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Review

Sustainable Aviation—Hydrogen Is the Future

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Abstract: As the global search for new methods to combat global warming and climate change continues, renewable fuels and hydrogen have emerged as saviours for environmentally polluting industries such as aviation. Sustainable aviation is the goal of the aviation industry today. There is increasing interest in achieving carbon-neutral flight to combat global warming. Hydrogen has proven to be a suitable alternative fuel. It is abundant, clean, and produces no carbon emissions, but only water after use, which has the potential to cool the environment. This paper traces the historical growth and future of the aviation and aerospace industry. It examines how hydrogen can be used in the air and on the ground to lower the aviation industry's impact on the environment. In addition, while aircraft are an essential part of the aviation industry, other support services add to the overall impact on the environment. Hydrogen can be used to fuel the energy needs of these services. However, for hydrogen technology to be accepted and implemented, other issues such as government policy, education, and employability must be addressed. Improvement in the performance and emissions of hydrogen as an alternative energy and fuel has grown in the last decade. However, other issues such as the storage and cost and the entire value chain require significant work for hydrogen to be implemented. The international community's alternative renewable energy and hydrogen roadmaps can provide a long-term blueprint for developing the alternative energy industry. This will inform the private and public sectors so that the industry can adjust its plan accordingly.

Keywords: aviation energy; pollution; advanced technology; education; policies and regulations

1. Introduction

1.1. Summary of Historical Background

Man has always been interested in flight. Long before the Wright brothers [1] perfected an apparatus that allowed heavier-than-air flight, others attempted the same feat. The ancient Greeks attempted flight, and there are countless tales in Indian Vedic texts that depict the use of airborne craft. Such vehicles were used to transport people and goods and were used in warfare. The texts reference the power and pollution caused by airborne vehicles [2]. Passages also suggest that people could die from the fumes during their take-off or while the craft was operating. The toxic nature of aircraft exhaust fumes was recognized then as it is today.

Air pollution is still a significant concern for the aviation industry [3]. While the aviation industry's 2.1 percent contribution to global carbon emissions [4] is much lower than the 11 percent that road transport contributes [5], it attracts more attention, because the impact globally is more significant due to the contrails formed by jet engines [6]. Graver, et al. [7] suggest that aviation's emission contribution is higher, at 2.5 percent, and adds 918 million metric tonnes of carbon dioxide to the atmosphere [7]. This grows with every additional aircraft put into service. Manufacturers must invest in research to develop quieter, fuel-efficient aircraft [8]. Additionally, new energy sources such as solar power, hydrogen cells [9–11], and algae [12] are being developed.

1.2. Size of the Aviation Industry

The size of the aviation industry can be measured using multiple metrics. By every measure, there has been steady growth. Aviation is more than aircraft. It includes aircraft manufacturers, parts suppliers, allied services, and other (e.g., military or unmanned (drones)) aircraft. It is a collective term covering many goods and services built around aircraft. Aircraft are the most visible part of the aviation industry.

Aviation and aerospace are two aspects of air travel. The latter aspect relates to goods and services of aircraft that travel into space. It is often linked with aviation. It is also an area of rapid growth, with more nations and private citizens investing in space travel. While the COVID-19 pandemic disrupted air travel and impacted passenger services, IATA Economics [13] predicts that it will recover. The rate of recovery of services will differ. IATA Economics [13] estimates that the Asia-Pacific region will recover first, with lower passenger revenue losses at $7.5 billion in 2021 down from $31.7 billion in 2020.

1.3. Energy Needs and Pollution

Like automobiles, locomotives, and other self-propelled vehicles, aircraft rely on engines that provide thrust to move [14]. Aircraft bodies are designed to take advantage of aerodynamics and provide lift to raise them above the ground. Aircraft, like other vehicles, have improved substantially since the first model. Each aspect of the aircraft has been studied, from developing and designing more efficient engines, improved fuels with greater energy-to-weight ratios, [14] to better-designed, lighter structures that allow a more efficient use of interior space and stronger bodies that improve their safety.

As the number of aircraft in use increases, not just in the commercial sector but also with defence agencies worldwide, there has been a substantial increase in pollution. Multiple aspects of aviation pollution are being studied. Air pollution is the most apparent, and researchers have examined its impact in urban and regional areas [15], at different airports [16], using various technologies, such as remote sensing images [17], and its overall impact on the environment [5,18]. Other researchers have narrowed the scope by focusing on engine carbon and nitrogen oxides emissions [19–21]. However, while aircraft emissions attract attention, other areas of the aviation industry also add to global pollution. The increase in passenger travel correlates to increased waste generated in operations. For example, there has been an increase in disposable materials used on passenger flights to improve operating efficiencies—such as food trays, cups, cutlery, etc. The use of plastics, while helping to reduce the overall weight of the airplane, adds to the pollution the aviation industry generates.

The aviation industry has grown worldwide, especially in countries with poor transport infrastructures. Road and rail offer options to move people and goods from one place to another. However, costs play a significant role in determining whether to build roads or lay railway tracks to different locations. Railways are always a preferred option for moving large quantities of people and goods. They provide a dedicated route from one point to the next with minimal interruptions. The cost of laying a mile of rail is high. This is estimated to be over a million dollars per kilometre. Roads offer greater flexibility; however, the carrier size limits the quantity a vehicle can carry along the route.

Countries including the USA, Russia, and China have vast geographies to manage, and air travel is the most convenient way of getting from one point to another. The Middle East, on the other hand, while small, is challenged by needing to build roads and services that will not be affected by the moving sands. Hence, here too, air travel thrives.

2. Renewable Energy

In the previous decades, fossil fuels have become the most dominant source for the Earth's energy consumption. The growth in power demands and the increased use of the traditional thermal power plant were catalysts towards environmental pollution and the rapid exhaustion of fossil fuels [22]. These fossil fuels consist of various poisonous and hazardous contaminants that enter the environment and affect human health in multiple ways. Even though the environmental impacts of utilising fossil fuels on plants, air, soil, Earth's water, etc., are many, the problems associated with air contamination, greenhouse effects, and their cooling result are more critical. It is unfeasible for humans to sustain and carry on with their current lifestyle in the future without considering the source of their energy supply at an economical cost [23].

Every method of energy production has environmental consequences that contribute to unfavourable situations. The harmful ecological impacts of these methods have far-reaching consequences. Energy obtained from natural resources that are neither limited nor exhaustible, such as wind and sunshine, is known as renewable energy or renewable resources. Renewable energy is a viable alternative to traditional energy sources that rely on fossil fuels. It has the advantage of being far less destructive to the environment. According to the International Energy Agency, the use of renewable energy is increasing as technological advancements drive down prices and begin to deliver on the promise of a clean energy future.

Alternative Fuels' Performance and Emissions

Alternative liquid fuels are similar to commercial jet fuel when used in aviation gas-turbine engines [24]. Altarazi et al. [25] simulated a King-Tech K180 turbojet engine using dual biodiesel (palm methyl ester and Thespesia populnea methyl ester). The results showed that the specific fuel consumption decreased for B10-Jet fuel compared to Jet-A1 fuel [25]. In addition, CO and CO_2 emissions were lower for all dual biodiesel blends compared to Jet-A1 fuel. However, NO_x emissions were reported to be higher for all blends except B10-Jet fuel and gave a comparable value to Jet-A fuel emissions [25].

According to the case study done on a diesel engine running in the Automotive Lab in Universiti Malaysia Pahang, a hydrogen amount of between 21.4 L/min and 42.8 L/min has a profound effect on the diesel engine COV and the performance of the engine. The engine showed more sensitivity to the enrichment. The modified engine operates at higher loads with higher hydrogen flow rates; for instance, at 2000 rpm the knock resistance was improved at 20 Nm. The thermal break efficiency at the same load and hydrogen flow rate at 2000 was improved (30.8%) [26]. The same study showed that NO_x and CO_2 emission decreased as the amount of hydrogen increased. It was also seen that the NO_x decreased as the load decreased, while CO decreased as engine load increased. Furthermore, results showed that the maximum cylinder pressures and rate of pressure rise decreased as the amount of hydrogen increased, while the rate of heat released (ROHRs) decreased [27].

Kumar et al. [28] studied the diesel engine performance and the emissions using Jatropha methyl ester and its blend with methanol, orange oil, and hydrogen as dual fuels. The brake thermal efficiencies at the peak power output were improved and found to be 29.3 per cent, 29.4 per cent, and 30.7 per cent when injected with 18 per cent of hydrogen, 31 per cent of methanol, and 46 per cent orange oil, respectively [28].

3. Aviation Fuel

Aviation fuel is a misnomer. While it usually refers to fuel that is used in aircraft, it does not accurately reflect all fuels used in the aviation industry. The industry comprises a range of services, and early aircraft used motors similar to those in automobiles, and therefore, similar fuels [14]. Fuel powers an engine to create thrust and operate the different aircraft systems. However, the aviation industry [29] is more than aircraft, and it uses a range of energy sources for different power operations. Airports, for example, rely on electric power to operate, while the fleet of vehicles that move passengers and goods around the airport may make use of gasoline. Hence, there are many aviation fuels available, and the use of each has a different impact on the environment and climate. However, it is possible to negate this impact by employing new technologies and investing in sustainable and renewable energy sources.

While traditionally petroleum-based fuels have been used to power aircraft, researchers have sought to develop fuels that deliver tremendous energy and can be consumed entirely, providing higher operating efficiencies. However, this does not eliminate the pollutants entering the atmosphere, as while the engine works both carbon dioxide (CO_2) and nitrogen oxides (NO_x) are formed. Schürmann, Schäfer, Jahn, Hoffmann, Bauerfeind, Fleuti and Rappenglück [20] claim an inverse relationship between the engine thrust and CO_2 emissions. There are lower CO_2 emissions at a higher thrust but an increase in NO_x. Hence, a more significant push is to move to sustainable or alternate aviation fuels.

The Air Transport Action Group [30] describes sustainable fuels as fossil fuels blended with renewable hydrocarbons. The carbon emissions can be captured rather than released into the atmosphere. Several airlines have already switched to using these fuels to lower their carbon footprint [31]. According to IATA Economics [32], the airline industry spent over $188 billion on fuel in 2019. While this dropped in the following year due to the pandemic, it is expected to grow once more post-pandemic. The travel restrictions allowed airlines to upgrade their aircraft and opt for higher efficiencies and lower pollution. In addition to petroleum-fuelled aircraft, manufacturers testother alternative energy sources and develop new aircraft bodies.

The industry has already implemented initiatives to lower its environmental impact on the ground. Studies show that the air around urban airports has more significant pollutants than regional ones [15,33–35]. In addition to the health concerns of staff working at airports, this also adds to the aviation industry's carbon footprint. Fortunately, the industry and local governments recognize this issue and work towards solutions. Regional and secondary airports are being established to spread air traffic concentration.

Additionally, these airports, especially new airports, incorporate multiple sustainable practices that ensure that clean green energy powers their many systems [22,36–38]. Airports are turning to solar power [39], hydrogen [40], and adding storage systems to capture and store energy for future use. These technologies reduce the industry's reliance on traditional petroleum-based energy sources.

4. Aviation Development and Pollution during and Post COVID-19

The COVID-19 pandemic has offered a chance to measure air transport's impact on the environment. Turk and Kamiya [23] estimate that this pause in travel resulted in an 8 percent drop in CO_2 emissions in 2020. They note, however, that this drop is only temporary, as sustainable practices did not cause it. Various authors have modelled what the aviation sector will look like post-pandemic. Oxford Economics [41] expects that there will still be a 45 percent revenue drop in 2021 compared with 2019. Marcontell, et al. [42] agree that the recovery may not be quick and expect it to be 2023 before aviation reaches the 2019 levels.

This delayed recovery may provide an opportunity to employ more technologies that reduce aviation's impact on the environment. Gossling [43] argues that the pandemic might positively impact aviation. He suggests that the COVID-19 pandemic offers a chance to re-boot the industry to make it economically and environmentally sustainable.

However, Tisdall and Zhang [44] note that the industry's decision-making process is flawed and reactive rather than strategic. The authors suggest that unless there is a change in the decision-making process, the industry will respond similarly in the next pandemic. Therefore, it is essential to prioritise issues that will develop resilience in the industry.

There are multiple areas where improvements can be made to reduce the aviation industry's impact on the environment and remain economically viable. On the ground, the move towards greener, self-sustaining airports is a step in the right direction. Energy-efficient airport designs that reduce their energy consumption by switching off or maximising different operational areas are a start [45]. These energy savings can be added to the use of better building materials that provide superior insulation. The open spaces within the airport precincts can be used to generate and store energy. Airports could also use electric vehicles and reduce their reliance on petroleum-based vehicles.

Careers in aviation keep growing. As the industry grows, new roles are created. Some of these roles (such as licensed aircraft maintenance engineers and pilots) are defined by policies enacted to ensure quality, reliability, and safety within the industry [46]. Other roles are redefined to align with improved designs, practices, and processes, such as aircraft maintenance. Engineers need to develop specific skills to repair and maintain different aircraft types, and aircrews must comply with pandemic safety regulations.

While the short-term response of most airlines was to retrench staff to stay solvent, in the longer term industry experts predict that there will be a shortage of staff. The job outlooks for pilots, flight attendants, and aircraft maintenance engineers are promising [47–49]. As more aircraft become operational and newer models are put into operation, there will be a demand for certified skilled maintenance staff to work on specific aircraft types. Likewise, new safety protocols will have to be followed in response to the pandemic. This is not only for the aircrews but also for the ground staff that clean the aircraft, handle baggage, and operate customer services at the front desk.

Employability is also linked with training, as educational programs prepare students for these roles. Training institutions, however, only deliver what is required by legislation, which in many cases does not change as rapidly as technology does. Unmanned aerial vehicles (UAVs or drones) saw a rapid development during the pandemic [50]. This area is expected to grow further.

One of the most significant challenges the industry faces is the lack of education products that address and prepare students for the changes in the aviation space. Most of the current training products are vocational, targeting employers' specific skills. However, depending on the job, some of these skills will need upgrading by the time the student graduates.

Surging natural gas prices mean the cleanest form of hydrogen is now the cheapest to produce—new research recommends giving green technology a major boost after years of being held back by cost. Making hydrogen by splitting water using electricity from renewable sources costs almost a fifth less in Britain than using power produced by natural gas, according to calculations by the market intelligence group ICIS [51]. Green hydrogen is regarded as key to hitting climate goals because producing it does not generate carbon emissions, unlike making it from natural gas.

"Following the commodity price spike of 2021, ICIS hydrogen data shows that green hydrogen is now cheaper than [fossil fuel alternatives]," said Jake Stones, the hydrogen editor at ICIS [52]. Hydrogen does not generate carbon dioxide when it is burned, so politicians hope it can replace fossil fuels for various uses, such as in heavy machinery and even home heating. Boris Johnson has put hydrogen at the heart of a "green industrial revolution" plan. Producing it cleanly is a significant obstacle to its broader use, particularly given the high costs. Globally, hydrogen from natural gas typically costs between about USD 1 to USD 2 per kg, compared with USD 3 to USD 8 per kg for green hydrogen. Soaring natural gas prices have changed the equation for the time being, however. A global crunch in gas supplies means that gas prices in Britain are now trading at about GBP 1.80 to GBP 2.00 per therm, up from about GBP 0.30 pence per therm last summer. ICIS said the price of hydrogen produced from natural gas jumped from GBP 1.43 per kg on 1 April 2020 to GBP 4.16 per kg on 8 November 2020.

5. Hydrogen as an Alternative Fuel for Aviation

To reduce pollution and make aviation more sustainable, fossil fuels are being replaced by renewable energy sources. Hydrogen is recognised as a clean fuel, as it can be consumed without polluting the air. Pure hydrogen is not readily available and must be extracted or manufactured. Hence, different processes for creating hydrogen fuel are available, which, while reducing carbon emissions, are not entirely pollutant-free. Green hydrogen is the only carbon-neutral hydrogen, as there is no carbon generated throughout the process of creating and using the fuel. Grey hydrogen [53] creates carbon in the extraction/manufacturing process. An improved version of grey hydrogen is blue, where the carbon produced during manufacturing is captured and stored [53,54]. Renewable energy sources are used to produce Green Hydrogen [53]. Table 1 shows the three spectrum colours of hydrogen: grey, blue, and green, based on their carbon output. There are three main challenges to extracting and using hydrogen: the production process, costs, and storage, as depicted in Figure 1.

Table 1. Spectrum colour of hydrogen types based on carbon output.

	Grey Hydrogen	Blue Hydrogen	Green Hydrogen
Process/ Technology	Steam methane reforming (SMR) Auto-thermal reforming (ATR)	Carbon capture and storage (CCS)	Electrolysis
Source	Natural gas, gasifier coal, or heavy oil	CO_2-rich stream	Water
Carbon output	8.5–10 kg	0.8–4.4 kg	No carbon emissions

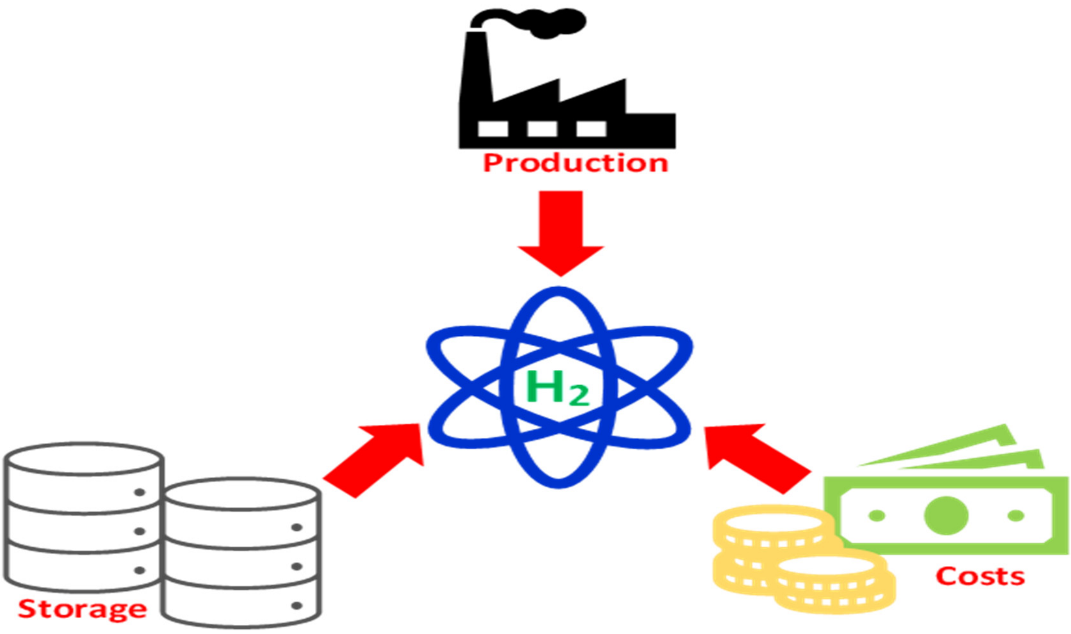

Figure 1. Three concerns of the hydrogen study.

5.1. Production

The four ways to produce hydrogen are thermolysis, electrolysis (electric), photolysis (photonic), and biolysis (bioenergy) [55–57]. The other ways relate to combined energy sources [58,59]. Many researchers tend to increase the efficiency in the process through additive energy such as catalysis [60–62].

SMR technology is the standard method for producing hydrogen. It combines two reactions as in equation one and follows a multi-step chemical process to produce grey hydrogen [63]:

$$\underset{\text{14–40 bar}}{\underset{\text{External heat}}{\text{Methane} + \text{Water} \overset{\text{Nickel catalyst}}{- - - -} \text{H}_2 + \text{CO}}} \quad (1)$$

The hydrogen production could be from nuclear energy by electrolysis or direct thermal conversion, and it could be from renewable sources like wind or solar. The main target is to set aviation policies for the hydrogen initiative from 2025–2050. The implementation is as in Figure 2.

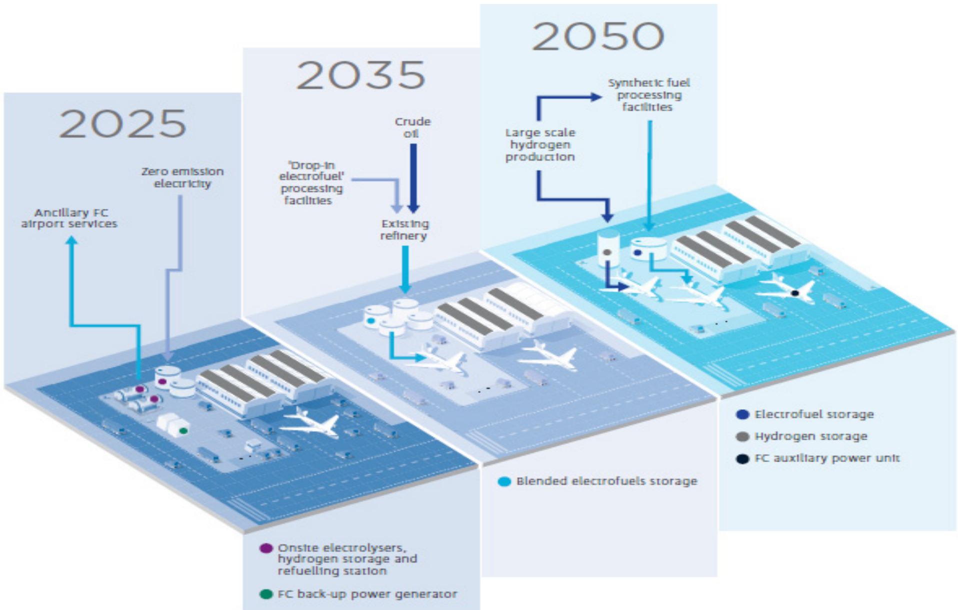

Figure 2. Hydrogen technologies in the aviation sector [11].

The hydrogen industry development for commercial aviation can be categorised into the following areas:

1. Airport application, where hydrogen fuel cells power the activities in the airport, such as their ground support and transport.
2. Existing infrastructure, where aircraft or platform applications do not need any change and can use electro-fuels as a drop-in-jet fuel, which is produced by mixing CO_2 with hydrogen as illustrated in Figure 3.
3. Emerging infrastructure, where aircraft are being redesigned or modified to accept hydrogen fuel tanks. This area could be divided into hydrogen for propulsion and non-propulsion.

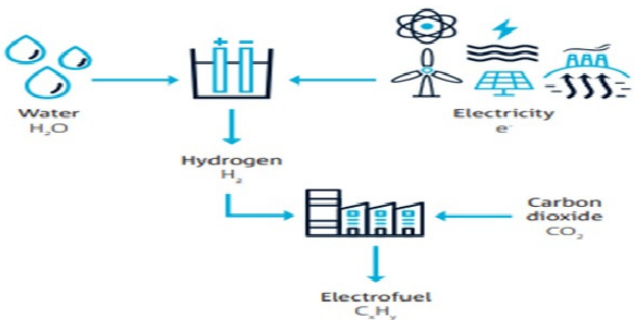

Figure 3. Electro-fuel process [11].

There are several pathways used to produce hydrogen. One is by producing hydrogen through fossil fuels. This process is called thermochemical (e.g., using steam methane reforming and carbon capture and storage). The second is electrochemical (e.g., using alkaline electrolysis and a polymer electrolyte membrane), which separates oxygen and hydrogen from water by using electricity. The electricity used in this process must be zero or low emissions [64]. Most of the formula reactions used in the technologies to produce hydrogen are summarised in Table 2.

Table 2. Technologies for hydrogen production.

Production Technology	Components	Equations [65]
Steam forming process [66,67]	Natural gas (e.g., methane)	$CH_4 + H_2O + heat = CO + 3H_2$ $CO + H_2O = CO_2 + H_2$ reaction heat
Exothermic process [66,67]	Partial oxygen with methane	$CH_4 + 1/2O_2 = CO + 2H_2$ + reaction heat
Endothermic gasification process [67,68]	Coal	$C_{(s)} + H_2O + heat = CO + H_2$
Electrolysis [67,69]	Water and redox	* H_2O + electric = $H_2 + 1/2O_2$
Biomass gasification process [67,70]	Biomass (e.g., agriculture, and animal or organic wastes)	Biomass + (oxygen, heat, and steam) = H_2

* At low temperatures (<100 °C), the types of electrolysis that could be used are alkaline electrolysis and PEM [63]. At high temperatures (up to 1000 °C), the electrolyser used is solid oxide [63].

5.2. Cost Analysis

It is very important to discuss and analyse the cost of hydrogen production, storage, transportation, refuelling stations, manufacturing, engine conversion, and fabrications, as well as staffing and operations. Since Wilbur and Orville Wright's first 12 s flight in 1903 at Kitty Hawk, there were around 22,680 operational aircraft at the start of 2019 [8]. Airbus and Boeing, the two largest commercial aircraft manufacturers, predict that by 2039 there will be around 48,000 operational aircraft [8,71]. This increase in aircraft will positively impact the aviation industry globally. According to Boeing [71], there would be a need for 2.08 million airline staff by 2039 to operate aircraft across pilots, cabin crew, and maintenance technicians. This increase will also impact other roles and services in allied industries, such as tourism, trade, and logistics, that rely on aviation services.

While increased air operations could potentially increase pollution, it pushes the industry to seek its environmental sustainability sooner. The current prediction for green hydrogen as an alternative fuel relies on the declining fossil fuel supply and capital cost curve. Figure 4 shows that the aircraft tractors and de-icing trucks are hydrogen's main ground support.

Figure 5 shows a comparison between different sectors' uses of hydrogen in 2020. The colour scale presents the possibility of using hydrogen in other sectors. The difference between the capacity to pay and the delivery price is the economic gap for 20 industry applications in 25 industries based on the incumbent technology. The positive sign of the financial gap refers to the hydrogen-based technology being able to compete with incumbent technology economically. At the same time, the negative sign of the economic gap expresses that the current technology is still competitive [63].

The first step of the hydrogen readiness for market application has been reached. The use of green hydrogen to reduce emissions is part of the carbon reduction policies of many countries, such as member states of the European Union, Japan, Korea, and China [72]. Cost-effective hydrogen production is possible if demand increases [73]. Bloomberg estimates that hydrogen production needs $150 billion in subsidies to scale its production and ensure its parity with natural gas [74].

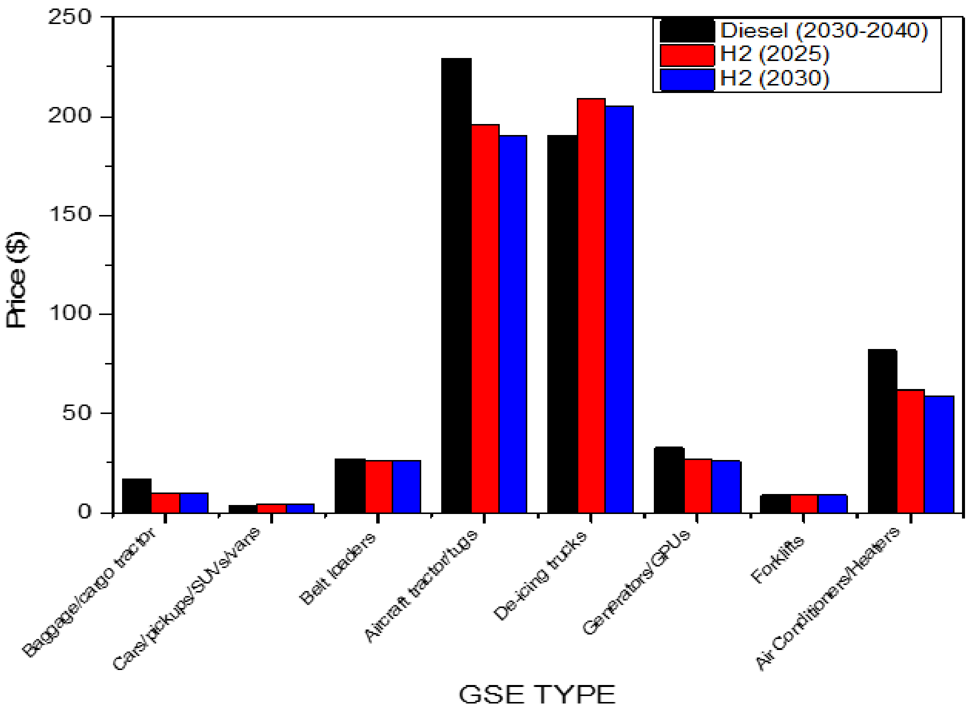

Figure 4. Ground support equipment prices based on diesel/H_2 [11].

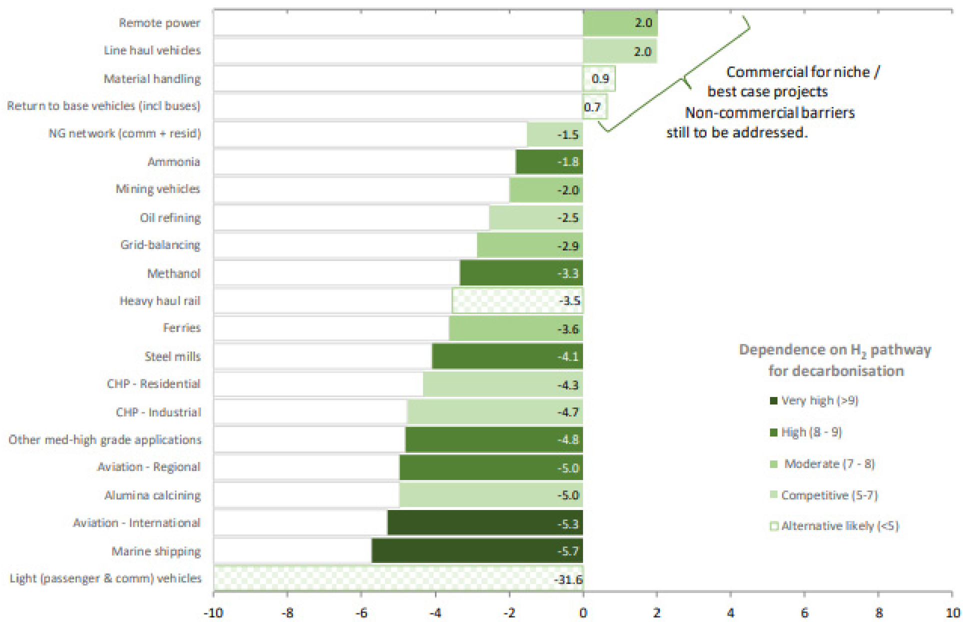

Figure 5. Economic comparison between different sectors in 2020 [63].

Hydrogen fuel use is insignificant in the Australian market. As presented in Figure 6, around 650 ktpa of hydrogen in Australia is produced by natural gas steam methane reforming. This process synthesises 65 percent of ammonia and 35 percent to refine crude oil. As shown in Figure 7, the aviation industry will keep relying on crude oil prices until sustainable fuel is competitive. Liquid hydrogen will become more competitive than green Jet-A and refinery-based Jet-A [63].

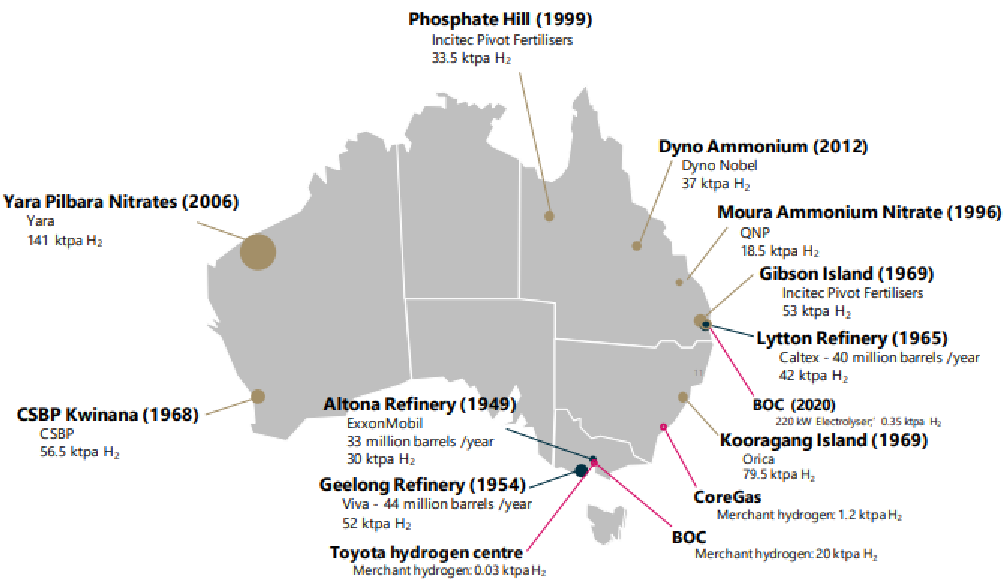

Figure 6. The current hydrogen usage in Australia.

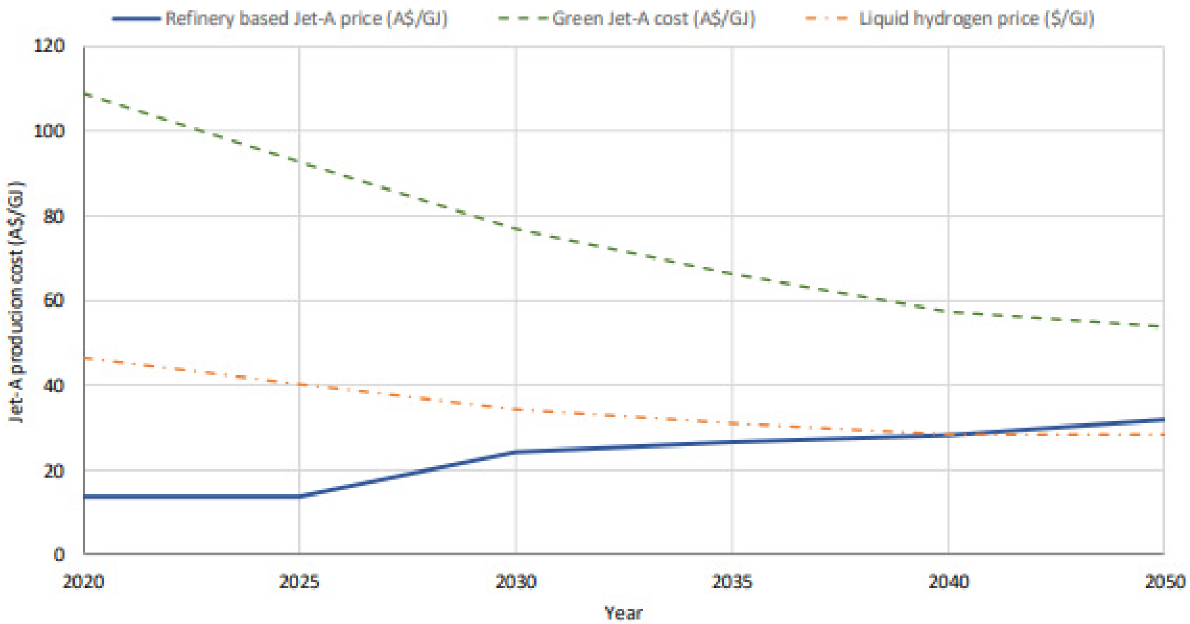

Figure 7. Forecast price for Jet-A and liquid hydrogen [63].

5.3. Storage and Safety

Hydrogen is the most abundant element in the universe. Despite that, there are challenges to collecting and storing it for use. Hydrogen production does not need as large an area as biofuel. There is no impact on the environment from using the hydrogen fuel cell. The gravimetric energy density of liquid hydrogen is three times higher than LNG and diesel. Unlike fossil fuels, almost no greenhouse gas emissions are generated by the hydrogen fuel cell. Hydrogen fuel cells can be recharged in five minutes, while the electric car needs more than 30 min to recharge [75]. The several cons and pros of hydrogen fuel cells are presented in Table 3.

Table 3. Advantages and disadvantages of hydrogen fuel cells.

Advantage	Disadvantage
Almost zero emissions	Inflammable
High energy efficiency	Storage challenges
No noise or visual pollution	Poor Infrastructure
Quick charging time	High cost of production
Long shelf life	Extraction process

There are two ways to use hydrogen as a fuel in aircraft [76]:

1. Use hydrogen as aviation fuel to replace kerosene in large aviation aircraft.
2. Use hydrogen fuel cells as a power source in small propeller aircraft instead of petrol engines.

However, reinforced storage tanks are required to contain the fuel. Safety and maintaining an aircraft's balance make placing the tanks on an aircraft a challenge

The aircraft and engine designs must be modified if hydrogen is to be used as aviation fuel. Fuel could be stored in the area behind the passenger cabin. This, however, shifts the plane's centre of gravity. A second potential storage placement is having one tank in front of the passenger cabin and one tank behind [77]. The energy potential would increase between 6 to 19 percent if medium-range aircraft used the tank on the top. Another option is to place two hydrogen tanks at the top of the cabin and one in the fuselage tail.

To optimise the energy density, the temperature for storing liquid hydrogen in an insulated tank has to be very low [78]. The hydrogen quantity, footprint of storage, and energy use have to be considered to select the appropriate storage technology [64]. These technologies are compression (with a gas state at 50–150 bar, 25 °C), liquefaction (with the hydrogen in liquid form at −235 °C, 1 bar), and chemical (e.g., using ammonia and metal hydrides in ambient conditions) [64]. Figure 8 illustrates the hydrogen storage parts.

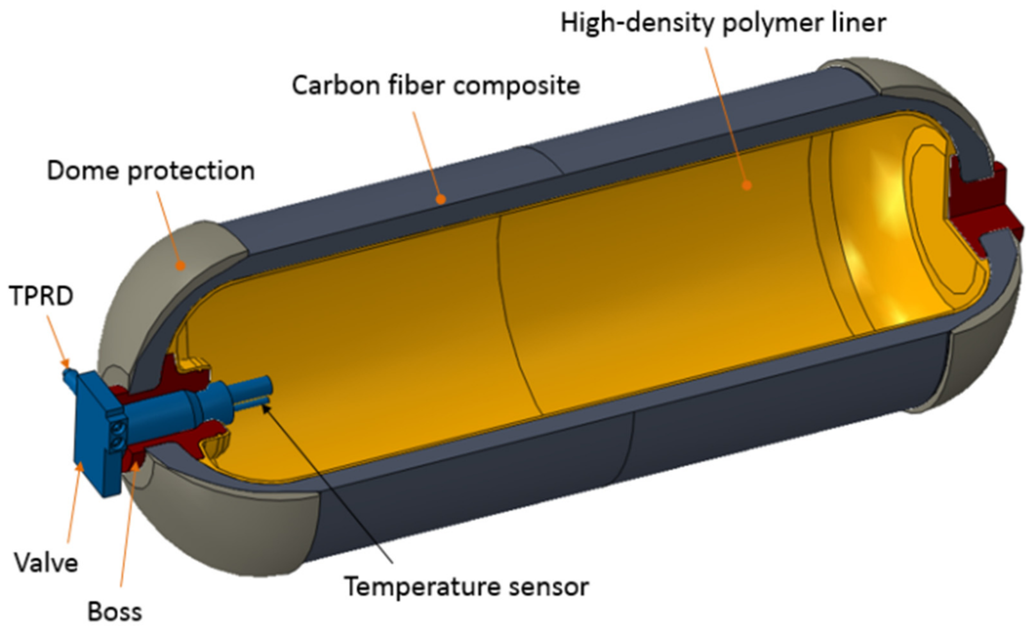

Figure 8. Tank components for storing hydrogen [64].

The auxiliary power unit (APU) operates the electrical system while the aircraft is on the ground. The APU also starts the jet engines and supplies the air for cooling and heating. APUs are placed behind the fuselage and contain a small turbine engine. The APU aims to produce electrical energy; in this case, the existing turbine engine must be replaced with a fuel cell [64]. Figure 9 shows the possible placement for a fuel cell.

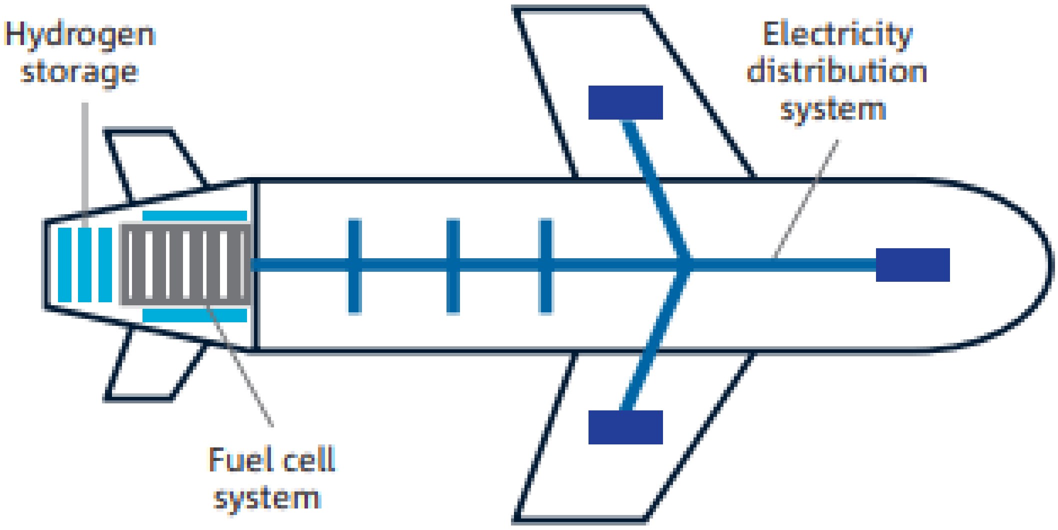

Figure 9. Fuel cell placement in aircraft fuselage [64].

Hydrogen fuel cells' applications in aviation include in the APU, GSE, UAVs, and space. The APU has different primary power source, backup, and start-up functions. It works as a compressed air and electricity source for other aircraft components when the main engine is off. It also provides the energy for lighting and the air condition. It works as a primary power source while the aircraft is stationary, whereas the internal power is used during the cruise. The traditional APU causes aircraft emissions of around 20 percent fuel consumption as well as noise. So, reducing these problems could be addressed by replacing the conventional APU with fuel cell devices or installing a hybrid system by combining the fuel cell with the APU system. Fuel cell types are the proton exchange membrane (PEMFC) and the solid oxide fuel cell (SOFC). The PEMFC is lighter than the SOFC. The SOFC's efficiency increases due to its high operation temperature. The fuel consumption is reduced by 40 percent during cruising and 75 percent during stationary. In addition, 80 per cent of the NO_x will be reduced if the SOFC APU is used [79]. The hybrid system for GSE was applied at Tokyo airport [80] and Hawaii airport [81] to run shuttle services.

The on-board storage of hydrogen presents various issues. Hydrogen has a greater energy per unit mass in comparison to kerosene. At the normal atmospheric pressure and temperature, one litre of kerosene fuel is equivalent to roughly 3000 gallons of gaseous hydrogen. This is clearly not ideal for aviation. Another option is to pressurise the hydrogen to 700 bars as utilised in the car industry. However, the weight and volume are crucial for aeroplanes. By lowering the temperature to -253 °C, hydrogen turns from a gas to a liquid, increasing its energy density. Many sectors, including aerospace, currently employ cryogenic liquid hydrogen storage tanks [73].

With Ariane, Airbus gained information on system installation, cryogenic testing, fuel sloshing management, and even how to construct the inner tank. While there are some similarities, there are also many key differences. Commercial aeroplane hydrogen storage tanks must withstand around 20,000 take-offs and landings and retain hydrogen liquid significantly longer than space launches [73].

To ensure combustion engines' long-term safety and visibility, "clean-burning" fuels derived from renewable sources must be developed. Another aspect that makes hydrogen fuel safe is its high ignition temperature. According to Yusaf et al. [73], the ignition temperature of hydrogen is around 858 K, which is much higher than the gasoline ignition temperature (530 K); in addition, hydrogen is lighter than air. It is important to mention here that additional advanced training for aviation maintenance engineers is required to be able to deal with future advanced hydrogen technology in the aviation sector.

6. Environmental Effects

The European Union's Climate Target Plan is an emission reduction of 55 per cent by 2030 and becoming carbon neutral by 2050, as passed by the European Commission [82]. By 2030, Europe plans to launch its first commercial plant for hydrogen-based jet fuel called Norsk e-Fuel, a consortium of four companies. The lack of infrastructure prevents hydrogen from being an alternative to fossil fuels. The IATA target addresses climate change; one of these targets is reducing the CO_2 emissions in 2005 to 50 per cent by 2050. Between 2009 and 2020, the fuel efficiency improved 1.5 per cent per year on average [83]. Aircraft use biofuel as a sustainable aviation fuel (SAF) instead of commercial aviation fuel, because its carbon footprint is lower than commercial aviation fuel. According to the U.S. Environmental Protection Agency, the SAF has reduced U.S. GHG emissions by 9 to 12 percent [84].

A challenge the aviation industry faces is that the increase in aircraft will also cause an increase in the energy demand, pollution and, in turn, impact on the environment. Studies show that while aircraft contribute less than three percent of the total air pollutants [85,86], the flights cause disruptions in the atmosphere that increase global warming [6]. Halil et al. [87] used an aircraft turbojet engine run on biofuel, hydrogen, and JP-8 fuel.

Juste et al. [88] ran a gas turbine using kerosene with a small amount of hydrogen. In the results, the specific fuel consumption decreased due to using hydrogen. The water vapour produced by hydrogen was 2.6 times greater than that from kerosene, and hydrogen's emissions were lower than those of kerosene [88]. According to ISO 14,6887-2 and SAE J2719 standards, the contaminants allowed to be in hydrogen for fuel cells [89].

The discussion above leads to an understanding of the main benefits hydrogen can bring to the climate change issue plaguing all humanity. Water exhausted by using hydrogen will cool the planet in future instead of what the current era is experiencing. It will be a game-changer for global warming [89,90].

7. Conclusions

The aviation sector contributes to global GHG emissions. Around 3 percent of the carbon emissions worldwide are produced by burning conventional aviation fuel. While the search for a viable, sustainable green energy continues, hydrogen was found to be the most promising alternative to commercial jet fuels. It produces zero pollutants when used. However, producing carbon-neutral hydrogen is not yet cost-effective. Despite the many reported benefits of utilising hydrogen, many drawbacks prohibit it from being competitive compared to other alternative fuels. In addition to a lack of infrastructure and storage concerns, the expense of manufacturing it and the required changes in aircraft construction are some of the downsides. This article has recounted the history of aviation, examined fuel cell technology, and identified challenges that need to be solved to accelerate the uptake of sustainable green hydrogen in the aviation sector. It has also provided solutions to these concerns.

The main argument against hydrogen has not been safety but rather the high expense of the fuel. Although "green" hydrogen may be created using water and renewable energy, most of the hydrogen produced today is so-called "grey hydrogen", which is produced by burning fossil fuels and is not much more environmentally friendly than burning those fuels themselves. The European Commission underscored this fact when it announced its EU hydrogen strategy in 2020, stating that hydrogen is a vital component to meeting the European Green Deal's 2050 climate neutrality target and citing the evident environmental advantages of hydrogen. The policy intends to decarbonise hydrogen production by relying primarily on renewable energy sources, such as wind and solar energy, and extending its usage in areas where hydrogen may replace fossil fuels.

This paper concludes that renewable hydrogen technologies would be mature, and hydrogen would be widely implemented by 2030 in many sectors, particularly the aviation industry.

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