Climate-Tech to Watch: Hydrogen-Powered Aviation

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Policymakers and the aviation industry see hydrogen as a promising low-carbon fuel for aviation. But to make hydrogen-powered flight a reality, they first need to bring down the cost of green hydrogen and overcome aircraft design challenges.

KEY TAKEAWAYS

- Commercial aviation accounted for roughly 2.5 percent of global carbon dioxide (CO_2) emissions in 2018, and that share is expected to grow. And according to the Energy Information Administration, the aviation sector is not on track to reach the goal of net-zero emissions by 2050.
- Leaders in the aviation industry see hydrogen as a potential solution to addressing the climate impacts of short- to medium-haul flights. But it currently costs two to four times more per megawatt hour (MWh) than conventional jet fuel.
- For hydrogen to be viable, costs will have to come down, aircraft manufacturers will need to make significant modifications to planes and engine designs, and operators will require new fuel-distribution infrastructure.
- Several companies, including Airbus, are working on demonstrator aircraft; however, it is unclear when these prototypes will be commercially available.
- Lawmakers have provided tax credits and research, development, and demonstration (RD&D) support to lower hydrogen prices. But further RD&D support is needed to bring hydrogen-powered aircraft to market, understand the climate impacts, and make low-cost, clean hydrogen widely available.

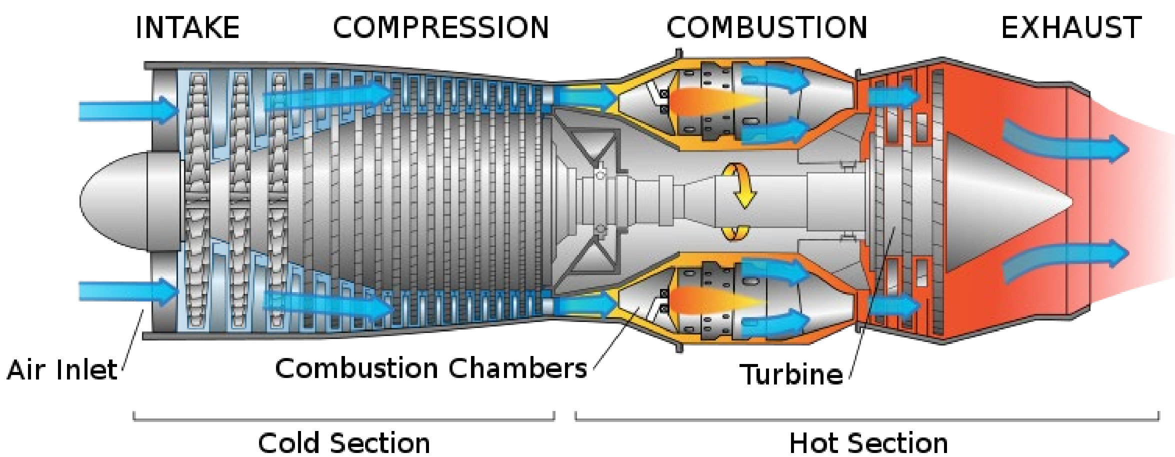
WHAT IS IT?

Hydrogen can be used in a fuel cell as a power source in aircraft by combustion in a modified jet engine. It can also be used to create synthetic fuels, which are discussed separately in this series.[1] The high energy density of hydrogen—roughly 2.5 times higher than that of jet fuel—and potential for zero CO_2 emissions make it an attractive alternative to conventional jet fuel. However, to make hydrogen a viable fuel to decarbonize aviation, the industry will require radical new aircraft designs and a scaled-up supply of low-carbon hydrogen.[2]

HOW DOES HYDROGEN PROPULSION WORK?

In a gas turbine engine, ambient air is drawn into the engine, where a compressor raises the pressure and feeds the air into the combustion chamber. Fuel is then injected into the combustion chamber, mixed with the high-pressure air, and burned. The resulting hot high-pressure air is what generates thrust.[3] Unlike rocket engines, which carry their own oxygen, jet engines pull oxygen from the surrounding air. With certain modifications, jet fuel-burning gas turbine engines can combust hydrogen in place of conventional jet fuel. Hydrogen emits no CO_2 emission during combustion, but overall emission will depend on how the hydrogen is produced—and nitrogen oxide (NO_x) emissions are still a concern.[4]

Figure 1: Diagram of a typical gas turbine jet engine[5]



Hydrogen can also be used to generate electric power in a fuel cell—a device that converts the chemical energy in hydrogen to electrical energy and heat through a series of reactions involving oxygen, with a byproduct being water. Fuel cells can be used independently for propulsion in propeller aircraft (e.g., turboprops). However, given the power density limitations of fuel cells, long-distance flights with heavy payloads are unlikely to ever be powered entirely by fuel cells.[6] To increase range and payload size, fuel cells can also be used in a hybrid-electric propulsion system with a hydrogen-burning gas turbine engine.[7] In a hybrid system, the fuel cell acts as the main power source during cruise flight and the gas turbine is designed to deliver the major thrust for takeoff and climb. Environmental benefits of a hybrid system include improved fuel efficiency and reduced NO_x emissions and contrail formation.[8]

ROLE IN THE ENERGY TRANSITION

In 2018, commercial aviation accounted for roughly 2.5 percent of global CO_2 emissions and as much as 3.5 percent of warming when non-CO_2 impacts on climate were included.[9] The share of global greenhouse gas (GHG) emissions from the commercial aviation sector is growing. According to the International Energy Agency (IEA), the industry is not on track to meet decarbonization goals.[10] Achieving the level of decarbonization that will be necessary to avert the worst effects of climate change will require a variety of new technologies, many of which are not yet commercially available.

Hydrogen is considered a promising alternative to traditional jet fuel mainly due to its high specific energy. Hydrogen-powered aircraft could have fewer range limitations compared with electric aircraft and can be suitable for anything from smaller commuter flights to medium-haul aircraft.[11] A recent analysis by the International Council for Clean Transportation (ICCT) finds that hydrogen-powered aircraft models expected to enter service in 2035 could serve as much as one-third of passenger aviation traffic.[12] Table 1 illustrates where the main low- and zero-carbon technologies for aviation could be deployed in the commercial aviation sector.

Table 1: Where low- and zero-carbon technologies could be deployed in commercial aviation[13]

	2020	2025	2030	2035	2040	2045	2050
Commuter 9–19 seats < 60-minute flights < 1% of industry CO_2	SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF
Regional 50–100 seats 30–90-minute flights ~3% of industry CO_2	SAF	SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF	Electric or hydrogen fuel cell and/or SAF
Short-haul 100–150 seats 45–120-minute flights ~24% of industry CO_2	SAF	SAF	SAF	SAF possibly some hydrogen	Hydrogen and/or SAF	Hydrogen and/or SAF	Hydrogen and/or SAF
Medium-haul 100–250 seats 60–150-minute flights ~43% of industry CO_2	SAF	SAF	SAF	SAF	SAF possibly some hydrogen	SAF possibly some hydrogen	SAF possibly some hydrogen
Long-haul 250+ seats > 150-minute flights ~30% of industry CO_2	SAF	SAF	SAF	SAF	SAF	SAF	SAF

Sustainable aviation fuel (SAF) is expected to be the largest driver of decarbonization for the aviation industry until the mid-2030s, since it is already commercially available and entry into service for hydrogen aircraft is not anticipated until around 2035 at the earliest.[14] Still, uncertainty remains around whether SAF can be produced sustainably at a large enough scale to meet 100 percent of global jet fuel demand. Power to Liquid (PtL) SAF, an alternative method for producing jet fuel from hydrogen, has fewer feedstock limitations; however, producing SAF using the PtL pathway is costly and inefficient, requiring CO_2 to be captured twice.[15] According to the Aerospace Technology Institute (ATI), liquid hydrogen is projected to become greener and less expensive than PtL SAF by mid-2030.[16] Alternative propulsion technologies such as hydrogen potentially offer a way to reduce jet fuel demand for shorter flights so that SAF can be used for the hardest-to-decarbonize trips.

TECHNICAL CHALLENGES

The global aviation industry will need to overcome significant technical challenges in order to make hydrogen propulsion a viable alternative to traditional jet fuel. One of the greatest hurdles is fuel storage onboard aircraft. A much larger volume of liquid hydrogen is required to provide the same amount of energy as traditional jet fuel, and it needs to be contained at very high pressures and low temperatures to maintain a liquid state. Most commercial aircraft store fuel in the wings; however, the large fuel tank size required to store liquid hydrogen means the fuel tank must be located in the main body of the aircraft—or fuselage—instead.[17] This creates a trade-off between fuel storage and passenger capacity.

Another major challenge is assessing the non-CO_2-related climate impacts of hydrogen combustion. At cruising altitudes, water vapor interacts with soot and particles in the atmosphere to form trails of condensation, contrails. These contrails have a short-lived effect on atmospheric temperatures—with a lifetime ranging from a few days to a year. While hydrogen combustion emits no CO_2, it does emit NO_x and nearly three times more water vapor than does fossil-based jet fuel.[18] Initial simulations suggest that hydrogen combustion reduces contrail formation, but more research—particularly airborne research—is needed to fully understand the climate impacts of hydrogen combustion.[19]

GLOBAL PROGRESS

Hydrogen aircraft have been flown in the past, but wide-scale use has been hindered by technical constraints. However, recently adopted targets for decarbonizing the industry have spurred renewed interest from governments and industry.[20] The technology is still in its very early stages—IEA has given it a technology readiness level (TRL) of 3–4, or early prototype stage—and hydrogen aircraft will not be commercially available until at least 2035.[21]

Several companies are working to retrofit existing turboprop aircraft with a fuel cell powertrain. HEAVEN, a project in Spain, has received funding from the EU to build an onboard liquid hydrogen storage system and integrate it into an experimental aircraft. The hydrogen storage system has been completed and test flights were anticipated to begin in 2022.[22] The German Aerospace Center is leading a similar project, in partnership with Deutsche Aircraft, that will integrate a fuel cell system into a Dornier 328 turboprop aircraft. The demonstration plane is scheduled for initial takeoff in 2025.[23] A Dutch consortium has also received funding from the

Dutch government to retrofit a 40–80 passenger propellor plane with a hydrogen fuel cell power train. The consortium expects to be able to carry passengers from Holland to London by 2028.[24]

Figure 2: Dornier 328 turboprop aircraft[25]

One of the largest industry players in this effort is Airbus, which along with Boeing has a market share of 90 percent of the aircraft market. As part of its ZEROe program, Airbus is working to develop three concepts for hybrid hydrogen-powered aircraft, which it intends to bring to market by 2035. The largest of the three designs, a narrow-bodied turbofan aircraft, could carry 165 passengers up to 3,400 km.[26] As part of the program, Airbus is also researching the impact of hydrogen combustion on contrail formation.[27] New aircraft designs typically require significant investment from manufacturers and represent a major risk, so Airbus's confidence in hydrogen propulsion is a promising sign for the future of the technology.[28]

PROGRESS IN THE UNITED STATES

The U.S. Department of Energy roadmap for decarbonizing aviation does not see hydrogen as playing a significant role before 2050, and federal support has been limited; however, some progress has still been made in the United States. In 2008, Boeing flew the world's first crewed hydrogen fuel cell-powered flight, proving that the technology is possible.[29] Boeing has since received funding from the Defense Advanced Research Projects Agency (DARPA) to develop a cryogenic fuel tank for hydrogen storage that would help address some of the storage-related challenges.[30]

Several other U.S. companies have also been working to make hydrogen-powered aviation a reality. In 2021, Pratt & Whitney was awarded $3.8 million from Advanced Research Projects Agency–Energy (ARPA-e) to develop hydrogen propulsion technology.[31] And Los Angeles-based start-up Universal Hydrogen is working on a design for hydrogen fuel capsules that can be easily transported and loaded directly into an aircraft. Universal Hydrogen is building a manufacturing hub in New Mexico that will be operational by 2024 and has agreements with 11 air carriers to retrofit regional aircraft to fly on hydrogen.[32] Another major contender is ZeroAvia, a Washington-based start-up that has raised $74 million to develop the first small, short-range hydrogen aircraft.[33] In January 2023, ZeroAvia completed a test flight of a 19-seat Dornier 228 turboprop aircraft partially powered by a hydrogen fuel cell powertrain. Even though the technology is a long way from being commercially available, ZeroAvia already has 1,500 engines on preorder.[34]

KEY POLICY ISSUES

The development of new aircraft designs has historically been driven by large investments from aircraft manufacturers (mainly Boeing and Airbus), and often comes with high risk. Public RD&D support will be needed to accelerate the market readiness of hydrogen-powered aircraft, understand the climate impacts of hydrogen combustion, and make low-cost, low-carbon hydrogen widely available. The Infrastructure, Investment, and Jobs Act of 2021 authorizes and appropriates $9.5 billion for clean hydrogen. On top of that, the Inflation Reduction Act offers a production tax credit for clean hydrogen.[35]

Hydrogen is more expensive than jet fuel and the larger fuel tanks required to store liquid hydrogen onboard aircraft will reduce capacity, and thereby revenue, as a result. Tax credits and research and development (R&D) support will go a long way toward reducing the costs of hydrogen; however, even with a significant reduction in the cost of hydrogen, the use of hydrogen for combustion in aircraft or in fuel cells will still cause a substantial increase in airline expenses.

Currently, the Levelized Cost of Hydrogen (LCOH) is between two and four times more per MWh compared with the average market price for conventional jet fuel over the past 20 years.[36] A white paper by ICCT estimates that using green hydrogen to fuel aircraft would cost more than using conventional jet fuel but less than using synthetic e-kerosene, which can also be produced from hydrogen. ICCT has argued that carbon pricing will be needed to close the gap with fossil jet fuel.[37]

Furthermore, aviation is a global industry and global action will be needed to achieve net zero. Some progress has been made in this direction. The International Civil Aviation Organization (ICAO), a United Nations agency, recently adopted a long-term aspirational goal for international aviation of net zero by 2050; however, the target is nonbinding and does not set any specific national targets. U.S. leadership could accelerate the commercial availability of hydrogen aircraft, but ultimately more international cooperation will be needed to ensure that other countries adopt clean aviation technologies.

LOOKING FORWARD

SAF is projected to play the largest role in reducing the climate impact of aviation in the near term, but there are still substantial uncertainties about whether SAF can be produced sustainably at a large enough scale.[38] Other decarbonization pathways such as hydrogen need to be explored to put the aviation industry on track to reach net zero. Making hydrogen aircraft commercially available will require significant public sector funding for RD&D along with complementary policies and international cooperation.

Acknowledgments

The author would like to thank David Hart and Ed Rightor for their help on this report.

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ENDNOTES

1. "Hydrogen: An important pathway to our decarbonisation ambition," Airbus, accessed September 28, 2022, https://www.airbus.com/en/innovation/zero-emission/hydrogen; Hannah Boyles, "Climate-Tech to Watch: Sustainable Aviation Fuel" (ITIF, October 2022), https://itif.org/publications/2022/10/17/climate-tech-to-watch-sustainable-aviation-fuel/.
2. International Air Transport Association (IATA), "Fact Sheet 7: Liquid hydrogen as a potential low carbon fuel for aviation" (August 2019), https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/fact_sheet7-hydrogen-fact-sheet_072020.pdf.
3. Ibid.
4. Ibid.
5. Jeff Dahl, *Jet Engine*, 2007, Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Jet_engine.svg.
6. Bruce S et al., "Opportunities for hydrogen in aviation," 2020, CSIRO https://www.csiro.au/-/media/Do-Business/Files/Futures/Boeing-Opportunities-for-hydrogen-in-commercial-aviation.pdf.
7. Airbus, "Hydrogen fuel cells explained," news release, October 15, 2020, https://www.airbus.com/en/newsroom/news/2020-10-hydrogen-fuel-cells-explained.
8. Fuel Cells and Hydrogen 2 Joint Undertaking, *Hydrogen-powered aviation: a fact-based study of hydrogen technology, economics, and climate impact by 2050*, Publications Office, 2020, https://data.europa.eu/doi/10.2843/471510.
9. Hannah Ritchie, "Climate change and flying: what share of global CO_2 emissions come from aviation?" (Our World in Data, October 2020), https://ourworldindata.org/co2-emissions-from-aviation.
10. Jacob Teter and Hyeji Kim, *Aviation* (Paris: International Energy Agency, September 2022), https://www.iea.org/reports/aviation.

11. Fuel Cells and Hydrogen 2 Joint Undertaking, *Hydrogen-powered aviation.*
12. Jayant Mukhopadhaya and Dan Rutherford, "Performance analysis of evolutionary hydrogen-powered aircraft" (The International Council on Clean Transportation (ICCT), January 26, 2022), https://theicct.org/publication/aviation-global-evo-hydrogen-aircraft-jan22/.
13. Air Transport Action Group (ATAG), *WAYPOINT 2050: Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net-zero aviation by mid-century*, (September 2020), 54, https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf.
14. Ibid.
15. Bernd Heid et al., "Clean skies for tomorrow: Delivering on the global power-to-liquid ambition" (McKinsey, August 2022), https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/clean-skies-for-tomorrow-delivering-on-the-global-power-to-liquid-ambition.
16. "Our Vision for Zero-Carbon Emission Air Travel" (Aerospace Technology Institute, March 2022), https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-ALL-REP-0004-FlyZero-Our-Vision-for-Zero-Carbon-Emission-Air-Travel.pdf.
17. Jayant Mukhopadhaya and Dan Rutherford, "Performance analysis of evolutionary hydrogen-powered aircraft."
18. Fred Pearce, "How Airplane Contrails Are Helping Make the Planet Warmer," *Yale Environment 360*, July 18, 2019, https://e360.yale.edu/features/how-airplane-contrails-are-helping-make-the-planet-warmer; International Air Transport Association (IATA), "Fact Sheet 7: Liquid hydrogen as a potential low carbon fuel for aviation."
19. Clean Sky 2 JU, *Hydrogen-powered aviation A fact-based study of hydrogen technology, economics, and climate impact by 2050* (May 2020), https://op.europa.eu/en/publication-detail/-/publication/55fe3eb1-cc8a-11ea-adf7-01aa75ed71a1/language-en.
20. International Civil Aviation Organization, *2019 Environmental Report*, (ICAO, 2019), 124–130, https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg124-130.pdf.
21. International Energy Agency (IEA), ETP Clean Energy Technology Guide (Technology Readiness Level), accessed September 28, 2022, https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide?selectedSector=Aviation.
22. Jonathan O'Callaghan, "Quiet and green: Why hydrogen planes could be the future of aviation," *Horizon,* July 8, 2020, https://ec.europa.eu/research-and-innovation/en/horizon-magazine/quiet-and-green-why-hydrogen-planes-could-be-future-aviation.
23. Deutsche Aircraft, "On the way to climate-neutral flying: the Federal Ministry for Economic Affairs and Climate Action is funding a project to further develop hydrogen fuel cell technology," news release, April 4, 2022, https://www.deutscheaircraft.com/news/on-the-way-to-climate-neutral-flying-the-federal-ministry-for-economic-affairs-and-climate-action-is-funding-a-project-to-further-develop-hydrogen-fuel-cell-technology.
24. Linnea Ahlgren, "Dutch Consortium Commits to Hydrogen Flights To London By 2028," *Simple Flying,* June 13, 2022, https://simpleflying.com/netherlands-london-hydrogen-flight/.
25. Cory W. Watts, *The Dornier 328*, 2007, Wikimedia Commons, https://commons.wikimedia.org/wiki/File:THE_Dornier_328_(419180217).jpg.
26. Jayant Mukhopadhaya and Dan Rutherford, "Performance analysis of evolutionary hydrogen-powered aircraft."

27. Airbus, "Airbus to take up the hydrogen contrail characterisation challenge," news release, July 20, 2022, https://www.airbus.com/en/newsroom/press-releases/2022-07-airbus-to-take-up-the-hydrogen-contrail-characterisation-challenge.

28. "Making Net-Zero Aviation Possible," Mission Possible Partnership, July 2022, https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/decarbonizing-the-aviation-sector-making-net-zero-aviation-possible.

29. Jonathan O'Callaghan, "Quiet and green: Why hydrogen planes could be the future of aviation."

30. Chris Gebhardt, "With all-composite cryogenic tank, Boeing eyes mass-reducing space, aviation applications," *NASA Space Flight,* March 5, 2022, *https*://www.nasaspaceflight.com/2022/03/boeing-all-composite-cryo-tank/.

31. Advanced Research Project Agency-Energy (ARPA-E), "Open 2021 Project Descriptions," (2021), https://arpa-e.energy.gov/sites/default/files/documents/files/OPEN%202021_Project%20Descriptions_Final.pdf.

32. The Paper staff, "Universal Hydrogen to Invest Over $250 Million In ABQ Hydrogen Hub" (The Paper, March 10, 2022), https://abq.news/2022/03/universal-hydrogen-to-invest-over-250-million-in-abq-hydrogen-hub/.

33. ZeroAvia, "ZeroAvia Secures Additional $24.3 Million to Kick Off Large Engine Development for 50+ Seat Zero-Emission Aircraft," news release, March 21, 2021, https://www.zeroavia.com/press-release-series-a4-funding.

34. Julia Buckley, "This small airplane could hold the key to zero-carbon flying," *CNN*, January 20, 2023, https://www.cnn.com/travel/article/zeroavia-hydrogen-test-flight-climate/index.html.

35. U.S. Department of Energy (DOE), *DOE National Clean Hydrogen Strategy and Roadmap* (Washington, D.C.: DOE, 2022), https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf.

36. "Making Net-Zero Aviation Possible," Mission Possible Partnership, July 2022, https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/decarbonizing-the-aviation-sector-making-net-zero-aviation-possible.

37. Jayant Mukhopadhaya and Dan Rutherford, "Performance analysis of evolutionary hydrogen-powered aircraft" (The International Council on Clean Transportation (ICCT), January 26, 2022), https://theicct.org/publication/aviation-global-evo-hydrogen-aircraft-jan22/.

38. Air Transport Action Group (ATAG), *WAYPOINT 2050: Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency*; "Making Net-Zero Aviation Possible," Mission Possible Partnership.