High on Hydrogen!

Manhattan College
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2023 Gateways to Blue Skies:
Clean Aviation Energy Competition

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Abstract

For the 2023 NASA Gateway to Blue Skies Competition, the team from Manhattan College has elected to research the viability of hydrogen Fuel to power the commercial aviation industry in the future. Moving forward, it is our belief that hydrogen fuel has the ideal combination of properties ranging from energy density, to tremendous availability, to pollution-free use, for replacing jet fuel as the source of energy for the next generation of passenger aircraft. This document will discuss the creation, storage, transportation, process of loading hydrogen into commercial aircraft, climate impacts, safety, and readiness levels.

Our research has revealed that in terms of generation, a combination of blue hydrogen and green hydrogen, via biomass gasification and hydrogen electrolysis, respectively, is the best answer to meeting the demand for hydrogen fuel in the near future. Looking forward, layered double hydroxide coatings on electrolyzer electrodes hold the key to unlocking hydrogen production in an entirely green fashion, using seawater as the main resource to fuel aircraft in coastal states' airports. Meanwhile, the landlocked middle states can rely on biomass gasification to provide their hydrogen fuel, as they produce much of America's crop and vegetation waste. Gasification will be performed in conjunction with carbon capture technology, to repurpose the carbon dioxide byproduct to aid the photosynthesis process of future crops. The next logical steps for the adoption of hydrogen as an alternative fuel are its storage and transportation. There are many methods of possible storage for hydrogen; these include in a gaseous form or a liquid form, which have the obstacles of needing to be stored at extremely high pressure and cryogenic temperature, respectively. However, the most promising method of storage for gaseous hydrogen is bonding hydrogen to a liquid organic hydrogen carrier, which results in an oil-like compound that can safely be kept at atmospheric conditions. These obstacles pose a problem for transportation, especially with regard to methods commonly used today to transport gasoline and other modern fuels. It is our belief, however, that a combination of cutting-edge technologies, including autonomous vehicles, eVTOLs, and hyperloops is the future of hydrogen fuel transportation between production facilities and airports. Once the hydrogen fuel arrives at the airport, it can be used to power planes in one of two methods, either powering electric motors with a hydrogen fuel cell or used in a combustion process, similar to modern-day jet fuel turbines. We propose using gaseous hydrogen for shorter flights (less than two hours) and liquid hydrogen for longer flights (more than two hours) to benefit from the positive aspects of each phase of the fuel. Research into the safety of hydrogen fuel proved that hydrogen's low atomic weight, penchant for quick dispersion, and need for high concentration to achieve combustion means that hydrogen is relatively safe to use as a fuel source when compared to natural gas and gasoline. Finally, much of the environmental impacts of hydrogen fuel come during its production. However, with the proper carbon capture technology and usage of the stored carbon gasses in processes such as fermentation or use in the photosynthesis of crops, much of the pollution can be mitigated. Looking towards the future, green hydrogen production and the use of hydrogen fuel cells in aircraft lend to the belief that the coming decades will see water as the only byproduct of hydrogen fuel adoption.

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1. Generation

The first step toward shifting the future of the aviation industry toward being fueled by hydrogen is the generation of an ample supply of fuel to power all commercial flights. Luckily, hydrogen is the most abundant element in the universe and can be sourced from the earth's natural resources, namely water and vegetation material through different techniques. Water covers roughly 70% of the Earth's surface, making it an ideal source of fuel due to its vast abundance and renewable nature. Vegetation material is also renewable and abundant, as each year harvests for food production provide ample waste material.

The production of hydrogen fuel is categorized into three color-based groups; gray, blue, and green hydrogen [1]. The vast majority of today's hydrogen gas is produced as gray hydrogen, which involves the use of industrial processes powered by the burning of fossil fuels that are directly responsible for greenhouse gas emissions and other forms of pollution [1]. Thus, it is believed that gray hydrogen production contributes 830 million tons of carbon dioxide pollution each year, according to the International Energy Agency [2]. To meet the need to reduce carbon emissions, some companies have begun producing blue hydrogen. Blue hydrogen production retains much of the industrial polluting practices associated with the aforementioned gray hydrogen but also features the addition of steps to capture the carbon emissions before they are released into the atmosphere [1]. The captured carbon emissions are stored underground or within large hills and mountain ranges [1]. However, this is a costly process and stores more carbon-based gasses than the world can consume in industry. However, as carbon capture and storage technology are further advanced, it is theorized that blue hydrogen will become a cost-effective intermediate step in clean hydrogen production due to its ability to be retrofitted onto existing gray hydrogen facilities [1]. Finally, green hydrogen involves the use of a renewable, clean energy source to power a process that produces zero carbon emissions [1]. Green hydrogen can be produced using sources such as solar and wind power, in addition to nuclear power [1, 3]. Unfortunately, in the current energy landscape, roughly 95% of the world's hydrogen is produced using gray methods, and just under one percent of all hydrogen produced can be considered green hydrogen [1, 3]. In order to eventually produce exclusively clean fuel by the time hydrogen is adopted into use in commercial aviation, it is necessary to improve the ratio of more environmentally conscious green hydrogen to gray hydrogen through time.

In terms of environmental "greenness," the most promising currently available process for the production of hydrogen fuel is hydrogen electrolysis. This entails the separation of water into hydrogen and oxygen gas by applying electrical current through it [4, 5]. The pure oxygen captured as a byproduct of electrolysis can be used for medical devices such as oxygen tanks used at hospitals [6]. Hydrogen electrolysis has the potential to be performed in an entirely green fashion, even on a large scale. This is evidenced by the use of clean, renewable energy sources, such as solar or wind, to power the electrolysis process [1]. Notably, these processes are already in use in places such as the Fukushima Hydrogen Energy Research Field in Japan, the largest green hydrogen plant of its kind in the world [7].

Three major types of electrolyzers currently exist: alkaline, polymer electrolyte membrane (PEM), and solid oxide [4, 5]. Alkaline electrolysis is the simplest of the three and is defined by its use of a liquid electrolyte medium in which the electrodes are placed [4, 5]. When electric current is applied, hydroxide ions are sent from one electrode to the other, and a diaphragm with a small pore size separates the desired gas products [4, 5]. PEM is a more expensive form of electrolysis due to its use of a specialized polymer membrane, engineered specifically to facilitate the separation of hydrogen and oxygen gasses, by allowing exclusively hydrogen ions to pass through it [4, 5]. PEM electrolyzers also use a solid electrolyte and are currently the industry leader in terms of efficiency and production [4, 5]. Finally, solid oxide electrolysis is currently the rarest of the three and is still a young developing technology. However, solid oxide electrolyzers provide the potential upside of beginning the electrolysis process with steam instead of liquid water, circumventing the need for the phase change to occur before the hydrogen and oxygen gasses are separated, thereby reducing the amount of energy required to form the gas products [4, 5].

A major concern with the process of hydrogen electrolysis is its use of highly purified water which can present a potential problem with the world's fresh drinking water supply [8]. While other, less pure forms of water can currently be used to perform hydrogen electrolysis, they often contribute to accelerated deterioration of the electrolyzer's components. The major problem faced using impure water is deposits of insoluble materials, which build up on the surface of electrodes and reduce the electrolyzer's efficiency. To remedy this problem, researchers at several universities, like Stanford and Houston, have been investigating ways to develop a coating for the electrodes, where the majority of oxidation and damage occur, to allow for the use of sea/saltwater in electrolyzers [8, 9]. This type of coating is referred to as layered double hydroxides (LDH) [8, 9]. LDHs are mineral-based coatings that, when combined with transition metals, can be applied to the surface of an electrolyzer's electrodes to protect them against corrosion when they are exposed to alkaline environments such as seawater [8, 9]. They also have the benefit of improving the chain of chemical reactions occurring in an electrolyzer to undergo the more desirable oxygen evolution reaction, rather than the unintentional chlorine evolution reaction [8, 9]. This results in hydrogen gas with oxygen rather than a chlorine byproduct. As LDH coatings help unlock seawater's potential in hydrogen production, the hope is that airports in coastal cities in particular can obtain their hydrogen fuel directly from the sea without the need for large irrigation or infrastructure projects to be carried out. In summation, the ability to use seawater for electrolysis will eliminate one of electrolysis's most hindering obstacles, its need for purified water. By removing the burden that large-scale electrolysis in its current state would place on the world's freshwater supply, the industry will be propelled forward, gaining substantial traction for further funding and research as a potential fuel source to replace fossil fuels, including jet fuel.

Electrolysis, however, is not the only process that produces hydrogen fuel. Namely, biomass gasification is a thermochemical reaction process that produces hydrogen gas from biological scrap from harvested crops by heating them at low pressure to just below the point of combustion, at which point hydrogen and syngas (a combination of methane, carbon dioxide, & carbon monoxide) are released in a gaseous form [10, 11]. Unfortunately, without the proper equipment and storage for the capture and storage of carbon emissions, this process falls into the gray hydrogen production category, due to its industrial processes having byproducts including the pollutants carbon dioxide and carbon monoxide [3]. By heating but not combusting the organic materials, the emission of harmful carbon gasses is reduced but is not totally eliminated [10, 11]. Moving forward, to meet the rising demand for hydrogen fuel, new and existing biomass gasification plants should be equipped with carbon-capturing machinery to reduce the process's harmful greenhouse gas impact [1]. Carbon capture is a process that involves various methods, both biological and artificial, to trap carbon emissions before they escape into the atmosphere [12]. An example of biological carbon capture are carbon sinks, which use natural vegetation habitats to absorb carbon dioxide, and an example of artificial carbon capture can be seen in the emerging technology known as ionic liquids, which are fluids that have had their molecular structure altered to absorb carbon dioxide [12]. To supplement the supply of hydrogen produced by the electrolysis of seawater, we hypothesize that a cost-effective solution in the continental United States' "middle states" may be to use biomass gasification rather than transporting massive amounts of seawater hundreds or even thousands of miles to carry out hydrogen production by way of electrolysis. Since a large portion of the US's crops are cultivated in the Midwest, it seems natural to use the available biological waste resources to produce hydrogen fuel for airports in that region. Ideally, as previously mentioned carbon capturing technology similar to blue hydrogen production will be used, but rather than storing the carbon dioxide, it will be applied to subsequent batches of crops to aid the photosynthesis process. Much of the carbon dioxide emissions that are captured will be stored briefly, and then transported to local farms, from which the crops originated. This carbon dioxide can then be applied to new crop growths via pipe systems within large greenhouse structures, similar to modern-day watering systems. In this way, many of the adverse tradeoffs of employing blue hydrogen production to fuel landlocked airports can be offset.

Hydrogen gas can be used in either a liquid or a gaseous form. The aforementioned processes yield hydrogen fuel in its gaseous state. Liquefaction is a process that can turn gaseous hydrogen into a liquid, by way of cooling the hydrogen and passing it through a series of specialized valves, until it yields a liquid fuel product that can then be stored in insulated cryogenic tanks [13,14]. Liquefaction has the unfortunate effect of reducing the energy content of the hydrogen fuel by about 30%, and it also brings tremendous cost due to the specialized machinery and abundance of energy required to carry out the process [14].

The current state of technology for the generation of hydrogen gas as a fuel source is a promising sign for its future in aeronautics. Table 1 shows a projection of the amount of hydrogen fuel that needs to be produced in order to keep up with the global demand for aviation fuel based on an average annual fuel consumption from the years 2005-2021. Both liquid and gaseous hydrogen were both analyzed individually for future production scaling based on the assumption that they will each be solely replacing jet fuel. Based on past trends, the demand will presumably increase with time and further production scaling projections must be completed. In terms of methods of fuel production, hydrogen has proven to be a very favorable option to replace traditional jet fuel. The abundance of water and crop waste on Earth provides reliable, renewable energy for a theoretically indefinite period of time. Research being done by leading universities to improve the efficiency and productivity of electrolysis technology also provides tremendous hope for the future of hydrogen as a fuel source looking forward to the 2050s.

Table 1: Projected Hydrogen Fuel Demand Based on Energy Density Compared to Modern-day Demand of Jet Fuel [13, 15, 16, 17]

Fuel	Density (kg/L)	Energy Density (MJ/L)	Annual Consumption (L & kg)
Jet Fuel	0.84 kg/L	40.320 MJ/L	2.814×10^{11} L; 2.364×10^{11} kg
Gaseous Hydrogen	0.0012 kg/L	0.144 MJ/L	7.88×10^{13} L; 9.46×10^{10} kg
Liquid Hydrogen	0.07 kg/L	8.000 MJ/L	1.42×10^{12} L; 9.94×10^{10} kg

2. Storage

The hydrogen needs to be safely stored before it can be transported to the airport to be used on aircraft. Hydrogen is generated in its gaseous phase, and it needs to be stored in an energy efficient as well as cost-effective method in order to ensure its maximum utilization. This plays a vital role in the transportation stage as well as in storing the hydrogen before it is loaded into the aircraft. The two common methods used to store hydrogen are storing gaseous hydrogen and liquid hydrogen. Storing hydrogen regardless of its form is a challenging process due to the extremely low boiling point of liquid hydrogen that requires cryogenic tanks or with a very low density of gaseous hydrogen where using the high-pressure tanks is vital. In addition, hydrogen has low density where 1 kg of hydrogen gas requires a volume of 11 m^3 at ambient temperature and atmospheric pressure [18]. By compressing the gaseous hydrogen or by decreasing the temperature of the liquid hydrogen below the hydrogen's critical temperature, hydrogen can be contained and stored [18].

2.1 Gaseous Hydrogen & LOHCs

Hydrogen stored in the gaseous phase is known as gaseous hydrogen. It is stored by containing hydrogen gas in very high-pressure tanks in order to achieve a higher storage density [19]. Although this ensures the maximum storage possible, maintaining these tanks at such high pressures is a very expensive process. Hydrogen has a very low volumetric energy density (8 MJ/L) as compared to that of gasoline (32 MJ/L) [20]. This accounts for the large space necessary for hydrogen storage using this method. In addition, gaseous hydrogen is also odorless which makes it difficult to detect any leakage through the tanks. Liquid organic hydrogen carriers (LOHCs), an alternative way of storing hydrogen, have been researched since the 1980s [21]. These are organic compounds that exist as liquids or low melting point solids under ambient storage conditions. Using this system to store hydrogen is potentially safe and requires relatively cheap storage materials [21]. Since LOHC is an oil-like medium, it can be stored and transported under normal conditions similar to transporting gasoline [22]. This can cut down storage expenses significantly by eliminating the need for high-pressure tanks needed for the storage of gaseous hydrogen. One m^3 LOHC enables the safe storage of 57 kg of hydrogen [22]. When compared to storing hydrogen as gaseous hydrogen, using LOHCs is the best choice given the elimination of extensive capital and energy requirements involved in the former method.

The concept of storing hydrogen using LOHC is based on reversible hydrogenation and dehydrogenation cycles. In the LOHC hydrogenation reaction, hydrogen is chemically bound to the LOHC at high temperatures and high pressures [23]. This reaction is achieved with the help of a specifically designed catalyst. This is an exothermic process and generates around 10 kWh/kg of H_2 at 200-250 ℃ [24]. The heat generated can be stored and used later in the endothermic dehydrogenation process or for other uses within the facilities to increase the overall efficiency of the system. The hydrogenated LOHC+ can be transported and used through the existing infrastructures used for gasoline and diesel [22]. When the hydrogen gas needs to be extracted, the LOHC+ is passed through a dehydrogenation reactor in which, hydrogen is released in its pure form through the catalytic dehydrogenation reaction taking place at high temperature and at a pressure close to atmospheric pressure [23]. This is an endothermic process and requires around 11 kWh/kg of H_2 at 250-300 ℃ [24]. Once the hydrogen is extracted, the unloaded LOHC- can be transported back to the hydrogen generation site, where it can be hydrogenated again to repeat the process as shown in Figure 1. This enables the LOHC medium to be reused several hundred times [25].

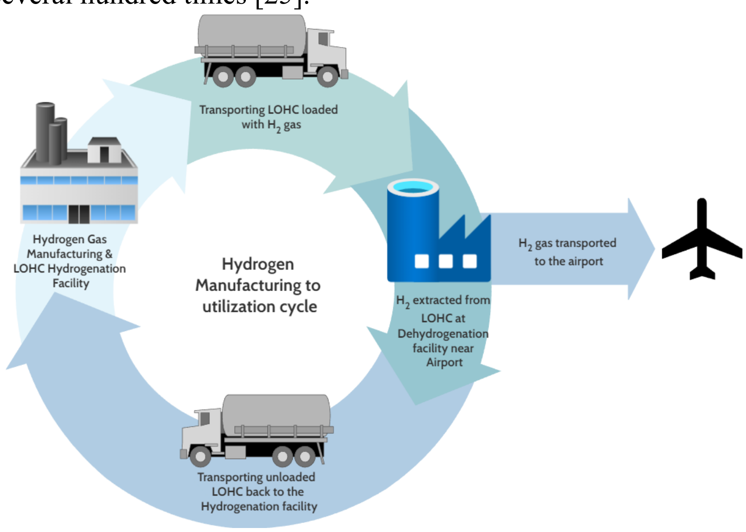

Figure 1: The Hydrogen Manufacturing to Utilization Cycle

One way to maximize the usage of the energy released through the exothermic hydrogenation process is by using it in the electrolysis process to generate hydrogen gas for coastal facilities. The production of 1 kg of hydrogen from water requires around 39 kWh of electricity [26]. However, this value may change depending on the efficiency of the electrolysis system. Some of this electricity can be sourced from the thermal energy generated by hydrogenation. This can be achieved by using thermoelectric generators that can convert thermal energy into electrical energy [27]. One of the important factors in the electrolysis process is the temperature at which the reaction occurs. As the temperature of the system increases, the efficiency also increases [28]. Thermochemical water-splitting processes use high-temperature heat (500°–2,000°C) to drive a series of chemical reactions that produce hydrogen [29]. Using the heat energy released during the hydrogenation process to provide heat for the electrolysis process can ensure the optimal use of the produced heat. This increases the efficiency of the entire process. Since hydrogen generation through electrolysis and the LOHC hydrogenation happens at the same coastal facility, this can be achieved as the energy does not require to be stored and transported over long distances. Another way to use the generated energy is by using the excess heat for other domestic uses in the facility like a water heating system, or even using it in winter for heating purposes if the facility is located where it experiences a cold climate. Thermal stores can be used for this purpose. These are water tanks that are insulated and have the ability to store heat as hot water for several hours [30]. These tanks can vary in size from around 250 liters to 500 liters or more and can provide hot water to the facility. These should be used the same day to ensure no energy loss.

Heat batteries can be used to store energy. In these batteries, heat can be stored in materials known as phase change materials (PCM). The heat is stored in the batteries when this material changes phase from a solid to a liquid. The spare heat or electricity can be used to charge the PCM within the battery. The phase change material changes back into a solid with a release of heat when heat energy is needed [30]. This method of energy storage can be a viable option for using the generated heat in the LOHC dehydrogenation facility by transporting these heat batteries from the hydrogenation facility. Although heat batteries are currently used by installing them in the facility, and using them to store energy, it can be anticipated that technologies that can enable the transportation of these heat batteries will be developed by the 2050s. This will enable the optimal storage of heat released from hydrogenation that can be transported to the dehydrogenation facility at a different location.

Researchers are also studying the hot pressure swing reactor to improve the efficiency of the LOHC system by using the heat generated from hydrogenation directly for the dehydrogenation process. In this process, the required heat for the dehydrogenation of hydrogen-rich LOHC compound can be provided from the previous hydrogenation process that occurred in the same reactor before. However, this requires the catalytic hydrogenation and dehydrogenation to take place in the same hot reactor and the hydrogenation to be carried out at a slightly higher temperature than dehydrogenation. This allows the storage of hydrogenation heat in a suitable heat storage system for its reuse in subsequent dehydrogenation [31]. Hydrogenation occurs at low temperatures and high pressure while dehydrogenation occurs at high temperatures and low pressure. In this reactor, the reactor pressure is kept constant by continuous dosing of hydrogen. The heat released by the exothermic hydrogenation reaction leads to a temperature increase and the reactor is switched from hydrogenation to dehydrogenation mode by pressure adjustment at the back pressure regulator [31]. This is a potential option for using the heat generated from hydrogenation directly in the dehydrogenation process given that both reactions occur at the same facility.

2.2 Liquid Hydrogen

When hydrogen is stored in the liquid phase, it is known as liquid hydrogen. Using liquid hydrogen can be a viable alternative to power most of the aircraft for more than 2 hours even though it can result in energy loss through the liquefaction process. Hydrogen has a very low boiling point of -253°C (−423°F). Therefore, in order to liquefy hydrogen gas, it needs to be cooled to cryogenic temperatures below its boiling temperature to store it in a safe manner and prevent it from boiling [32]. After the liquefaction process, liquid hydrogen can be stored in cryogenic tanks. However, storing hydrogen as liquid comes with several challenges. An extensive amount of energy is required in the liquefaction process and to maintain the cryogenic tanks at very low temperatures. Apart from that, more than 30% of hydrogen's energy content is consumed during the liquefaction process resulting in a loss of energy [32]. Furthermore, great care is to be provided while transporting liquid hydrogen to maintain it below its boiling point to prevent any boil-offs, that is liquid vaporization. In a liquid hydrogen storage system, around 0.3%– 3% of the hydrogen is lost due to boil-off [23]. Using insulated cryogenic containers is an efficient way to prevent boil-offs. This is done by having a double wall construction and by evacuating the space between the walls to nearly eliminate heat transfer from convection and conduction. Most liquid hydrogen tanks are spherical in shape in order to provide the lowest surface area for heat transfer per unit volume. A large tank will have a proportionally less heat transfer area when compared to a small tank. This is because the volume increases faster than the surface area when the diameter of the tank increases. This way, the rate of boil-off can be reduced which reduces [33].

3. Transportation

Hydrogen imposes a challenge on our current infrastructure. Compared to other types of energy, like electricity, which is readily available, transporting hydrogen creates a greater cost. There are several methods for transporting hydrogen, including transferring it in gaseous form, in liquid form, and using LOHCs. Gaseous hydrogen can be transported in pressurized tanks, or it can be transported through existing pipeline infrastructure by mixing hydrogen and natural gas [34]. Liquid hydrogen can be transported using insulated cryogenic pipelines or special cryogenic tanks. However, transporting the cryogenic tanks imposes a safety concern because liquid hydrogen is highly explosive, and having it on a moving truck around traffic creates concern [35].

To benefit from LOHCs, for coastal regions, the hydrogen produced at a manufacturing facility is hydrogenated into LOHC+ and put into tanks similar to the ones used for gasoline and diesel. The tanks can be transported in various methods depending on the location of the manufacturing facility, the LOHC extraction facility, and the location of the airport. These include electric vertical take-off and landing vehicles (eVTOLs), fully-autonomous or electric trucks, and underground hyperloop tunnels. EVTOLs have been a developing technology for years that hopefully will be in widespread use in the future. Beta Technologies, a company based in Vermont, is working on eVTOLs that can carry up to six passengers or a total cargo weight of 1,500 lbs with a range of around 289 miles [36, 37]. Beta Technologies is also working on a charging network called the beta charge cube that would effortlessly provide power to electric vehicles, eVTOLs, and electric aircrafts. They plan to have a network of 150 charge cubes by 2025 [37]. These technological advances of eVTOLs propose a solution for LOHC+ tanks to be transported to different coastal regions. Another method of transporting hydrogen is by using autonomous or electric Trucks. These trucks will provide coastal transportation to the dehydrogenation facility located near the airport. The trucks can also be used to transport heat batteries, which are used to store energy during the hydrogenation process. Considering the weight of the battery, using trucks can be a better option compared to eVTOLs. Waymo is a company based in California also previously recognized as Google's Self-Driving project [38]. Their service called Waymo One provides electric autonomous car rides in Phoenix, Arizona, and some rides in San Francisco, California. [39] They are also working on bringing rides to Los Angeles, California. Waymo is also working on autonomous trucks that can be used to transport cargo. Currently, Waymo Via is a name given to Waymo's autonomous truck network. [40] These trucks are being tested by the company for autonomous use and transportation of cargo. Waymo Via is also partnered with Uber Freight to work on advancing and scaling the use of autonomous trucks [41]. Another company working on electric trucks is Tesla, based in Austin, Texas [42]. Their semi truck is fully electric with integrated safety and advanced technology. This truck uses 2kWh per mile and has a range of up to 500 miles. This truck is already on the road, with PepsiCo receiving their first big shipment from Tesla [43].

For airports located in non-coastal regions, biomass gasification will be used to generate hydrogen until the infrastructure is available for hyperloop technology to transfer green hydrogen from coastal area to these regions. Depending on the location of the biomass gasification plant, similar transportation methods to coastal regions will be used. The high-pressurized gaseous hydrogen tanks will be transported using eVTOLS and fully-autonomous or electric trucks. When the infrastructure is available for underground hyperloops, then LOHC+ tanks from coastal manufacturing facilities will be transported to extraction facilities in non-coastal regions for airport use. Hyperloops allow for a safer and faster transport of hydrogen compared to trucks, especially over long distances [44]. Hyperloop Transportation Technologies, a company based in California, proposes to bring the hyperloop concept into reality [37]. Hyperloop is a proposed concept of a capsule inside vacuum-sealed tubes powered by magnetic tracks and a small electric current [45]. The concept proposes the pod to reach up to 760 mph [45, ,46, 47]. There are many other companies working on this concept, such as Virgin Hyperloop, also known as Hyperloop One [48, 49, 50].

Once LOHC+ tanks are transported, a facility located near the airport will extract the gaseous hydrogen and fill it into high-pressure tanks to be used for short-range flights or convert it to liquid hydrogen and store it in cryogenic tanks in a liquefaction facility, which is anticipated to be at the same location as dehydrogenation facility to be used for long-range flights. Depending on the location of the LOHC extraction facility and its distance from the airport, hydrogen tanks can be either stored in the facility or transported to the airport storage facility. When needed, personnel stationed at the aircraft will place an order for the autonomous vehicles to transport the hydrogen tanks from the airport storage facility directly to the aircraft for use by the fuel cells. The transportation process of hydrogen can be best visualized in Figure 2.

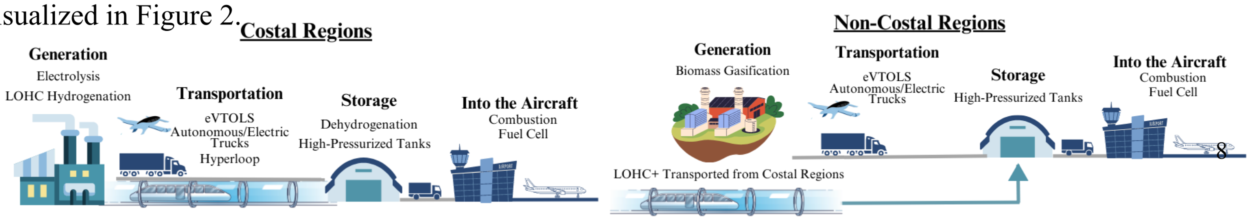

Figure 2: Hydrogen Transportation Process

Universal Hydrogen, a company based in California, proposes this concept of directly putting hydrogen tanks into the aircraft. In their model, gaseous hydrogen tanks are transported in modular capsules and put directly into the aircraft [51]. Rod Williams, chief commercial officer at Universal Hydrogen said, “The modules are loaded onto the aircraft, they're latched down, and then they basically serve as the fuel tank within the aircraft to supply the fuel to the powertrain” [52]. When all the hydrogen is consumed, empty tanks are taken back to the facility to be refilled and swapped with full tanks. This whole process saves fueling time significantly. Big companies like JetBlue, American Airlines, and Airbus have already invested in Universal Hydrogen [51].

4. Into the Aircraft

The application of hydrogen in aircraft is the next step that needs to be considered. As using hydrogen in aircraft is still in the development process, there are many challenges that the new generation of engineers needs to face and carry on, such as ways to use hydrogen to power the aircraft, and store the hydrogen on the airplane. Even though using hydrogen in aircraft is still in the early stage, some aviation industries have already tried using hydrogen to replace current aircraft fuel. Two main ways proposed to power the aircraft with hydrogen as a fuel are combustion and using a fuel cell [53]. For the former proposed method, the process is similar to the traditional internal combustion engines, except hydrogen is used in place of the fossil fuel counterpart [54]. Although using a combustion engine is an almost carbon-free process, it releases other pollutants, such as nitrogen oxides, or NOx [55]. NOx is an atmospheric pollutant that could cause poor air quality, create brown-orange haze, and is generated through the reaction of nitrogen and oxygen at high temperatures and pressures within the engine’s combustion chamber [56]. Hence, hydrogen engines often require an exhaust treatment system to reduce NOx emissions [54]. On the other hand, using a fuel cell produces no emissions except water vapor; It converts the chemical potential energy of a hydrogen molecule into electrical energy and creates water and heat as by-products in the case of using green hydrogen [57]. Furthermore, a fuel cell is more efficient than a combustion engine, as a fuel cell can convert hydrogen into electricity at an efficiency rate of up to 60% while a combustion engine can only generate electricity with an efficiency rate of 33%-35% [58]. Additionally, a fuel cell has superior durability due to its simple design, which features fewer moving parts, and its need for minimal maintenance. This results in a high level of reliability and is less prone to mechanical failures compared to a combustion engine [59]. Overall, a fuel cell is often considered a better choice than a combustion engine due to its great advantages in many applications.

Although using a fuel cell is promising to achieve carbon-free emission, storing hydrogen on an airplane introduces some challenges. Hydrogen is very light compared to traditional aviation fuel but has three times higher specific energy as compared to traditional aviation fuel. On the other hand, the volumetric energy of hydrogen is much lower in the way that four times the volume of hydrogen is needed to produce the same thrust in an airplane, which consequently makes it harder to store hydrogen in an aircraft [60]. To address this problem, in the design of future airplanes, more space must be assigned to hydrogen tanks for instance by using blended wings or replacing a part of the fuselage space with hydrogen fuel tank storage, which requires giving up approximately 9 rows of economy class seats towards the back of the cabin. This would require airlines to increase the number of flights to maintain their existing passenger flow, which could lead to air traffic congestion. On the other hand, the use of liquid hydrogen significantly reduces the required fuel tank space by 80% to deliver the same amount of energy compared to gaseous hydrogen[61]. Also, the volume ratio of liquid to gas is approximately about 1:848[62], making liquid hydrogen more feasible for commercial aircraft to travel long distances than gaseous hydrogen. In addition, the companies Hypoint and GTL are collaborating on the development of an ultra-lightweight cryogenic tank that can store liquid hydrogen in aircraft with dimensions of only 2.4 meters in length and 1.2 meters in diameter[63]. This is approximately equivalent to the space required for about three rows of economy-class seats towards the back of the cabin, providing significant space savings compared to gaseous hydrogen tanks. However, as previously mentioned earlier, about 30% of the energy contained in hydrogen is lost during the process of liquefaction, which also involves significant costs due to the specialized machinery required for the process and the large amount of energy needed to carry out the process. The amount of hydrogen fuel required to power the aircraft for about two hours depends on the model of the airplane and its consumption rate. For example, A Boeing 737 typically consumes around 13,627 liters of jet fuel per hour [64]. Given that liquid hydrogen requires four times the volume of jet fuel, an estimated 54,508 liters of liquid hydrogen would be needed to power the aircraft for every hour of flight. Furthermore, the liquid hydrogen has to be stored at the temperature of -252.9 °C for twelve hours or more, and this means that the development of onboard cryogenic systems is needed as the airliner's cryogenic pumps have to serve 10000-hour working lifetimes[61].On the other hand, gaseous hydrogen has a lower density compared to liquid hydrogen, as shown in Table 1. Expanding on from the previous example, using gaseous hydrogen as aviation fuel for Boeing 737 requires even a larger volume of tank to store it in the aircraft. Based on the earlier mentioned volume ratio of liquid to gas, approximately about 4.6×10^{7}liters of gaseous hydrogen would be required per hour of flight to power the aircraft without compression. However, gaseous hydrogen has an advantage over liquid hydrogen in that it does not incur energy losses of 30%, and its storage requirements are relatively simple since gaseous hydrogen does not require cryogenic temperatures like liquid hydrogen, which makes its storage and handling less complex and less expensive. To benefit from the positive aspects of gaseous hydrogen, we believe that gaseous hydrogen is a viable option for short-range flights, as the large fuel tank required for longer flights may not be feasible given the limited space in an aircraft. On the other hand, liquid hydrogen is a more suitable option for long-range flights due to its higher energy density and significantly reduced fuel tank space requirements.

5. Climate Impacts and Safety

As with any aspect of engineering research, safety is a crucial topic of focus. In order for hydrogen to be considered, its viability in regard to overall safety compared to other traditional fuels such as gasoline or natural gas needs to be assured as well as its overall effect on the environment. Research on the properties of hydrogen and its behavior in certain environments proves that hydrogen is a safer alternative fuel. While it is still a flammable substance and should still be handled with the appropriate care, hydrogen possesses some qualities that make it safer to use. Furthermore, by using hydrogen to fuel future aircrafts, the carbon footprint created is significantly reduced.

The first important aspect of hydrogen is its density; at 1.2 kg/m^3, it is the lightest known substance in the universe, roughly 14 times lighter than air [65]. As a result, hydrogen disperses very rapidly, which would minimize the risk in the case of a leak. In order for hydrogen gas to pose the risk of catching fire, it must be concentrated very highly, must have a certain amount of oxidizer present, and the mixture must reach a high enough temperature [65]. Even if hydrogen was present in low concentrations, less than 10%, the ignition energy required to ignite it would be much greater than that of gasoline and natural gas [66]. Furthermore, much lower concentrations of gasoline and natural gas when compared to hydrogen are required to pose a risk of explosion. The concentration range for which hydrogen can be explosive is 18.3-59%, but when compared to the same range for gasoline and natural gas, which is 1.1-3.3%, it is clear that hydrogen is much safer in this regard [66].

Liquid hydrogen in particular has safety factors that should be considered. Like gaseous hydrogen, it is still colorless and odorless and it also retains a low density meaning it will still rise above in most mediums. One difference that could be a concern to address is its temperature and boiling point. Liquid hydrogen must be kept at extremely low temperatures to avoid phase change into a gas. This is especially important since hydrogen also possesses one of the lowest boiling points of any gas, meaning evaporation could occur if the conditions for keeping the hydrogen cold are not sufficient [67].

One thing relevant to liquid hydrogen is the presence of ortho-hydrogen and para-hydrogen. These terms are collectively known as spin isomers of hydrogen and refer to the direction of the protons in a hydrogen molecule spin. Ortho-hydrogen molecules spin in the same direction while para-hydrogen molecules spin in opposite directions. Additionally, para-hydrogen exists at a lower energy state than ortho-hydrogen. As a result, keeping liquid hydrogen at the required temperature can result in the ortho converting to para-hydrogen, a process that typically releases heat and makes evaporation more likely.

This "boil-off" gas that results can cause burns to the skin if not handled properly and can cause typically reliable materials such as carbon steel, plastic, or rubber to become brittle and thus more prone to failure [67].

The fact that hydrogen gas is colorless, odorless, and tasteless may seem like it would be very dangerous in the event of a leak, as it would be undetectable, especially as its properties would cause it to rise [66]. However, this problem has been mitigated by developing hydrogen sensors, which help detect leaks. This is especially beneficial compared to the process used for gasoline and natural gas. Mercaptan, an odorant that contains sulfur, is added to these fuels in order to make them detectable. Odorants such as this are known to contaminate fuel cells [66]. Therefore, hydrogen can be optimal in the case of powering fuel cells.

It is important to note that although hydrogen may possess some benefits to safety, it should still be treated like any other flammable gas. This means taking measures to ensure that in the event of a leak, hydrogen is not able to form in large concentrations and cannot reach a temperature where it is capable of igniting. There are those who would be skeptical of the safety of hydrogen, especially when looking at disasters such as Hindenburg in 1937. In the aftermath of this tragedy, hydrogen, which was used to keep the airship afloat, was blamed for causing the fire that ultimately resulted in the destruction of the Hindenburg. However, it was found later that the airship's outer covering was coated with a reactive chemical, whose properties made it more closely resemble rocket fuel [66]. It is events like this that give hydrogen a bad reputation but with the right preventative measures, hydrogen can be successfully utilized as an alternative fuel with its safety benefits making it the more appealing choice over gasoline and natural gas.

Hydrogen fuel would greatly work to offset the effects of carbon emissions. However, it is unlikely that it can be completely eliminated. For this reason, how to make captured carbon emissions a benefit is a growing topic of interest. One benefit is using carbon as fuel in the making of consumer goods. This process, called gas fermentation, uses captured carbon emissions from various sources in order to create "green chemicals" which can then be used to make household items such as soaps, fabrics, and perfumes [68]. Similar to the making of wine or beer, engineered microorganisms are fed to carbon to produce ethanol, a building block in many products [68]. The practice of capturing carbon and reusing it is an innovation on the rise throughout the world and it further minimizes the impact of carbon emissions that come from typically large sources such as the aviation industries.

6. Readiness Levels and Proposed Timeline

With the involvement of the research on the area, hydrogen is no longer being considered just an experimental sustainable replacement to fuel. Companies are now working on reducing the price of hydrogen. Energy company SGH2 is building the world's largest green hydrogen project which will use waste gasification by combusting 42,000 tons of recycled paper waste annually to produce green hydrogen. Rolls Royce has also made successful tests with a 12-cylinder gas variant engine running on 100% hydrogen fuel [69]. Recently, the U.N. launched the Green Hydrogen Catapult Initiative, which brings seven of the biggest global green hydrogen project developers together to try and cut the cost of green hydrogen and increase production fifty times over by 2027 [69]. Furthermore, companies are replacing traditional fuel with hydrogen, allowing industries such as the aviation industry, to reduce the negative environmental impact they are causing drastically. Two startups, Universal Hydrogen and ZeroAvia have tested aircraft that have a hydrogen-powered engine under one wing and a conventional aviation fuel engine under the other. Universal Hydrogen used a modified ATR-72 regional airliner to turn a turboprop-powered plane into a hydrogen one which successfully completed a test flight, even cruising primarily on the hydrogen-powered engine for a lap which notably was silent. Although the modified aircraft usually holds 50 passengers, the large liquid hydrogen tank reduces the capacity to about 40. The current technology is being designed for short hauls since large liquid-hydrogen tanks onboard cause regional airliners to only travel about half of a gas-fueled plane's 1,600-kilometer range. The company is remedying this by developing a jet engine that can burn hydrogen for longer-haul aircraft [70]. ZeroAvia used a 19-seat aircraft in its test flight and has raised over $140 million in funding from investors. Also reportedly received over 1500 pre-orders for its hydrogen fuel-cell systems. Commercial launch is expected in 2025 [71]. An Intergovernmental Panel on Climate Change report states that if the rise in carbon emissions doesn't stop by 2025, damages may be irreversible [72]. Due to this, the Target True Zero initiative launched in 2021, which was meant to accomplish three main tasks: to bring leaders together to see different perspectives on alternative propulsion, to help stakeholders take actions to speed up the transition into clean aviation, and to make sure the climate impact of the aviation industry was realized [73, 74]. So far, the Target True Zero initiative seems to be successful, as the US Department of Energy released a Notice of Intent to fund the Bipartisan Infrastructure Law that is setting aside eight billion dollars to develop hydrogen hubs in the US [75]. Also seen in 2021, Pratt & Whitney was awarded $3.8 million from Advanced Research Projects Agency-Energy (ARPA-e) to develop hydrogen propulsion technology [72]. As a global effort, a new Aerospace Global Forum in the UK has been launched, hoping to accelerate the transition to net zero [48]. A report released by the World Economic Forum, with the University of Cambridge's Aviation Impact Accelerator, claims that by 2035, "Fully battery-electric aircraft could enable completely emission-free flight over the shortest distances. Hydrogen could electrify aircraft with fuel cells over mid-range distances or through direct combustion. Direct combustion can be applied to any aircraft operating any distances flown today" [73]. The UK has also led the Aerospace Technology Institute to form FlyZero to find an alternative to traditional fuels, finding that green liquid hydrogen was the most viable zero-carbon emission fuel with the potential to scale to larger aircraft utilizing fuel cells, gas turbines, and hybrid systems out of all other tested fuels. We have also seen the "New Aviation Propulsion Knowledge and Innovation Network" (NAPKIN) release a report claiming that zero-carbon-emission flights on sub-regional routes for aircraft of seven to nine seats are possible within a few years. [73][74].

Progress outside of the United States is also vast, with "HEAVEN," a project in Spain, receiving funding from the EU to build an onboard liquid hydrogen storage system and integrate it into an aircraft [7]. In Germany, they have started fuel cell aircraft developer H2FLY, saying that it has started final preparation integrating liquid hydrogen tanks into the HY4 test aircraft [51]. The German Aerospace Center has also partnered with Deutsche Aircraft also to integrate a fuel cell system into an aircraft. [7]. We have also seen the Netherlands start a private-public partnership called Hydrogen Aircraft Powertrain and Storage System (HAPPS). They aim to build a hydrogen system that can be used to retrofit existing regional aircraft, which would allow commercial hydrogen-powered planes to take off in 2028 [51]. Germany has started fuel cell aircraft developer H2FLY, saying that it has started final preparation integrating liquid hydrogen tanks into the HY4 test aircraft [51]. Governments aren't the only ones to combat carbon emissions, though. In 2023, Honeywell International Inc announced a new technology to produce lower-carbon aviation fuel from green hydrogen and carbon dioxide captured from the industry. It would combine green hydrogen and carbon dioxide siphoned off industrial smokestacks to create lower-carbon methanol, which would be turned into fuels. The process could reduce greenhouse gas emissions by 88% when compared to traditional jet fuel [76]. Airbus has also recently committed to green hydrogen power, and in 2021, Airbus and Air New Zealand started a joint initiative to research how hydrogen-powered aircraft can help the airline reach its net-zero emissions goal by 2050. Then, in May 2022, Airbus opened a Zero Emission Development Centre for hydrogen technologies in the UK. After that, in June 2022, Airbus signed a memorandum of understanding with "Linde," an industrial gas company, to work on developing hydrogen infrastructure at airports. They also plan on doing a demonstration flight for the A380 passenger airplane in 2026 using hydrogen fuel cells and burning hydrogen directly in an engine. [51].

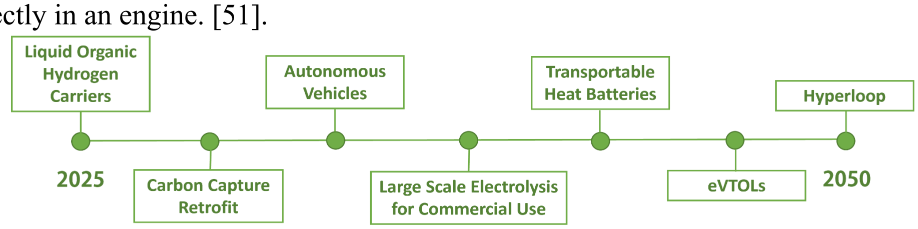

Figure 3: Estimated Timeline for technological advancements.

Appendix

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