A Review of Hydrogen-powered Aircraft

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Abstract: - Hydrogen energy is one of the critical clean energy sources. The status of arts of hydrogen energy applications in the aviation industry is reviewed, including two solutions of hydrogen-powered aircraft (direct combustion in internal combustion engines and fuel cell power generation), hydrogen production (fossil fuels and electrolyzed water), hydrogen storage (gaseous, liquid, and solid), multiple fuels assessment (mass & volume, well-to-wheel emissions, and cost). Specifically, the combustion emissions using hydrogen as fuel, two layouts of hydrogen tanks (the top tank layout and the dual tank layout), and two fuel cell solutions, proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC), are introduced in details. Finally, the trends of hydrogen-powered aircraft are pointed out.

Key-Words: - Hydrogen, fuel cell, aviation, hydrogen production, hydrogen storage, well-to-wheel emissions, fuel costs.

Received: April 27, 2024. Revised: October 29, 2024. Accepted: December 3, 2024. Published: December 31, 2024.

1 Introduction

In 2019, the global aviation industry (commercial, private, and military) emitted approximately 920 million tons of carbon dioxide (CO_2) throughout the year, accounting for approximately 2.5% of the total human-induced CO_2 emissions (37 billion tons) and approximately 12% of the emissions from the transportation industry, [1], [2], [3]. Therefore, the aviation industry plays an important role in the global effort to achieve carbon neutrality goals, [4].

Multi-electric technology [1], [5], [6], hydrogen energy technology [7], and flight path optimization technology [8], among others, are important means for carbon reduction. This article will provide a detailed introduction to the current application of hydrogen energy in the aviation industry, including two schemes of hydrogen-powered aircraft (direct combustion by internal combustion engines and fuel cell power generation), hydrogen production, hydrogen storage, and performance comparison of multiple fuels.

There are two forms of hydrogen utilization in commercial flights: direct combustion of hydrogen (liquid or gaseous) by internal combustion engines, and fuel cell power generation [9], [10], Figure 1.

The former is more similar to current jet airliners, while the latter's fuel cells work as batteries to provide electricity for fully electric or hybrid electric propulsion systems, [11], [12]. When comparing these two solutions in terms of social, economic, environmental, and technological aspects, although fuel cell solutions rank higher, the difference between them is not significant, [9].

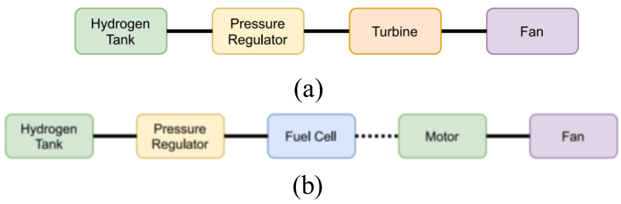


Fig. 1: Two schemes for hydrogen-powered aircraft [9], (a) Hydrogen fuel combustion power chain (b) Fuel cell power chain

The calorific value of hydrogen is 39.5 kWh/kg, which is four times that of aviation kerosene which has a calorific value of 11.7 kWh/kg, [13]. The volumetric energy density of cryogenic hydrogen is 2.80 kWh/L, slightly less than one-third of the 9.13 kWh/L of aviation kerosene, [3], [14], [15], [16]. Therefore, with the same fuel volume, the range of cryogenic hydrogen aircraft is less than one-third of that of aviation kerosene aircraft.

In order to maintain the same range and load capacity as traditional aviation kerosene solutions, both hydrogen power solutions require significant changes to the aircraft structure, especially the layout of hydrogen tanks, whether using compressed hydrogen or cryogenic hydrogen, [9].

2 Direct Combustion of Hydrogen as Aircraft Fuel

2.1 Combustion of Hydrogen

The combustion using hydrogen as fuel significantly reduces the emissions of pollutants compared to aviation kerosene. The combustion of hydrogen mainly releases water vapor, without CO_2, SOx, and smoke emissions, resulting in a reduction of over 70% in NO emissions. When using fuel cells for power generation, the emissions of pollutants are zero [9], [14].

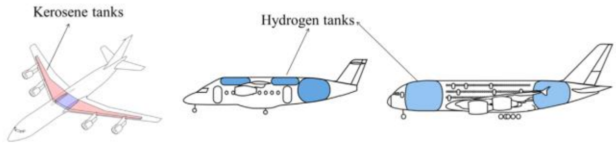
Although water vapor is a powerful greenhouse gas with a warming potential two to three times that of carbon dioxide, the interference of aircraft emissions of water vapor on the entire natural water cycle is limited because, at an altitude of 11 kilometers, the lifespan of water vapor is only about four to five months, while carbon dioxide can remain in the atmosphere for more than 100 years. Therefore, compared to other fuels, hydrogen has significant improvements in global warming potential, ozone depletion, environmental and social costs, and so on. However, if not handled properly, water vapor may form airplane contrails, blocking some of the heat radiating from the Earth's surface and exacerbating global warming. In addition, hydrogen and high concentrations of water vapor have adverse effects on many commonly used aircraft materials [9], especially metals such as hydrogen embrittlement and corrosion.

2.2 Layout of Hydrogen Tanks

Usually, using hydrogen as fuel requires modifying the design of aircraft and engines.

Cryogenic hydrogen must be kept at -253℃ when used in hydrogen-powered aircraft and can only be stored in highly insulated storage tanks. The volumetric energy density of cryogenic hydrogen is less than one-third of that of aviation kerosene. In order to maintain the same range, the volume of cryogenic hydrogen tanks is larger, the volume of the aircraft is also larger, and the fuselage is heavier. The wing space is limited and cannot guarantee the normal insulation of cryogenic hydrogen. Therefore, the cryogenic hydrogen tank cannot be located in the wing, and the fuselage is the optimal location for placing the cryogenic hydrogen tank, Figure 2.

For medium and short-range aircraft, cryogenic hydrogen tanks can be placed above the cabin. For long-range aircraft, cryogenic hydrogen is stored in two large storage tanks, one of them is located directly behind the cockpit, and the second is placed at the rear of the cabin, [14].



(a) (b) (c)

Fig. 2: Fuel tank layout of aircraft [14], (a) Traditional aircraft (b) Medium range hydrogen-powered aircraft (c) Long range hydrogen-powered aircraft

The layout of cryogenic hydrogen tanks has a significant impact on energy efficiency. For the top tank layout of medium and short-range aircraft, due to the larger weight of this type of storage tank, energy consumption increases by 6-19%. For the dual tank layout of long-range aircraft, there is a 12% increase in energy consumption, [14]. Therefore, hydrogen fuel is more suitable for long-range aircraft.

Due to the fact that the fuselage of a hydrogen-powered aircraft is used to store hydrogen tanks, its volume is larger and its weight is almost 6% larger than that of a regular aircraft. In addition, since the wings of hydrogen-powered aircraft are no longer used for fuel storage, the area and span of the wings can be designed to be smaller. However, when using hydrogen, the weight of the wings should increase to enhance their structural integrity, improve their bending resistance, and reduce aerodynamic vibrations. The smaller wings and larger fuselage of hydrogen-powered aircraft may have a negative impact on aerodynamic efficiency.

The combustion characteristics of hydrogen are different from aviation kerosene, and the engines of hydrogen-powered aircraft also need to change accordingly. The engine of a hydrogen-powered aircraft can be smaller.

When using hydrogen, changes in aircraft and engine design will result in a maximum 25% increase in production and maintenance costs, [14].

The EU Cryoplane project studied the impact of hydrogen tanks on aircraft energy consumption. The project showed that large hydrogen tanks can lead to an increase in aerodynamic resistance and structural weight of aircraft. Compared with traditional aircraft, hydrogen-powered aircraft will experience an increase in energy consumption of about 10%. The work at the University of Sydney in Australia shows that for small short-range hydrogen-powered aircraft, energy consumption is similar to that of the Cryoplane project (with a 5-18% increase). However, for long-range hydrogen-powered aircraft, unlike the Cryoplane project, the author believes that energy consumption will be reduced by 12%, [9].

3 Aviation Applications of Hydrogen Fuel Cells

A hydrogen fuel cell is an electrochemical device that generates electricity and water through the electrochemical reaction of hydrogen and oxygen. Fuel cells are silent, produce almost no vibration, and do not produce any NOx emissions. Among various types of fuel cell equipment, proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC) are the most commonly used in aviation [14], [17]. SOFC operates at high temperatures of 500-1000 ℃ and uses a dense ceramic layer as the electrolyte, while PEMFC operates at low temperatures of 80 ℃ and uses a proton conducting membrane as the electrolyte, [18].

At present, the maximum single-stack power of fuel cells in China is 300kW. Therefore, fuel cells are currently mainly used for small and medium-sized aviation loads.

An important application of fuel cells is APU (Auxiliary Power Unit), [14]. The emissions of APUs driven by traditional gas turbines account for about 20% of the total emissions of aircraft. Fuel cells can replace gas turbines to directly drive APUs, or combine with gas turbines to form hybrid APUs. Both SOFC and PEMFC can be used in APU systems. SOFC is more suitable for APU applications. SOFC operates at higher temperatures and supports hydrogen production from aviation kerosene reforming, with less strict requirements for fuel impurities. The disadvantage of SOFC-driven APU is that it is heavier than PEMFC or traditional APU because it requires auxiliary devices such as reformers, compressors, and pumps. If PEMFC drives APU, it is required that the aircraft must carry hydrogen gas.

Airbus and Boeing are currently conducting research projects with the goal of using fuel cells to generate electricity for all nonpropulsion systems on the aircraft. Boeing reported that the SOFC-powered APU can reduce aircraft fuel consumption by 75% when on the ground. The EU Cryoplane project estimates that SOFC-driven APUs can reduce 80% of nitrogen oxide emissions from aircraft on the ground, [14].

Another important application of fuel cells is ground equipment in airports, such as air starters, forklifts, luggage trailers, and air conditioning trucks. Fuel cell forklifts have been tested at Pearson Airport in Toronto and Munich Airport. The fuel cell luggage car has been used at Danish airports. Fuel cell passenger shuttle buses have also been used at Tokyo Airport in Japan and Hawaii Airport in the United States, [14].

4 Production of Hydrogen

Usually, hydrogen produced by electrolysis of water using renewable energy sources such as wind power and hydropower is called green hydrogen; The hydrogen produced by coal gasification is called brown hydrogen; The hydrogen produced from fossil fuels (such as natural gas) is called gray hydrogen; The hydrogen produced by methane and captured carbon dioxide is called blue hydrogen, [19], [20].

Currently, approximately 120 million tons of grey hydrogen are produced and consumed globally each year, mainly used in the refining industry and ammonia production. 96% of global hydrogen is produced from fossil fuels (natural gas 48%, oil 30%, coal 18%), and the remaining 4% comes from electrolyzed water, [19].

China is the world's largest producer of hydrogen, with a hydrogen production of approximately 25 million tons in 2019. Among them, green hydrogen accounts for 4%, coal-based hydrogen accounts for 62%, natural gas-based hydrogen accounts for 19%, and alcohol-based hydrogen accounts for 15%, as shown in Figure 3.

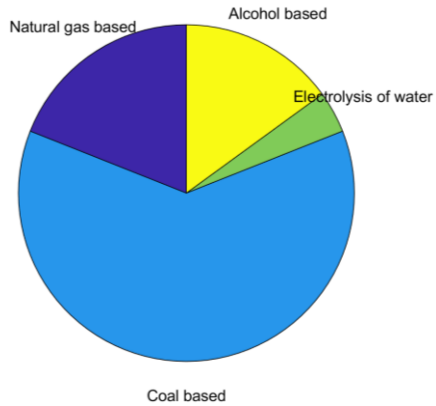


Fig. 3: Hydrogen productions in China

The cost of hydrogen production in China is shown in Table 1 (Appendix). Coal-based hydrogen production is the most economical at 0.869 Yuan·m^{-3}, followed by natural gas-based hydrogen production at 1.14 Yuan·m^{-3}, and methanol-based hydrogen production at 2.14 yuan·m^{-3}. The most expensive is hydrogen production through electrolysis of water, which costs 4.31 yuan·m^{-3}. With the rapid development of renewable energy such as wind power in China, it is expected that the cost of green hydrogen produced through wind power will be 0.875-1.81 yuan·m^{-3} by 2030, which can compete then with gray hydrogen.

Biomass hydrogen production is also a promising method to produce hydrogen, with common biomass including corn, corn stalk, sugarcane, edible oil, etc.

5 Storage of Hydrogen

At present, there are three main ways to store hydrogen: gaseous hydrogen storage, liquid hydrogen storage (cryogenic, organic liquid), [14], [21], [22], and solid hydrogen storage. High-pressure gaseous hydrogen storage technology is the most mature and commonly used hydrogen storage method, with a low cost. However, pressure-resistant containers are heavy and prone to leakage, and are mostly used in hydrogen fuel cell vehicles.

Cryogenic hydrogen technology has a high hydrogen storage density, complex low-temperature container structure, and a daily evaporation loss of 3% [14], which is expensive and commonly used in the aerospace industry. In the 1980s, Russian manufacturer Tupolev modified a commercial jet airliner Tu155, adding 18 cubic meters of cryogenic hydrogen tanks, [9].

Organic liquid hydrogen storage technology has a high hydrogen storage density and is easy to transport at room temperature, but the catalyst cost is high. The solid hydrogen storage method has low cost, but low hydrogen storage density, [21], [23]. The comparison of different hydrogen storage technologies is shown in Table 2 (Appendix), [21].

The prominent advantage of cryogenic hydrogen compared to gaseous hydrogen storage is its high density. The density of cryogenic hydrogen is 70.8 kg/m3, which is 3 and 1.8 times that of high-pressure hydrogen at 35 and 70 MPa, respectively, [14].

Table 3 (Appendix) presents the performance characteristics of common organic liquid hydrogen storage carriers [23], all of which have high hydrogen storage capacity and are expected to be applied in commercial flights. MCH (Methyl Cyclohexane) is liquid at room temperature, while decahydronaphthalene is a solid at room temperature. In terms of cost, MCH has the lowest price, naphthalene has the highest price, and carbazole and aromatic hydrocarbons have lower prices.

The organic liquid used for hydrogen storage is called "hydrogen oil", [23]. Hydrogen oil can be inherited perfectly from China's well-established petroleum storage and transportation system, such as achieving long-distance pipeline transportation like oil, and gas stations can easily be transformed into hydrogen refueling stations, thereby reducing the storage and transportation costs of hydrogen energy utilization on a large scale. There are already over 7km of methanol and dimethyl ether transmission pipelines both domestically and internationally, some of which are newly built, while others have been retrofitted from crude oil pipelines, [23].

6 Performance Comparison of Different Fuels

Common aviation fuels are mainly divided into three categories: fossil fuels, biofuels, and electric fuels. Hydrogen gas is generated through electrolysis of water, and then stores the hydrogen energy in the form of chemical bonds in liquid fuel, and this liquid fuel is called electric fuel. Compared to cryogenic hydrogen or compressed hydrogen, electric fuel has a higher bulk density and lighter weight, [3], [15]. Electric fuel is also known as synthetic fuel, power fuel, or power-to-liquid fuel, [3].

6.1 Mass and Volume of Fuels

According to Table 4 (Appendix) [24], for an 11000 km long-range aircraft, aviation kerosene accounts for 20% of the maximum takeoff weight and has a volume of 141 m^3. The mass-energy density and volume energy density of HVO (hydrogenated vegetable oil), FT (Fisher-Tropsch) synthetic oil, and methane to gasoline are similar to aviation kerosene, therefore the fuel quality and volume are similar to aviation kerosene. The volume of methanol is 2.3 times that of aviation kerosene, the mass is 2.2 times that of aviation kerosene, and the fuel mass accounts for 43.8% of the maximum takeoff volume. The volume of cryogenic hydrogen is 4.0 times that of aviation kerosene, and the fuel mass accounts for 71.3% of the maximum takeoff weight. The volume of 70MPa compressed hydrogen is 7.1 times that of aviation kerosene, and the fuel mass accounts for 119% of the maximum takeoff weight. The volume of lithium batteries is 5.3 times that of aviation kerosene, and the fuel mass accounts for 377% of the maximum takeoff weight.

For 1000 km medium and short-range aircraft, aviation kerosene accounts for 9.1% of the maximum takeoff weight and has a volume of 9 m^3. The maximum takeoff ratio of HVO, FT synthetic oil, and methane to gasoline is similar to that of aviation kerosene. Methanol accounts for 19.8% of the maximum takeoff volume. Cryogenic hydrogen accounts for 32.4% of the maximum takeoff weight. 70MPa compressed hydrogen accounts for 53.9% of the maximum takeoff weight. Lithium batteries account for 171% of the maximum takeoff weight.

It can be seen that when ambient temperature liquid fuels (aviation kerosene, biofuels, methanol, etc.) are used in aircraft, the fuel volume is relatively small and the fuel mass is relatively small, especially prominent in long flight distances.

6.2 Emissions of Fuels

The full lifecycle emissions of fuels include production emissions and usage emissions. The emission of aviation kerosene is 87.4 gCO2e/MJ, and compared to aviation kerosene, compressed natural gas can reduce emissions by 22%, as shown in Table 5 (Appendix), [24]. Biofuels and biofuels have no usage emissions, mainly production emissions. The minimum production emissions of biofuels are in double digits, ranging from 12-36 gCO2e/MJ. The minimum production emissions for electric fuel are in the single digits, with 2-3 (2.59) gCO2e/MJ for wind power fuel and 6-9 (6.67) gCO2e/MJ for solar power fuel.

Compared to traditional aviation kerosene, using corn stalk as the raw material, the greenhouse gas emission reduction of renewable aviation kerosene after hydrolysis treatment is 41% to 63%, after pyrolysis treatment is 68% to 76%, and after FT synthesis is 89%, [9].

6.3 Cost of Fuels

According to Table 6 (Appendix) [24], the cost of aviation kerosene is 45 euros/MWh. The cost of biofuels is 75-365 euros/MWh, which is 1.7-8.1 times that of aviation kerosene, and the cost of electric fuel is 155-605 euros/MWh, which is 3.4-14 times that of aviation kerosene.

The current price of fossil aviation fuel is 600 euros/ton, and the price of bio aviation fuel produced from cooked edible oil is between 950 euros/ton and 1015 euros/ton, [9].

7 Conclusions

Compared with aviation kerosene, the lower volume energy density of hydrogen and the insulation requirements of cryogenic hydrogen make the layout of hydrogen tanks different from traditional fuel tank layouts, which can affect the aircraft's volume, engine, etc. The top tank layout is suggested for medium and short-range aircraft, while the dual tank layout is for long-range aircraft, due to the larger weight of the storage tank, energy consumption increases by 6-19% compared with traditional kerosene aircraft.

Among various types of fuel cell equipment, PEMFC and SOFC are the most commonly used in aviation. At present, the power level of fuel cell technology is 300kW, mainly used for APU, ground auxiliary equipment, etc. Both SOFC and PEMFC can be used in APU systems. SOFC is more suitable for APU applications. SOFC operates at higher temperatures and supports hydrogen production from aviation kerosene reforming, with less strict requirements for fuel impurities. The disadvantage of SOFC-driven APU is that it is heavier than PEMFC because it requires auxiliary devices such as reformers, compressors, and pumps.

96% of hydrogen production comes from fossil fuels, and green electrolysis of water for hydrogen production needs further development.

Methanol-based organic liquid hydrogen storage technology has good commercial prospects compared with gaseous hydrogen storage, cryogenic hydrogen storage, and solid hydrogen storage.

From the perspective of volumetric mass, emissions, and economy, biofuels are the mid-term solution for commercial aviation carbon dioxide reduction [25], while hydrogen fuel (electric fuel) is the long-term solution for commercial aviation carbon dioxide reduction.

References:

[1] M. C. Cameretti, A. Del Pizzo, L. P. Di Noia, M. Ferrara, and C. Pascarella, "Modeling and Investigation of a Turboprop Hybrid Electric Propulsion System," *Aerospace,* vol. 5, no. 4, 2018, doi: doi.org/10.3390/aerospace5040123.

[2] W. Liao, Y. Fan, C. Wang, and Z. Wang, "Emissions from intercity aviation: An international comparison," *Transportation Research Part D: Transport and Environment,* vol. 95, p. 102818, 2021, https://doi.org/10.1016/j.trd.2021.102818.

[3] P. Su-ungkavatin, L. Tiruta-Barna, and L. Hamelin, "Biofuels, electrofuels, electric or hydrogen?: A review of current and emerging sustainable aviation systems," *Progress in Energy and Combustion Science,* vol. 96, p. 42, 2023, Art. no. 101073, doi: doi.org/10.1016/j.pecs.2023.101073.

[4] O. Balli, A. Dalkıran, and T. H. Karakoç, "Energetic, exergetic, exergoeconomic,

environmental (4E) and sustainability performances of an unmanned aerial vehicle micro turbojet engine," *Aircraft Engineering and Aerospace Technology,* vol. 93, no. 7, pp. 1254-1275, 2021, doi: doi.org/10.1108/AEAT-03-2021-0088.

[5] S. Sahoo, X. Zhao, and K. Kyprianidis, "A Review of Concepts, Benefits, and Challenges for Future Electrical Propulsion-Based Aircraft," *Aerospace,* vol. 7, no. 4, 2020, doi: doi.org/10.3390/aerospace7040044.

[6] O. Zaporozhets, V. Isaienko, and K. Synylo, "Trends on current and forecasted aircraft hybrid electric architectures and their impact on environment," *Energy,* vol. 211, p. 118814, 2020, https://doi.org/10.1016/j.energy.2020.118814.

[7] R. Qiu, S. Hou, and Z. Meng, "Low carbon air transport development trends and policy implications based on a scientometrics-based data analysis system," *Transport Policy,* vol. 107, pp. 1-10, 2021, https://doi.org/10.1016/j.tranpol.2021.04.013.

[8] M. Pawlak, "Effect of Energy Consumption Reduction on the Decrease of CO2 Emissions during the Aircraft's Flight," *Energies,* vol. 14, no. 9, 2021, doi: doi.org/10.3390/en14092638.

[9] F. Afonso, M. Sohst, C. M. A. Diogo, S. S. Rodrigues, A. Ferreira, I. Ribeiro, R. Marques, F. F. C. Rego, A. Sohouli, J. Portugal-Pereira, H. Policarpo, B. Soares, B. Ferreira, E. C. Fernandes, F. Lau, and A. Suleman, "Strategies towards a more sustainable aviation: A systematic review," *Progress in Aerospace Sciences,* vol. 137, p. 55, 2023, Art. no. 100878, doi: doi.org/10.1016/j.paerosci.2022.100878.

[10] A. Y. Arabul, E. Kurt, F. Keskin Arabul, İ. Senol, M. Schrötter, R. Bréda, and D. Megyesi, "Perspectives and Development of Electrical Systems in More Electric Aircraft," *International Journal of Aerospace Engineering,* vol. 2021, p. 5519842, 2021, doi: doi.org/10.1155/2021/5519842.

[11] A. Prapotnik Brdnik, R. Kamnik, M. Marksel, and S. Božičnik, "Market and Technological Perspectives for the New Generation of Regional Passenger Aircraft," *Energies,* vol. 12, no. 10, 2019, doi: doi.org/10.3390/en12101864.

[12] J. Ribeiro, F. Afonso, I. Ribeiro, B. Ferreira, H. Policarpo, P. Peças, and F. Lau, "Environmental assessment of hybrid-electric propulsion in conceptual aircraft design," *Journal of Cleaner Production,* vol. 247, p. 119477, 2020, https://doi.org/10.1016/j.jclepro.2019.119477.

[13] J. Rohacs and D. Rohacs, "Energy coefficients for comparison of aircraft supported by different propulsion systems," *Energy,* vol. 191, p. 116391, 2020, https://doi.org/10.1016/j.energy.2019.116391.

[14] A. Baroutaji, T. Wilberforce, M. Ramadan, and A. G. Olabi, "Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors," *Renewable & Sustainable Energy Reviews,* vol. 106, pp. 31-40, 2019, doi: doi.org/10.1016/j.rser.2019.02.022.

[15] A. G. Olabi, C. Onumaegbu, T. Wilberforce, M. Ramadan, M. A. Abdelkareem, and A. H. Al-Alami, "Critical review of energy storage systems," *Energy,* vol. 214, p. 22, 2021, Art. no. 118987, doi: doi.org/10.1016/j.energy.2020.118987.

[16] C. Goldberg, D. Nalianda, V. Sethi, P. Pilidis, R. Singh, and K. Kyprianidis, "Assessment of an energy-efficient aircraft concept from a techno-economic perspective," *Applied Energy,* vol. 221, pp. 229-238, 2018, https://doi.org/10.1016/j.apenergy.2018.03.163.

[17] E. Özbek, G. Yalin, S. Ekici, and T. H. Karakoc, "Evaluation of design methodology, limitations, and iterations of a hydrogen fuelled hybrid fuel cell mini UAV," *Energy,* vol. 213, p. 118757, 2020, https://doi.org/10.1016/j.energy.2020.118757.

[18] M. C. Massaro, R. Biga, A. Kolisnichenko, P. Marocco, A. H. A. Monteverde, and M. Santarelli, "Potential and technical challenges of on-board hydrogen storage technologies coupled with fuel cell systems for aircraft electrification," *Journal of Power Sources,* vol. 555, p. 14, 2023, Art. no. 232397, doi: doi.org/10.1016/j.jpowsour.2022.232397.

[19] T. Capurso, M. Stefanizzi, M. Torresi, and S. M. Camporeale, "Perspective of the role of hydrogen in the 21st century energy transition," *Energy Conversion and*

Management, vol. 251, p. 17, 2022, Art. no. 114898, doi: doi.org/10.1016/j.enconman.2021.114898.

[20] T. Yusaf, L. Fernandes, A. Abu Talib, Y. S. M. Altarazi, W. Alrefae, K. Kadirgama, D. Ramasamy, A. Jayasuriya, G. Brown, R. Mamat, H. Al Dhahad, F. Benedict, and M. Laimon, "Sustainable Aviation-Hydrogen Is the Future," *Sustainability,* vol. 14, no. 1, p. 17, 2022, Art. no. 548, doi: doi.org/10.3390/su14010548.

[21] P. Yu, J. Wang, J. Zheng, L. Zhang, and H. Wang, "Review on hydrogen energy utilization and development," *Automotive Applied Technology,* no. 24, pp. 22-25, 2019, doi: doi.org/10.16638/j.cnki.1671-7988.2019.24.008.

[22] B. C. Tashie-Lewis and S. G. Nnabuife, "Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy - A Technology Review," *Chemical Engineering Journal Advances,* vol. 8, p. 100172, 2021, https://doi.org/10.1016/j.ceja.2021.100172.

[23] H. Zhang, L. Tian, Y. Sun, W. Yang, S. Peng, C. Liu, L. Ai, and Y. Li, "Progress of research on hydrogen storage in organic liquid and thinking about pipeline transportation," *Oil & Gas Storage and Transportation,* vol. 42, no. 04, pp. 375-390, 2023.

[24] N. Gray, S. McDonagh, R. O'Shea, B. Smyth, and J. D. Murphy, "Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors," *Advances in Applied Energy,* vol. 1, p. 100008, 2021, https://doi.org/10.1016/j.adapen.2021.100008.

[25] S. E. Puliafito, "Civil aviation emissions in Argentina," *Science of The Total Environment,* vol. 869, p. 161675, 2023, https://doi.org/10.1016/j.scitotenv.2023.161675.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Fenge Li wrote this paper.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare.

APPENDIX

Table 1. Hydrogen production costs in China

Hydrogen production method	Unit hydrogen production cost/(yuan·m^{-3})
Coal-based hydrogen production	0.869
Natural gas hydrogen production	1.14
Methanol cracking for hydrogen production	2.14
Electrolysis of water	4.31
Electrolysis of water (wind power)	0.875-1.81(predicted at 2030)

Table 2. Comparison of different hydrogen storage methods, [21]

Hydrogen storage methods	Technology	Operation principles	Hydrogen storage materials	Unit mass hydrogen storage density	Advantages	Disadvantages
Gaseous hydrogen storage	High-pressure gaseous hydrogen storage	Compressing hydrogen under high-pressure conditions	High-pressure resistant materials	1.0%-5.7%	Low cost; low energy consumption; fast hydrogen charging & discharging speed; simple container structure	Small reserves; limited pressure for the storage tank material; dangerous transportation
Liquid hydrogen storage	Organic liquid hydrogen storage	Reversible reaction between hydrocarbon agents and hydrogen gas	Cyclohexane; Decahydro -naphthalene, etc	5.0%-7.2%	High hydrogen storage density and efficiency; high storage and transportation safety	High reaction temperature; low dehydrogenation efficiency; high catalyst cost & susceptibility to poisoning by intermediate products
	Cryogenic hydrogen storage	Cool hydrogen gas to -253℃ for liquefaction	Special materials that can withstand ultra-low temperatures	4.7%-10%	High hydrogen storage density; large hydrogen storage capacity	High liquefaction cost; high liquefaction energy consumption; evaporation loss; dangerous transportation
Solid hydrogen storage	Physical adsorption hydrogen storage	Hydrogen and its storage materials undergo physical or chemical changes to transform into solid or hydrides	Metal-organic framework; nanostructured carbon materials	1.0%-4.5%	High hydrogen storage density; Suitable hydrogen charging & discharging speed; good reversibility; high safety; low cost and good cycle life of hydrogen storage materials	Low mass hydrogen storage rate; high hydrogen charging and discharging temperatures for lightweight hydrogen storage materials; poor cycling performance
	Chemical hydride hydrogen storage		Metal hydrides; Complex hydrides; Organic hydrides			

Table 3. Common organic liquid hydrogen storage carriers and their properties, [23]

Organic liquid material	Melting point / ℃	Boiling point / ℃	Mass hydrogen storage rate	Hydrogen storage capacity /kg·m-3	Dehydrogenation temperature /℃
cyclohexane	6.5	80.74	7.2%	55.9	300~320
MCH	-127	100.90	6.2%	47.4	300~350
12H-NEC	-84.5	-	5.8%	-	- 170~200
Decahydro naphthalene	-30.4	185.50	7.3%	65.4	320~340
Formic acid	8.4	100.80	4.4%	53.0	-
methanol	-97.8	64.80	12.5%	-	-

Table 4. Fuel mass and volume comparison of medium/short/long range flight, [24]

Fuel type	Fuel subtype	1000km medium/short range flight			11000km long-range flight		
		Fuel mass(T)	Fuel volume(m^3)	Percent of MTOM	Fuel mass(T)	Fuel volume(m^3)	Percent of MTOM
Fossil fuel	aviation kerosene	7.20	9.01	9.1%	112	141	20.1%
Biofuel	methanol	15.7	20.8	19.8%	245	325	43.8%
	HVO	7.49	9.58	9.5%	117	150	20.9%
	FT fuel	7.22	9.17	9.1%	113	143	20.1%
	Methane to gasoline	6.82	9.25	8.6%	106	144	19.0%
Electric fuel	compressed H_2 70MPa	42.6	63.9	53.9%	666	998	119%
	Cryogenic H2	25.6	35.9	32.4%	399	561	71.3%
batteries	Lithium-ion batteries	135	48.1	171%	2111	751	377%

Note: The mass calculation of compressed hydrogen and Cryogenic hydrogen includes the mass of hydrogen storage equipment.

Table 5. full lifecycle emissions of fuels, [24]

Fuel type	Fuel subtype	Well to tank gCO_2e/MJ	Tank to wheel gCO_2e/MJ	Well to wheel gCO_2e/MJ
Fossil fuels	Jet fuel	15.0	72.4	87.4
	Diesel	17.4	72.1	89.5
	HFO	15.0	79.1	94.1
	CNG	10.9	56.7	67.6
	LNG	19.6	56.9	76.5
Biofuels	Biomethane	12.8-17.2	0	12.8-17.2
	Methanol	36-46	0	36-46
	HVO	30.1-698	0	30.1-698
	FT diesel	17-109	0	17-109
Electrofuels（Wind electricity）	Hydrogen	2.59-20.74	0	2.59-20.74
	methane	3.37-26.94	0	3.37-26.94
	methanol	3.28-26.25	0	3.28-26.25
	FT diesel	3.55-28.41	0	3.55-28.41
	Methanol-to-gasoline	3.81-30.5	0	3.81-30.5
Electrofuels（Solar PV electricity）	Hydrogen	6.67-66.67	0	6.67-66.67
	methane	8.66-86.58	0	8.66-86.58
	methanol	8.44-84.39	0	8.44-84.39
	FT diesel	9.13-91.32	0	9.13-91.32

	Methanol-to-gasoline	9.80-98.04	0	9.80-98.04

Table 6 Fuel cost, [24]

Fuel type	**Fuel subtype**	**Fuel cost (€/MWh)**	**Average fuel cost (€/MWh)**
Fossil fuels	Jet fuel	45	45
	Diesel	109	109
	HFO	36	36
	Natural gas	38.2	38.2
Biofuels	Biomethane	60-90	75
	Methanol	75-144	110
	HVO	140-195	168
	FT diesel	100-630	365
Electrofuels	Hydrogen	110-200	155
	Methane	120-650	385
	Methanol	120-680	400
	FT diesel	130-770	450
	Methanol-to-gasoline	160-1050	605