REVIEW ARTICLE

# Hydrogen-Powered Aircraft and Their Effectiveness in Reducing the Climate Impact of the Aviation Industry

Lok Kay Teo

Claremont High School, 311 E Georgetown Pl, Claremont, CA, 91711, USA

ABSTRACT: The aviation industry is a key part of the economy. Aerospace engineers have been looking for ways to reduce carbon emissions, and many have shown interest in hydrogen power. This paper evaluates long-haul hydrogen-powered aircraft and their effectiveness at reducing greenhouse gas emissions. Evaluation is based on different attributes of hydrogen and their interaction with both the environment and aircraft performance. This paper explores the production of hydrogen, its environmental impact, storage, and potential effects on efficiency and performance. Additionally, it explores the combustion of hydrogen, including the emissions and power generated. The three main types of emissions that will be evaluated are carbon dioxide, $NO_x$ ($NO + NO_2$) emissions, and contrail formation. They impact the environment differently, and their impacts directly impact the effectiveness of hydrogen-powered aircraft at reducing emissions. There are major possible developments in the future that would be able to significantly reduce their emissions. Although many properties of the greenhouse gases are not certain, this paper has found that hydrogen-powered aircraft are very effective at reducing the impact of the aviation industry on the climate.

KEYWORDS: Engineering Mechanics, Aerospace and Aeronautical Engineering, Hydrogen-Powered Aircraft, Hydrogen Storage, Greenhouse Gases.

## Introduction

The aviation industry undoubtedly has a large impact on the world. Aircraft ship both cargo and passengers all around the world daily. In 2011 alone, airliners transported 2.8 billion passengers and shipped 47.6 million metric tonnes of cargo.[1] They have also supplied tens of millions of jobs and contribute to a significant portion of global GDP.

However, the aviation industry has also had a significant impact on the climate. In 2019 alone, the air transport sector emitted upwards of 900 million tonnes of carbon dioxide.[2] Currently, the aviation industry accounts for 3.5% of total climate impact, and by 2050, the aviation industry is predicted to be responsible for 5% of total climate impact, illustrating how aviation emissions are bound to increase.[3] Because many of the emissions are released at high altitudes, the options of reversing the climate impact of the aviation industry are particularly challenging. The climate impact caused by the aviation industry presents new challenges, and its contributions need to be minimized.

Hydrogen-powered aircraft have the potential to lower aviation greenhouse gases on long-haul flights. When hydrogen is burned, no carbon dioxide, the most dominant greenhouse gas, is emitted.[4,5] This means that the climate impact caused by the aviation industry may be drastically reduced.

Hydrogen-powered aircraft have been considered by scientists and engineers as a viable solution to reduce climate impact in the future for years. However, many technical challenges stand in their way. Although the main concept of thrust production would largely remain the same, different engines that require new technologies would need to be developed to accommodate hydrogen as a fuel. Fuel tanks with new technology would also have to be developed, as the properties of hydrogen differ drastically from the properties of kerosene. These technical challenges make aircraft developers hesitant to shift toward hydrogen-powered aircraft.

There are two methods of hydrogen consumption: hydrogen combustion and fuel cells. This paper will only focus on hydrogen combustion. Fuel cells, although far more climate-friendly, are not the appropriate type of engine for long-haul flights, as they are used for smaller aircraft.[6] Therefore, fuel cells and their climate impact will not be analyzed in this paper. It will focus exclusively on hydrogen combustion engines.

In order to evaluate the effectiveness of hydrogen-powered aircraft at reducing the climate impact of the aviation industry, this paper will first examine the production of hydrogen, its efficiency, and its release of greenhouse gases. Next, this paper reviews hydrogen storage and its aerodynamic and weight effects, hydrogen's properties, technologies, and techniques that could be utilized, and future predictions on how efficient hydrogen storage systems may become. Then, this paper will explore combustion, the different ways in which hydrogen and kerosene are burned, and techniques that can be utilized to increase efficiency and decrease greenhouse gas emissions. Finally, this paper analyzes the amount of greenhouse gases that hydrogen-powered aircraft will produce, such as carbon dioxide, NOx emissions, and contrails, and the effect each of the gases will have on the atmosphere. These results will then be compared to current modern aircraft to determine the effectiveness of hydrogen-powered aircraft at reducing climate impact.

## Discussion

### *1. Hydrogen Production:*

In order for hydrogen to be used as a fuel for aircraft, it must first be produced. There are various forms of production of hydrogen, including steam reforming, partial oxidation, and electrolysis. Steam reforming uses methane, partial oxidation uses coal and oil, and electrolysis uses electricity. Unfortunately, most hydrogen is created through the usage of fossil fuels, limiting hydrogen's friendliness toward the climate.[5] Although electrolysis can be achieved with no emissions through green energy production, such as nuclear and wind energy, hydrogen is rarely ever produced using this method, and its environmental benefits are therefore minuscule.

Approximately 99.5% of greenhouse gases throughout the lifecycle of kerosene are released during combustion.[7] This means that the amount of greenhouse gases produced during kerosene production is very small and insignificant.

### *1.1. Steam Reforming Method:*

Steam reforming is the most popular method of producing hydrogen. In fact, more than 95% of hydrogen is created using this method.[8] This process reacts methane ($CH_4$) with steam ($H_2O$) to make carbon dioxide ($CO_2$) and hydrogen ($H_2$). The overall chemical reaction is:

$$CH_4 + 2H_2O \Rightarrow 4H_2 + CO_2.$$ [9] (R1)

The reaction can be broken down into two elementary steps.

$$CH_4 + H_2O \Rightarrow CO + 3H_2.$$ [9] (R2)

$$CO + H_2O \Rightarrow CO_2 + H_2.$$ [9] (R3)

For every four hydrogen molecules that are produced, a single carbon dioxide molecule is produced. This chemical reaction is endothermic, meaning that additional heat is required in order to make the methane and water vapor react. The change in enthalpy of the first elementary step is 206 kJ/mol, the second elementary reaction is -41 kJ/mol, and the reaction can only take place at temperatures over 700ºC.[10] In fact, 30-35% of the methane used to produce hydrogen is used to create the heat necessary for the reaction.[10] Creating heat adds to the overall carbon dioxide production. For the production of 129 kg of hydrogen, 1275 kg of $CO_2$ is emitted.[4] The steam reforming method has an efficiency of about 85%, which is very efficient relative to other methods of energy production, such as burning coal.[10] Given that 90% of hydrogen is already created using the steam reforming method and the efficiency of this method is very high, this method of producing hydrogen will probably remain the most favorable for hydrogen producers. Therefore, the climate impact of the production of hydrogen is unlikely to decrease in the future.

### *2. Hydrogen Storage:*

After hydrogen is produced, it must be shipped to airports. While an airplane flies, it must store fuel onboard. Only compressed and liquid hydrogen are viable for long-haul flights.[11] Hydrogen storage systems differ from modern kerosene storage systems, and the efficiency that hydrogen storage systems offer differs from the efficiency of modern kerosene storage systems. Therefore, using hydrogen as a fuel would change the amount of energy needed for consumption during the flight, which would expand its climate impact. The type of fuel that will be focused on will be liquid hydrogen.

### *2.1. Properties of Liquid Hydrogen:*

Liquid hydrogen has a few properties that make storing it different from kerosene.

Firstly, hydrogen has a specific energy that is three times greater than kerosene.[5] If the same amount of grams of hydrogen and kerosene are combusted, hydrogen will release three times more energy. This decreases the weight of hydrogen that needs to be stored on a flight by roughly three.

Next, hydrogen has an energy density that is four times less than kerosene, with hydrogen having an energy that is 8 MJ/$m^3$ and kerosene having a volumetric energy density of 32 MJ/$m^3$.[12] For example, if a cubic meter of both hydrogen and kerosene is burned, the kerosene will produce four times more energy. This becomes problematic, as it would require the volume of fuel storage of modern aircraft to increase by four. This would increase the weight and size of the aircraft substantially and pose new sets of problems.

The extra fuel storage would take up more space and increase the size of the aircraft. Not only might this add to weight, but if the fuselage is bigger, the aircraft will have more aerodynamic drag. The extra fuel space would add 10% more aerodynamic drag compared to modern kerosene-powered aircraft.[5]

Then, liquid hydrogen has a boiling temperature of 20K.[13] This is -253ºC, and although it is much colder higher in the atmosphere, it is not quite -253ºC. Therefore, there needs to be systems to cool the fuel inside the aircraft as well as insulation to keep it cool. Furthermore, when liquid hydrogen is stored, it needs to be pressurized.[11] This will require the fuel tanks to be stronger to be capable of pressurizing the fuel.

The freezing temperatures of liquid hydrogen also require the storage system to be airtight.[14] The freezing temperature of oxygen and nitrogen is higher, and if oxygen or nitrogen enters the hydrogen storage tanks, it will freeze. Frozen pipes might block pipes and cause other disruptions with fuel flow.

These three properties of liquid hydrogen make the storage systems that would store the liquid hydrogen much more complex, high-tech, and heavier than current modern fuel storage systems. All of these attributes would decrease total aircraft efficiency.

### *2.2. Gravimetric Efficiency:*

Gravimetric efficiency is defined as the ratio of the weight of the fuel to the weight of the fuel and the fuel tank combined.11 For example, if a fuel tank weighs 1 kilogram and can hold 99 kilograms of fuel, the gravimetric efficiency would be 99%. A heavier fuel tank would mean a lower gravimetric efficiency because the weight of the fuel and the fuel tank would increase as well.

Because a decrease in gravimetric efficiency generally means a heavier fuel tank and a heavier overall aircraft, gravimetric efficiency needs to be as high as possible. A high gravimetric efficiency would lead to higher overall efficiency, longer range, and lower climate impact.

Current modern airplanes have gravimetric efficiencies of nearly 100% (Table 1).[13] Although hydrogen-powered aircraft have not been developed yet, current technologies could support a gravimetric efficiency of about 30-45%, where 30% would represent a conservative estimate.[15] However, if hydrogen fuel tanks are developed, gravimetric efficiency could increase with an optimized and theoretical value of 65-70%.[13]

Gravimetric efficiency has a large impact on efficiency and range. It was found that increasing the gravimetric efficiency of an aircraft from 30% to 80% could increase the range from 4000 to 7000 nautical miles for long-range aircraft.[15] The same study also found that increasing gravimetric efficiency above 80% had a decaying impact on range.[15] This suggests that after years of development, the gravimetric efficiency of hydrogen-powered aircraft will contribute to a lack of efficiency and range slightly compared to conventional and modern kerosene-powered aircraft. However, first-generation hydrogen-powered aircraft will be significantly less efficient and will not even be able to complete long-haul flights. Therefore, hydrogen-powered aircraft may seem less efficient at first, and the efficiency penalty from a lower gravimetric efficiency would slowly disappear.

In total, a hydrogen-powered aircraft would be a little less efficient than a modern kerosene-powered jet (Table 1). A study was conducted where three aircraft flew a 7829 nautical-mile flight. The first aircraft was a conventional kerosene-powered aircraft, the second aircraft was a hydrogen-powered aircraft with a gravimetric efficiency of 45%, and the last aircraft was a hydrogen-powered aircraft with a gravimetric efficiency of 67%. The hydrogen-powered aircraft with a gravimetric efficiency of 45% consumed 20-40% more energy than the kerosene-powered aircraft, and the hydrogen-powered aircraft with a gravimetric efficiency of 65% consumed 10-20% more energy than the kerosene-powered aircraft. It is predicted that optimized hydrogen-powered aircraft will be able to use as little as 5% more energy than kerosene-powered aircraft.[16]

**Table 1:** Hydrogen and kerosene statistics.[12,13,15] Table 1 finds that the volumetric energy density of Kerosene is higher than that of hydrogen, allowing for a higher gravimetric efficiency.

| Fuel type | Hydrogen | Kerosene |
|---|---|---|
| Volumetric energy density | 8 MJ/m³ | 32 MJ/m³ |
| Boiling temperature | -253°C | Not concerning |
| Gravimetric efficiency | Low | High |

### *3. Combustion:*

Combustion is the stage where the fuel is ignited in the engine and refers to the burning of the fuel. Hydrogen burns differently from kerosene and releases different gases. Although hydrogen burns very similarly to kerosene, entirely new engines will need to be developed to accommodate it.

For example, because of the lower volumetric energy density, 30% of the space in the combustion chamber must be hydrogen, while modern aircraft only require 5% of the combustion chamber to be fuel. As a result, only 70% of the combustion chamber will be filled with oxygen. This limits the amount of fuel that can be ignited at a single instant, also limiting thrust. Therefore, hydrogen-powered engines will be weaker than modern engines, and new and larger engines will probably have to be built in order to service long-haul flights with the same performance.

Since hydrogen's energy density is three times greater than kerosene, hydrogen engines generally operate at larger combustion temperatures.[17] It burns approximately 140K hotter than kerosene.[6] There are a few techniques that can be utilized to lower the temperature, leading to various benefits.

#### *3.1. Hydrogen Combustion Properties:*

Firstly, hydrogen has a higher ignition temperature than kerosene.[17] Part of this is because of the higher specific energy of hydrogen. This has effects on the amount of emissions that are released.

Next, despite requiring to fill up 30% of the combustion chamber to burn, hydrogen can be burned much leaner than kerosene. Hydrogen's stoichiometric fuel-to-air ratio is 1:34, which is less than half of kerosene's fuel-to-air ratio, which is 1:15.[11] This means that hydrogen has a lower lean stability limit. This leads to lower fuel flows and greater overall efficiency.

Finally, hydrogen has a lower residence time than kerosene.[16] This means that it burns faster. This impacts the formation of various greenhouse gases that may form inside the combustion chamber.

#### *3.2. Hydrogen Combustion Emissions:*

One of the major greenhouse gases that is produced by aircraft is nitrogen oxide ($NO_x$) emissions, which are nitrogen dioxide ($NO_2$) and nitric oxide (NO).[18] They are produced at high temperatures, such as in combustion chambers, when nitrogen ($N_2$) and oxygen ($O_2$) react with each other.

The temperature inside the engine directly impacts the amount of $NO_x$ that forms. The low lean stability limit of hydrogen will allow a hydrogen-powered engine to burn at a leaner mix and burn at a lower temperature, even though hydrogen normally burns at much higher temperatures.[19] This will lead to the combustion chamber of a hydrogen-powered engine being 150-200K cooler than the combustion chamber of a kerosene-powered engine.[16] This will also lengthen the lifespan of the engines, leading to less maintenance, repairs, and replacements.[4]

Because of the low residence times, less $NO_x$ will also be produced because $NO_x$ has less time to form.[11] This means that hydrogen inherently produces less $NO_x$ than kerosene with respect to residence times.

Finally, there is a special technique to reduce the $NO_x$ emissions of an aircraft called rich-lean combustion. The inner nozzle supplies a rich mixture, and the outer nozzle supplies a lean mixture. A study finds this technique to be able to reduce NOx emissions by around 40% alone.[20] Advancements and developments within the field of hydrogen-powered aircraft will lead to greater abilities to further reduce emissions.

### *4. Emissions Comparison:*

There are three main kinds of emissions that come from aircraft. They are carbon dioxide, nitrogen oxide ($NO_x$), and


DOI: 10.36838/IJHSR811.133

contrail formation. They each impact the environment in different ways. Although water vapor is a greenhouse gas, it has a short lifetime of only a few months and low radiative forcing, at 2 $mW/m^2$, which makes its climate impact minimal and insignificant compared to other greenhouse gases.[6,18]

***4.1. Carbon Dioxide:***

Carbon dioxide is widely known to be the gas most responsible for climate impact. It has a radiative forcing of 34.3 $mW/m^2$, which measures the amount of energy reflected per unit of carbon dioxide.[16] Its radiative forcing is slightly limited because carbon dioxide has a relatively high concentration compared to other greenhouse gases.[21]

Given that current modern aircraft burn kerosene, which is a fossil fuel, they emit a lot of carbon dioxide. However, when hydrogen is burned, it does not produce any carbon dioxide. Therefore, the carbon emissions are almost eliminated (Table 2). The only carbon dioxide that needs to be accounted for is the amount of carbon dioxide that is produced during the production of hydrogen. As a result, the total amount of carbon emissions could be reduced by approximately 88%.[14]

***4.2. $NO_x$ Emissions:***

$NO_x$ emissions are also problematic for the atmosphere. They are also considered greenhouse gases. Approximately 15-20% of the $NO_x$ in the atmosphere 8-12 kilometers above the ground is produced by aircraft.[22]

$NO_x$ emissions behave and impact the climate differently. $NO_x$ emissions themselves have no impact on the atmosphere, but they produce ozone and reduce methane.[22] Both of these gases are greenhouse gases. Overall, $NO_x$ emissions have a radiative forcing of 8.2 $mW/m^2$, which is lower than carbon dioxide because part of $NO_x$ also helps reduce climate impact by eliminating methane.

Although when hydrogen burns it generally produces more heat, certain techniques can be implemented, such as feeding the engine a lean mix, that will be able to reduce the temperatures below those that burn kerosene. $NO_x$ emissions will have the potential to be lowered by approximately 70%.[5]

***4.3. Contrail Formation:***

Contrails are the clouds created by engines as the hot exhaust from the engines mixes with the cold air high in the atmosphere. These clouds reflect heat back to the surface of the Earth. Although scientists are unsure of the exact radiative forcing of contrails, as there is substantial uncertainty about their climate effects, some have estimated it to be about 111.[4] mW/m^2.[18] This is about three times the radiative forcing of carbon dioxide, albeit very uncertain. However, their climate impact is undoubtedly strong. They account for 50% of the aviation industry's climate impact.[23]

Other factors influence how big an impact contrails have on the environment. Hydrogen-powered aircraft produce approximately 2.6 times more water vapor than kerosene-powered aircraft.[24] This does not necessarily mean that hydrogen-powered aircraft will produce 2.6 times more contrails than kerosene-powered aircraft.

The contrails that the aircraft produce also depend on weather conditions, such as temperature, pressure, and humidity.[23] The method to determine the probability of these factors creating a contrail is called the Schmidt-Appleman Criterion.[25] Contrails have the chance to become persistent, last a long time, grow, and expand into larger and more impactful contrail cirrus when aircraft fly through ice-supersaturated regions.[26] If aircraft do not fly through these regions, contrails can be eliminated for both kinds of aircraft. Short-lived and small contrails would have no climate impact.[27]

For example, research suggests that hydrogen-powered aircraft should cruise at an altitude of 2-3 km below modern kerosene-powered aircraft. This would help reduce the formation of contrails and cut climate impact.[24]

Furthermore, since contrails are clouds, this impacts how they impact the environment. Firstly, it means that they have a very limited lifespan. Even persistent contrails only last for a few hours.[26] This means that when contrails are produced, they only impact the atmosphere for a few hours, whereas carbon dioxide impacts the atmosphere until it is destroyed, meaning that over time, the contrails emitted by an aircraft are much less harmful than the carbon dioxide emitted by an aircraft. Next, it means that contrails can reflect energy away from Earth, meaning that during the day, contrails have much less of a warming effect than at night.[18] In fact, although only 25% of total flights occur at night, contrails at night account for 60-80% of the total radiative forcing of all contrails.[24]

Optical depth is how much light or radiation a medium scatters and absorbs. The optical depth of the contrail determines the magnitude of the radiative forcing of a contrail.[18] This means that thicker contrails will trap more heat. Therefore, the climate impact of the contrails that hydrogen-powered aircraft make is based on how thick their contrails are.

Finally, since clouds are made by ice and ice formation requires nucleation points, which soot helps to provide.[21] Only kerosene-powered aircraft produce soot. Hydrogen-powered aircraft, which don't burn hydrocarbons, do not produce soot. Therefore, the formation of contrails will be a little bit less intense with kerosene-powered aircraft compared to hydrogen-powered aircraft, suggesting that contrails produced by hydrogen-powered aircraft might reduce the radiative forcing of their contrails compared to the contrails of kerosene-powered aircraft by 30-50%.[18]

Taking all of this into consideration, it is difficult to generalize a consistent amount of impact that contrails have on the environment (Table 2). Even with one source suggesting that contrails produced by hydrogen-powered aircraft will have less climate impact than contrails produced by modern kerosene-powered aircraft, other sources predict the opposite, and there is still doubt in too many areas to determine whether hydrogen-powered aircraft produce bigger or smaller contrails. What can be said is that the amount of impact can be controlled. Depending on the size of the contrail, the contrail can have a very little impact to three times that of carbon dioxide for several hours. Although there is a lot of uncertainty in general concerning contrails, if the conditions that create the large, environmentally unfriendly contrails are known, aircraft can at least avoid these areas to produce fewer contrails altogether by predicting their formation.

If contrail formation is closely monitored and flights actively look to avoid them, contrails could have very little impact on the environment. Therefore, the environmental impact of hydrogen-powered aircraft emitting more contrails than kerosene-powered aircraft can be largely limited.

Hydrogen-powered aircraft emit much less carbon dioxide and $NO_x$ emissions, but produce more contrails. If the contrail formation of aircraft is limited, their impact will also be limited, and the total amount of emissions and climate impact of hydrogen-powered aircraft will be greatly reduced. Sources predict that hydrogen-powered aircraft might have the potential to reduce climate impact by approximately 71%.[11]

**Table 2:** The climate characteristics of the most prominent aviation-induced greenhouse gases.[5,14,16,18] Table 2 finds that kerosene-powered aircraft produce more $CO_2$ and $NO_x$ emissions than hydrogen-powered aircraft.

| Greenhouse gas | CO2 | NOx | Contrails |
|---|---|---|---|
| Relative climate impact | Medium | Low | Very high |
| Certainty | High | Medium | Very low |
| Fuel that produces more of the respective greenhouse gas | Kerosene | Kerosene | Unsure |

## Conclusion

The life cycle of hydrogen includes its production, storage, and combustion.

Although burning hydrogen does not release any carbon dioxide, the most popular and cost-effective hydrogen production methods release carbon dioxide, which limits hydrogen-powered aircraft to reduce climate impact with respect to kerosene-powered aircraft.

The most appropriate type of hydrogen fuel for long-haul flights would be liquid hydrogen because it is more energy-dense than compressed hydrogen. Liquid hydrogen needs to be stored at extremely low temperatures, needs more space, and is therefore much more difficult to store than kerosene. New technology will need to be developed to store liquid hydrogen onboard aircraft, which increases complexity, weight, fuel consumption, and reduces efficiency. Furthermore, more aerodynamic drag is added due to the additional required space to store hydrogen. This magnifies hydrogen's impact on the climate because more fuel gets burned.

Hydrogen is used as a fuel similarly to kerosene, and hydrogen-powered engines will adapt the same functions and concepts used by kerosene-powered aircraft. However, it burns differently. Because of the nature of hydrogen, there are multiple techniques that can be implemented to reduce the temperature of the combustion, which in turn lowers $NO_x$ emissions.

Finally, the total amount of emissions emitted by hydrogen-powered aircraft is much lower than that of kerosene-powered aircraft. The amount of contrails will not be controlled by the technology within the aircraft, but rather the routes that aircraft utilize.

To evaluate the efficiency of the aircraft increases the climate impact of hydrogen-powered aircraft, but not to the large extent that hydrogen-powered aircraft reduce overall greenhouse gas emissions. Overall, this paper concludes that although the effectiveness of hydrogen-powered aircraft will be weaker at first and their total impacts may vary widely, they would be able to reduce greenhouse gas emissions of the aviation industry by over 70%.

Further research would include exploring materials that would better suit hydrogen storage, hydrogen engine combustion and optimization, and developing methods to predict and mitigate contrail formation, all of which would enhance the performance and environmental benefits of hydrogen-powered aircraft.

## Acknowledgments

I would like to thank Indigo, Dr. Devin Carroll, and Kieran Tait for guiding and helping write this paper. I attest that the ideas, graphics, and writing in this paper are entirely my own.

## References

1. J. Blanke; T. Chiesa, Eds., *The travel & tourism competitiveness report 2013: reducing barriers to economic growth and job creation*, 2013, The World Economic Forum.
2. Aerospace Technology Institute (ATI), *Aviation Emissions: Modeling the Road to Net Zero 2050*, Jul. 2022, Aerospace Technology Institute.
3. D. S. Lee; D. W. Fahey; P. M. Forster; P. J. Newton *et al.*, *Aviation and global climate change in the 21st century*, July 2009, Atmos Environ (1994), vol. 43, no. 22, pp. 3520–3537, doi: 10.1016/j.atmosenv.2009.04.024.
4. R. Shoukat; R. Redondi, *GHG emissions evaluation of conventional, electric, hybrid, biofuel, and hydrogen aircraft*, June 2025, Journal of the Air Transport Research Society, vol. 4, p. 100067,doi: 10.1016/j.jatrs.2025.100067.
5. F. Li, *A Review of Hydrogen-powered Aircraft*, Dec. 2024, WSEAS TRANSACTIONS ON SYSTEMS, vol. 23, pp. 409–418, doi: 10.37394/23202.2024.23.43.
6. I. Dincer; C. Acar, *A review on potential use of hydrogen in aviation applications*, 2016, IJSA, vol. 2, no. 1, p. 74, doi: 10.1504/IJSA.2016.076077.
7. C. Koroneos, A. Dompros, G. Roumbas, and N. Moussiopoulos, *Life Cycle Assessment of Kerosene Used in Aviation* (8 pp), Nov. 2005, Int J Life Cycle Assessment, vol. 10, no. 6, pp. 417–424, doi: 10.1065/lca2004.12.191.
8. C. Koroneos, A. Dompros, G. Roumbas, and N. Moussiopoulos, *Advantages of the use of hydrogen fuel as compared to kerosene*, May 2005, Resources, Conservation and Recycling, vol. 44, no. 2, pp. 99–113, doi: 10.1016/j.resconrec.2004.09.004.
9. E. Meloni, M. Martino, V. Palma, *A Short Review on Ni-Based Catalysts and Related Engineering Issues for Methane Steam Reforming*, Mar. 2020, Catalysts, vol. 10, no. 3, p. 352, doi: 10.3390/catal10030352.
10. P. Nikolaidis; A. Poullikkas, *A comparative overview of hydrogen production processes, Jan. 2017, Renewable and Sustainable Energy Reviews*, vol. 67, pp. 597–611, doi: 10.1016/j.rser.2016.09.044.
11. E. J. Adler; J. R. R. A. Martins, *Hydrogen-powered aircraft: Fundamental concepts, key technologies, and environmental impacts*, Aug. 2023, Progress in Aerospace Sciences, vol. 141, p. 100922, doi: 10.1016/j.paerosci.2023.100922.
12. C. J. Butler, *Hydrogen storage for aerospace applications*, Nov. 2024.
13. J. Huete; P. Pilidis, *Parametric study on tank integration for hydrogen civil aviation propulsion*, Oct. 2021, International Journal of Hy-


DOI: 10.36838/IJHSR811.133

drogen Energy, vol. 46, no. 74, pp. 37049–37062, doi: 10.1016/j.ijhydene.2021.08.194.

14. A. J. Colozza; L. Kohout, *Hydrogen Storage for Aircraft Applications Overview*, Sep. 1, 2002, Contractor Report E-13540, NASA/CR-2002-211867, Glenn Research Center, Brook Park, OH.
15. J. Huete; D. Nalianda; P. Pilidis, *Impact of tank gravimetric efficiency on propulsion system integration for a first-generation hydrogen civil airliner*, Aug. 2022, Aeronaut. J., vol. 126, no. 1302, pp. 1324–1332, doi: 10.1017/aer.2022.60.
16. C. Mourouzidis; G. Singh; X. Sun; J. Huete *et al.*, *Abating $CO_2$ and non-CO2 emissions with hydrogen propulsion*, July 2024, Aeronaut. J., vol. 128, no. 1325, pp. 1576–1593, doi: 10.1017/aer.2024.20.
17. B. Shadidi; G. Najafi; Tall Yusaf, *A Review of Hydrogen as a Fuel in Internal Combustion Engines*, Jan. 2021, Energies, vol. 14, no. 19, p. 6209, doi: 10.3390/en14196209.
18. D. K. Singh; S. Sanyal; D. J. Wuebbles, *Understanding the role of contrails and contrail cirrus in climate change: a global perspective*, Aug. 2024, Atmospheric Chemistry and Physics, vol. 24, no. 16, pp. 9219–9262, doi: 10.5194/acp-24-9219-2024.
19. Z. Stępień, *A Comprehensive Overview of Hydrogen-Fueled Internal Combustion Engines: Achievements and Future Challenges*, Jan. 2021, Energies, vol. 14, no. 20, p. 6504, doi: 10.3390/en14206504.
20. T. Shudo; K. Omori; O Hiyama, *$NO_x$ reduction and $NO_2$ emission characteristics in rich-lean combustion of hydrogen*, Sept. 2008, International Journal of Hydrogen Energy, vol. 33, no. 17, pp. 4689–4693, doi: 10.1016/j.ijhydene.2008.05.034.
21. W. A. van Wijngaarden; W. Happer, *Relative Potency of Greenhouse Molecules*, Mar. 30, 2021, arXiv: arXiv:2103.16465. doi: 10.48550/arXiv.2103.16465.
22. G. P. Brasseur; J. Müller; C. Granier, *Atmospheric impact of $NO_x$ emissions by subsonic aircraft: A three-dimensional model study*, Jan. 1996, J. Geophys. Res., vol. 101, no. D1, pp. 1423–1428, doi: 10.1029/95JD02363.
23. D. I. Barton; C. A Hall; M. K. Oldfield, *Design of a Hydrogen Aircraft for Zero Persistent Contrails*, Aug. 2023, Aerospace, vol. 10, no. 8, p. 688, doi: 10.3390/aerospace10080688.
24. D. Scholz, *Design of Hydrogen Passenger Aircraft – How much 'Zero-Emission' is Possible?*, Nov. 19, 2020, presented at the Hamburg Aerospace Lecture Series (DGLR, RAeS, VDI, ZAL, HAW Hamburg), doi: 10.5281/zenodo. 6233322.
25. H. Appleman, *The Formation of Exhaust Condensation Trails by Jet Aircraft*, Jan. 1953, Bulletin of the American Meteorological Society, vol. 34, no. 1, pp. 14–20, doi: 10.1175/1520-0477-34.1.14.
26. D. S. Lee; M. R. Allen; N. Cumpsty; B. Owen *et al.*, *Uncertainties in mitigating aviation non-$CO_2$ emissions for climate and air quality using hydrocarbon fuels*, 2023, Environ. Sci.: Atmos., vol. 3, no. 12, pp. 1693–1740, doi: 10.1039/D3EA00091E.
27. B. Kärcher, *Formation and radiative forcing of contrail cirrus*, May 2018, Nat Commun, vol. 9, no. 1, p. 1824, doi: 10.1038/s41467-018-04068-0.

## ■ Author

Lok Kay Teo is a senior at Claremont High School. He enjoys cooking, playing with cats, and hanging out with friends. He has been interested in airplanes all his life and looks to attend college and graduate with a degree in aerospace engineering.