventual widespread application of batteries in long-range aviation. Sources suggest that all-electric aircraft can account for an estimated 3% of total US passenger miles by 2040 (limited to short-range flight at this time), growing to an estimated 25% by 2050, illustrating an outlook of major growth for the industry[50]. Electricity has been slow to mature throughout this roadmap, but this phase should lead to the utilization of its full potential. Beyond the development of battery technology and electric aircraft, infrastructure for electric aviation will be established and broadened to ensure accessible recharging for flight.

Finally, sustainable green hydrogen will be implemented for short and medium-range applications within Phase 3. The value of the global hydrogen aviation industry is suggested to jump from an estimated $27.68 billion in 2030 to $174.02 billion by 2040, exhibiting massive growth as the usage of hydrogen aircraft becomes more widespread and efficient[51]. This roadmap's presented course of action involves the primary use of hydrogen aircraft for short- and medium-range flight; short-haul flights alone account for over 17% of total carbon emissions within the aviation sector, making the elimination of this impact through zero-emission hydrogen a significant contribution to the green future of aviation[52].

Table 2. Summary of goals for phase of the roadmap

Phase 1 (2023-2028)	Phase 2 (2028-2040)	Phase 3 (2040-2060)
● Implementation of SAF-powered planes ● Development of renewable energy and battery technologies	● Entrance of hydrogen fuel cells as a viable and mainstream option ● Extreme progress for SAF in the aviation industry ● Completely phase out traditional jet fuel and replace with three alternative fuel sources - Electricity for short-range flights - Hydrogen for medium-range flights - SAF for long-range flights	● Resolution to prior phases ● Reaching development goals and full future potential of the three introduced alternative fuel sources - Continued usage and expansion of SAF in long-range aviation - Advent of electricity in long-range aviation - Efficient application of hydrogen in short- and medium- range aviation

***Authors 'Note* -** The stages of development and initiative outlined within this roadmap are not intended as a definite, rigidly constructed series of proposed steps, as the broad scope and logistical complexities of this topic make all corresponding solutions nuanced and necessarily flexible. Rather, our roadmap holds the purpose of presenting a general guide to the progress which must be observed in working towards a future of sustainable aviation.

Conclusion

Alternative aviation fuels have great promise as a transformative solution to meet the aviation industry's environmental challenges. Our report presented a comprehensive roadmap towards a sustainable future for air travel, outlining key steps for the widespread adoption of alternative and greener fuels. In addition to meeting the goals listed, by focusing on research and development, policy support, and international collaboration, the aviation sector can gradually transition to greener and more eco-friendly operations. Additionally, this report and experience emphasizes the importance of setting ambitious targets, investing in cutting-edge technologies, and fostering a culture of innovation. Embracing this will not only lead to a significant reduction in carbon emissions but also establish the foundation for a more sustainable and resilient aviation industry in the decades to come.

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