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Can Hydrogen Fuel Reduce Aviation's Climate Impact?

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INTRODUCTION

As the United States looks to reduce its greenhouse gas emissions, lowering its carbon footprint will require an all-of-the-above strategy across multiple sectors. Decreasing aviation-sector emissions will be critical to ensuring the United States reaches its emissions goals. Indeed, the aviation sector accounts for about 720 million tons of energy-related carbon emissions, and world demand for jet travel has increased nearly continuously for decades, with the important exception of during the COVID-19 pandemic.[1] With the worst of the pandemic seemingly in the rearview mirror, however, passenger throughput is rebounding.

Reducing the aviation sector's greenhouse gas emissions will require a transition to new energy resources. Liquid hydrogen fuel (H_2) has emerged as a promising alternative to conventional jet fuel. Alternative clean energy options for aviation, such as batteries and sustainable aviation fuel (SAF), exist but have limitations. Several analysts have identified clean ammonia, which is produced from hydrogen and nitrogen via clean electricity, as a potential alternative to liquid hydrogen. However, this study assumes that the latter will prevail in the fuel competition, as the overwhelming majority of technical aviation experts interviewed by the author believe that liquid H_2 will ultimately be adopted by the industry. With few alternative technologies available for systematic decarbonization of the aviation sector, it is imperative that policymakers closely examine hydrogen's role in aviation decarbonization.

Several challenges will need addressing over the next ten years or more before the industry can begin to convert to, or partially switch to, hydrogen. Engineers must design planes to accommodate hydrogen; hydrogen-fuel infrastructure, although growing in the United States, must expand further to support hydrogen jet fuel needs at scale; and additional hydrogen uses, such as long-haul trucking, would improve the economic case. This issue brief will examine these challenges, and the policy solutions needed for including aviation in the nascent hydrogen economy and energy transition.

The Global Energy Center promotes energy security by working alongside government, industry, civil society, and public stakeholders to devise pragmatic solutions to the geopolitical, sustainability, and economic challenges of the changing global energy landscape.

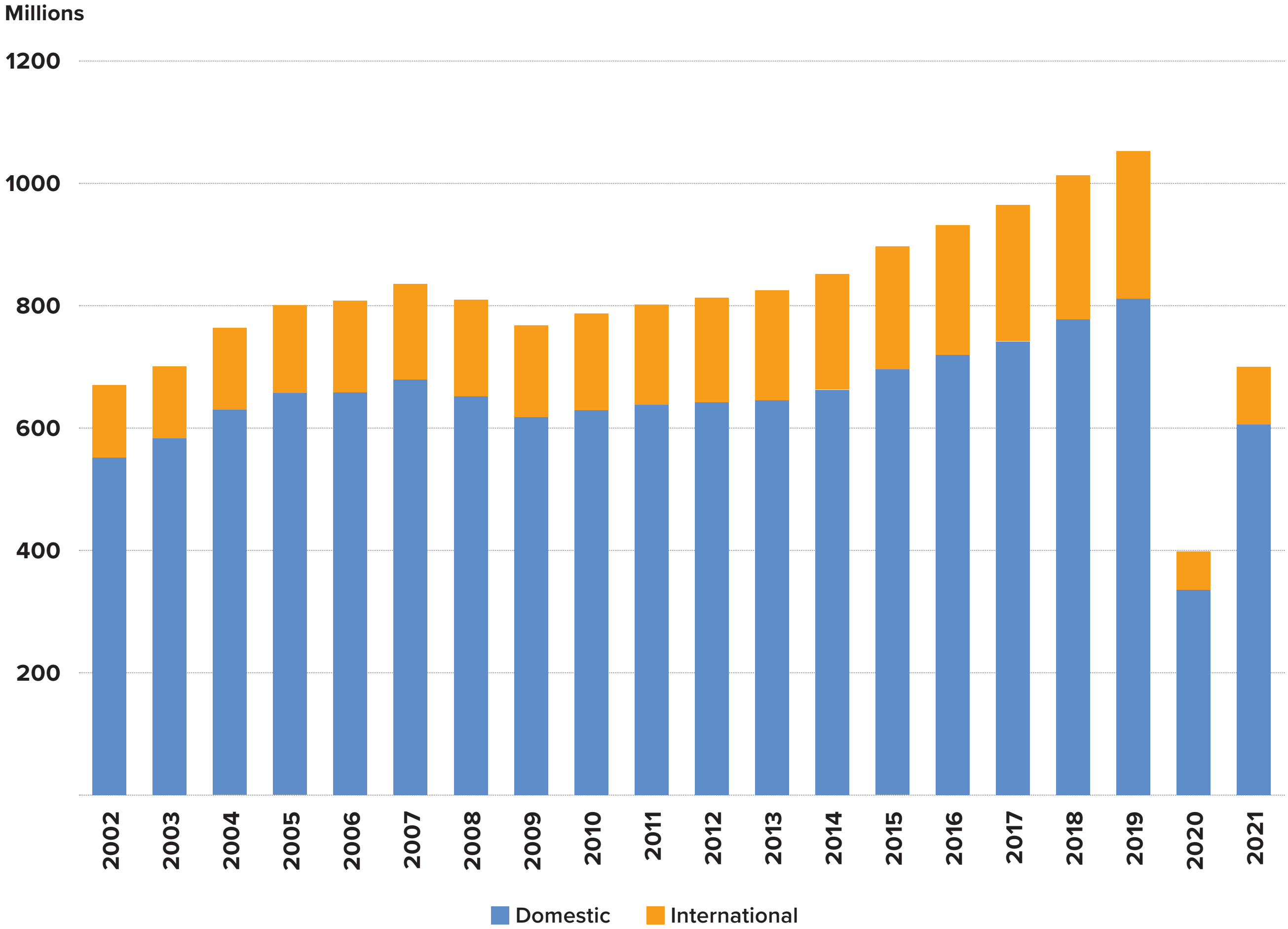
1 "Aviation," International Energy Agency, September 2022, https://www.iea.org/reports/aviation.

THE NEED FOR ALTERNATIVE JET FUELS

In the United States, data from the Environmental Protection Agency (EPA) show that the number of total travelers in 2021 rose 76 percent from 2020 levels, reaching nearly 66 percent of 2019 throughput levels.[2]

More recent Transportation Security Administration (TSA) passenger throughput data indicate that 2022 passenger throughput will track at above 90 percent of 2019 levels.[3] As passengers return to the skies, aviation-related emissions will also rise. Indeed, aviation-related emissions rose continuously from 2013 until the pandemic temporarily grounded air traffic.

Figure 1: Number of US Jet Passengers

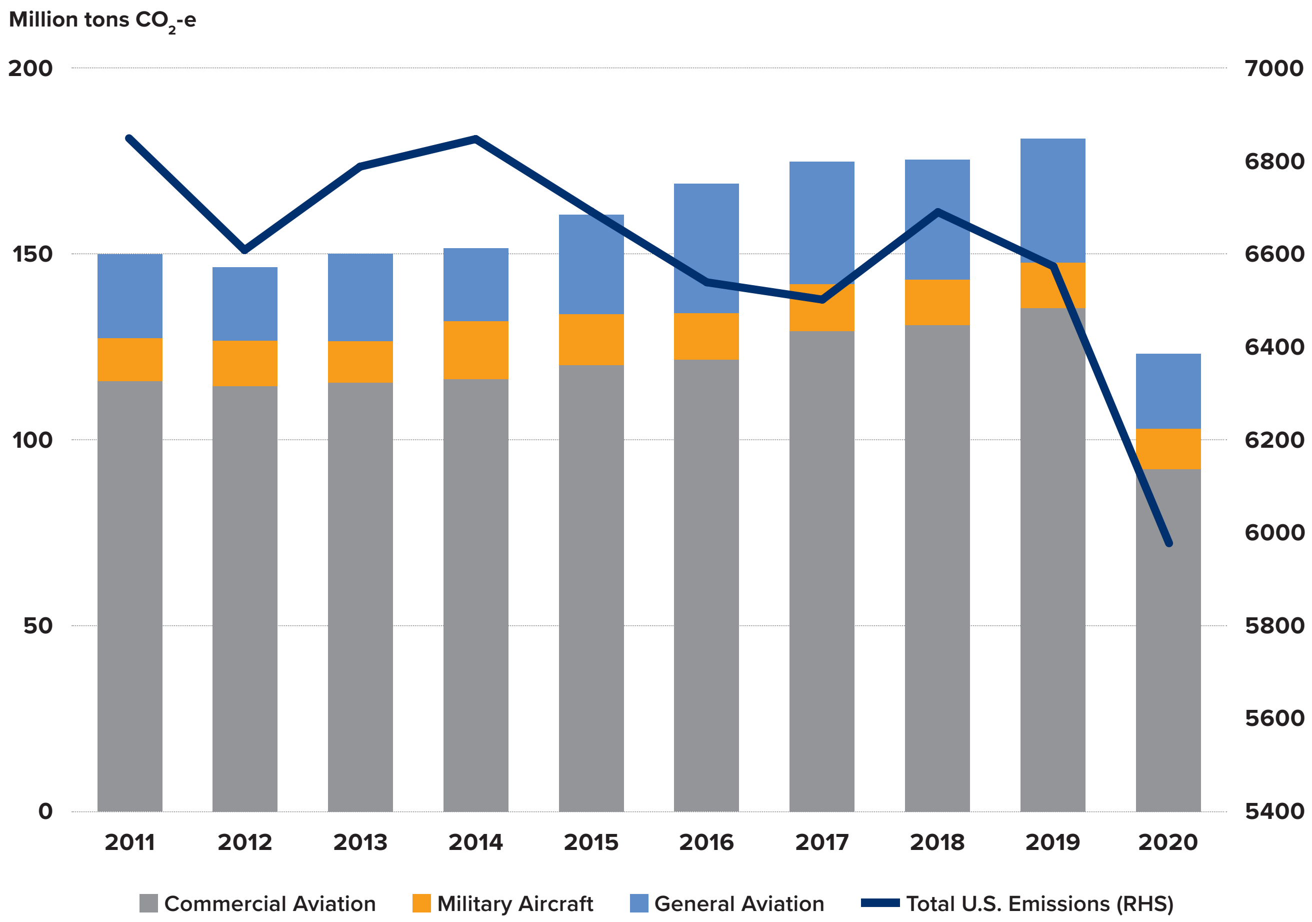


Source: "Passengers: All Carriers—All Airports," Bureau of Transportation Statistics, last visited November 21, 2022, https://www.transtats.bts.gov/Data_Elements.aspx?Data=5.

2 "Passengers: All Carriers—All Airports," Bureau of Transportation Statistics, last visited November 21, 2022, https://www.transtats.bts.gov/Data_Elements.aspx?Data=5.

3 "TSA Checkpoint Travel Numbers (Current Year versus Prior Year(s)/Same Weekday)," US Transportation Security Administration, last updated November 21, 2022, https://www.tsa.gov/coronavirus/passenger-throughput.

Figure 2: US Aviation Emissions



Source: Environmental Protection Agency[4]

Strong consumer demand for air travel is not just a US story. The International Air Transport Association (IATA) notes that total world operated flights in 2022 are expected to reach 33.8 million, or nearly 87 percent of 2019 levels.[5] The IATA also expects that passenger revenues will increase from $239 billion in 2021 to $498 billion in 2022, an increase of more than 108 percent.[6] As the global middle class expands, demand for air travel—and, therefore, for jet fuel—will also increase. Although business travel remains lower due to COVID, demand for commercial flights will likely continue to rise for the foreseeable future. Aviation demand and aviation-sector greenhouse gas emissions (GHG) are, therefore, set to rise from pandemic levels, necessitating sustainable approaches that can economically reduce emissions at scale.

CLEANER OPTIONS FOR POWERING AIR TRAFFIC

Researchers in industry, government, and academia are exploring options to reduce aviation's climate impact through alternative types of fuel or power sources. Alternatives to conventional jet fuel include batteries, which produce no emissions during flight; sustainable aviation fuels (SAF), which have lower carbon emissions; and hydrogen, which emits water when used as a fuel.

While batteries and SAF can be implemented relatively quickly, they do not represent long-term solutions, due to significant—potentially insurmountable—hurdles to scaling up for long-distance travel and ultimately meeting the

4 "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020." US Environmental Protection Agency, 2022, Table ES-2, 37, https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-main-text.pdf.; "Fast Facts on Transportation Greenhouse Gas Emissions." US Environmental Protection Agency, July 14, 2022, https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions.; "Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions, 1990-2020" US Environmental Protection Agency, May 2022, https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P10153PC.pdf.

5 "Travel Recovery Rebuilding Airline Profitability—Resilient Industry Cuts Losses to $9.7 Billion," International Air Transport Association, press release, June 20, 2022, https://www.iata.org/en/pressroom/2022-releases/2022-06-20-02/#:~:text=Flights%20operated%20in%202022%20are,%24239%20billion%20generated%20in%202021.

6 Ibid.

requirements of the global aviation sector. Batteries are generally considered unsuitable for long-distance flights due to their weight requirements. Indeed, jet fuel's energy density stands at 43 megajoules per kilogram (MJ/kg)—versus only 0.72 MJ/kg found in today's lithium-ion batteries.[7] Electrified airplanes would, therefore, need to carry massive battery packs, especially for long-haul flights, which would limit the number of available seats and harm the economics of battery-powered planes. On the other hand, SAF, which relies on waste oils and fats as well as woody biomass, will likely face supply constraints. Additionally, though SAF costs are declining, they are nevertheless about three to four times more expensive than kerosene.[8] Finally, SAF is not emissions free, as it still releases about one-fifth of the carbon released by kerosene jet fuel.[9] While SAF will play a role in aviation decarbonization, particularly in the short and medium terms, due to its versatility and ease of use as a drop-in fuel, policymakers will likely need to prioritize H_2 jet-fuel development to achieve midcentury net-zero goals.

Hydrogen is increasingly regarded as an environment-friendly and cost-effective fuel source for hard-to-decarbonize sectors, including aviation. Unlike burning coal or other hydrocarbons, hydrogen combustion or use in fuel cells produces water as a byproduct—not carbon or other GHG. Although most existing hydrogen fuel is produced from hydrocarbons, it can also be produced via processes powered by renewables or very low-emissions energy sources, including solar, wind, natural gas with carbon storage, and nuclear. Hydrogen is widely expected to become a cleaner fuel source as renewables adoption increases due to the Inflation Reduction Act's climate provisions.

Hydrogen development has been constrained, to date, by multiple factors, including: economic disadvantages relative to other fuel sources; challenges adapting equipment for H_2 fuel in nontraditional applications, such as steel, cement, and trucking; limited H_2 infrastructure along the supply chain, beginning in generation and continuing through transmission, end use, and storage; the difficulty of creating and handling liquid H_2, which must be frozen to -253 degrees Celsius; and, finally, different standards and rules, particularly across international lines.

There is also uncertainty around the GHG impact of contrails from water vapor. One IATA study estimated that H_2 combustion emits about 2.6 times more water vapor than kerosene fuel.[10] According to a 2021 study published in *Nature*, contrail cirrus is the largest single contribution to aviation net effective radiative forcing, greater than aircraft carbon-dioxide (CO_2) and nitrogen oxide (NOx) emissions.[11] Net effective radiative forcing, or the condition that occurs when the amount of energy that enters the Earth's atmosphere is different from the amount of energy that leaves it, can force changes to the Earth's climate.[12] Accordingly, some studies being undertaken would enable airlines to avoid the cool, humid air that can lead to contrail formation.[13] Airbus has launched a test program to study the contrails produced by a hydrogen-combustion engine.[14] While the scientific debate on contrail formation remains unresolved, it is an important area of research, given its potential GHG impact.

Some of the problems around hydrogen's economic competitiveness are being addressed. As H_2 technology continues to improve, market forces will continue to drive hydrogen prices lower, while governments are mobilizing resources to improve H_2 economics (including through the US Department of Energy's Hydrogen Shot initiative, which seeks to reduce the cost of clean hydrogen by 80 percent, to $1 per one kilogram in one decade—or the "1 1 1" goal).[15]

US clean hydrogen also received a major boost from the Inflation Reduction Act (IRA), a US law that was enacted in August 2022. The legislation provides support for the entire hydrogen value chain, with incentives extended to manufacturing and mining, clean energy generation, and an H_2 tax credit of up to $3 per kilogram.[16] Numerous studies

7 Johnathan Holladay, Zia Abdullah, and Joshua Heyne, "Sustainable Aviation Fuel: Review of Technical Pathways," US Department of Energy, September 2020, https://www.energy.gov/sites/prod/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf.

8 Siddharth Vikram Philip and Ben Elgin, "Airlines Rush Toward Sustainable Fuel But Supplies Are Limited," Bloomberg, November 10, 2021, https://www.bloomberg.com/news/articles/2021-11-10/airlines-rush-toward-sustainable-fuel-but-supplies-are-limited?sref=lDgLmqjg.

9 Peter Wilson, "Airliners Powered by Sustainable Fuel Remain a Distant Goal," *New York Times*, June 29, 2022, https://www.nytimes.com/2022/06/29/climate/planes-sustainable-fuel-flight.html.

10 "Liquid Hydrogen as a Potential Lowcarbon Fuel for Aviation," International Air Transport Association, August 2019, https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/fact_sheet7-hydrogen-fact-sheet_072020.pdf.

11 Christiane Voigt, et al., "Cleaner Burning Aviation Fuels Can Reduce Contrail Cloudiness," *Communications Earth & Environment* 2, 1 (2021), https://doi.org/10.1038/s43247-021-00174-y.

12 David Chandler and Kerry Emanuel, "Radiative Forcing," MIT Climate Portal, September 25, 2020, https://climate.mit.edu/explainers/radiative-forcing#:~:text=Radiative%20forcing%20is%20what%20happens,infrared%20radiation%20exiting%20as%20heat.

13 Jennifer Chu, "New Maps Show Airplane Contrails over the U.S. Dropped Steeply in 2020," MIT News, March 7, 2022, https://news.mit.edu/2022/airplane-contrails-map-0307.

14 "Airbus to Take up the Hydrogen Contrail Characterisation Challenge," Airbus, press release, July 20, 2022, https://www.airbus.com/en/newsroom/press-releases/2022-07-airbus-to-take-up-the-hydrogen-contrail-characterisation-challenge.

15 "Hydrogen Shot," US Department of Energy, Hydrogen and Fuel Cell Technologies Office, last visited November 21, 2022, https://www.energy.gov/eere/fuelcells/hydrogen-shot.

16 Andrew C. Hanson, et al., "The Inflation Reduction Act and the Rise of Clean Hydrogen," Perkins Coie, August 26, 2022, https://www.perkinscoie.com/en/news-insights/client-update-the-inflation-reduction-act-and-the-rise-of-clean-hydrogen.html.

suggest that the legislation will significantly improve hydrogen economics, particularly green hydrogen produced from renewables feedstocks.[17]

Despite challenges to short- and medium-term adoption, hydrogen offers unique opportunities for aviation decarbonization over the long term. Clean hydrogen produces few emissions, while its refueling capabilities are similar to existing jet fuel: H_2 is capable of rapid refueling and works well in cold climates. Moreover, there is already a proof of concept, as a Soviet Tupolev Tu-155 conducted dozens of flights in 1988 while using liquid H_2.[18] While H_2-fueled jet-flight technology has existed for decades, the economic integration of liquid H_2 (LH_2) aboard flights is still in its infancy, and a variety of companies are experimenting with different design models, including turbofans, turboprops, and blended-wing bodies.[19] Airbus alone is testing three different hydrogen-fueled models, while startup ZeroAvia completed the world's first hydrogen-fueled commercial-grade aircraft flight in 2020.[20] Policymakers at the Federal Aviation Administration, and perhaps the Department of Energy's Loans Program Office, could help accelerate H_2 adoption by directly supporting the initial prototyping and research-and-development (R&D) phases of H_2 jet-fuel development.

While there are many opportunities for H_2-powered planes, the technology also faces many hurdles. The most important obstacle is the cost of overhauling the fleet and related infrastructure. Estimates vary wildly due to uncertainty around adoption, but the costs of designing new airframes, building the infrastructure to generate H_2, investing in a new fuel ecosystem, and maintaining hydrogen-fueled planes will be immense. A 2020 McKinsey study for the European Commission found that aircraft initial capital expenditures for H_2 aircraft are expected to be higher than for conventional aircraft, due to LH_2 tank-structure integration, increased aircraft size, and other factors.[21] The study also assessed that H_2 planes' larger air frames and onboard storage tanks could result in more safety checks and maintenance costs, particularly in the short term, although it also noted that maintenance costs for the propulsion system could fall over time.[22]

In addition to financial obstacles, there are several technical challenges that will need to be overcome through R&D. A study from the International Council on Clean Transportation found that, "Compared to fossil-fuel aircraft, LH_2-powered aircraft will be heavier, with an increased maximum takeoff mass (MTOM), and less efficient, with a higher energy requirement per revenue-passenger-kilometer (MJ/RPK). They will also have a shorter range than fossil-fuel aircraft."[23] Similarly, refueling times for H_2 aircraft, while shorter than charging times for battery-powered planes, may nevertheless be longer than for kerosene-fueled aircraft.

BUILDING HYDROGEN AVIATION INFRASTRUCTURE

There is little to no existing hydrogen aviation infrastructure to speak of, outside of highly specialized and niche markets, such as the National Aeronautics and Space Administration (NASA), or onsite forklifts at airports. Hydrogen-capable airports will require access to unprecedented amounts of liquid hydrogen, and will therefore need to be sited near hydrogen production or dedicated H_2 pipelines, just as existing airports access jet fuel through refined-product pipelines. For instance, the Hartsfield-Jackson Atlanta International Airport is hundreds of miles from refining capacity, but lies astride the Colonial crude-product pipeline. The United States has an existing stock of 1,600 miles of hydrogen-dedicated pipelines, mostly concentrated in the Gulf Coast.[24] Consequently, hydrogen-capable airports outside of the Gulf Coast will be confronted with a dilemma: barring a possible (but unlikely) buildout of long-haul hydrogen-dedicated pipelines, airports may need to rely on the blending of hydrogen into existing natural gas pipelines that service the airport with, potentially, some hydrogen separation performed at the airport itself. Although there is some debate over the cost and practicality of this approach, most studies on the topic indicate that at least a fraction of natural gas pipeline capacity can be repurposed for H_2 use, at least on a technical basis. Alternatively, or as a complement to H_2 from pipelines, airports can turn to local, or even onsite, H_2 production. Trucking LH_2 to airports could serve as an interme-

17 John Larsen, "A Turning Point for US Climate Progress: Assessing the Climate and Clean Energy Provisions in the Inflation Reduction Act," Rhodium Group, August 18, 2022, https://rhg.com/research/climate-clean-energy-inflation-reduction-act/.

18 Mark Piesing, "The Epic Attempts to Power Planes with Hydrogen," BBC, March 21, 2022, https://www.bbc.com/future/article/20220316-the-epic-attempts-to-power-planes-with-hydrogen.

19 "Zeroe: Towards the World's First Zero-Emission Commercial Aircraft," Airbus, June 24, 2021, https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe.

20 Ibid.; Kelsey Reichmann, "ZeroAvia Completes First Hydrogen-Powered Flight," *Aviation Today*, September 29, 2020, https://www.aviationtoday.com/2020/09/29/zeroavia-completes-first-hydrogen-electric-turboprop-flight/.

21 "Hydrogen-Powered Aviation: A Fact-Based Study of Hydrogen Technology, Economics, and Climate Impact by 2050," McKinsey & Company and European Commission, May 2020, https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf.

22 Ibid.

23 Jayant Mukhopadhaya and Dan Rutherford, "Performance Analysis of Evolutionary Hydrogen-Powered Aircraft," International Council on Clean Transportation, January 2022, https://theicct.org/wp-content/uploads/2022/01/LH2-aircraft-white-paper-A4-v4.pdf.

24 "Hydrogen Pipelines," US Department of Energy, Hydrogen and Fuel Cell Technologies Office, last visited November 21, 2022, https://www.energy.gov/eere/fuelcells/hydrogen-pipelines.

diate solution, but the scale of H_2 would almost certainly require alternative supplies. As they weigh the costs and benefits of each sourcing approach, airports and airlines will likely seek to ensure supply by seeking local (but not necessarily onsite) H_2 production.

In addition to nearby production, airports may also benefit from proximity to other end users. One obvious complementary end user is the long-haul trucking industry. While most industry experts believe that electric vehicles will be utilized for short-haul, intra-city commutes, hydrogen may prove to be the superior alternative for long-haul, intercity trips, due to hydrogen's superior charging speeds and cargo capacity.[25] Airports that are sited near long-haul trucking nodes could, therefore, benefit from economies of scale, shared infrastructure, and a "hydrogen ecosystem" of know-how and skilled labor. LAX, for instance, is situated close to the Los Angeles and Long Beach ports and their associated long-haul trucking complexes. Airports can also help create other local end-user demand, such as by requiring ground-transportation vehicles at airports to switch to hydrogen.

Still, local geography in California would likely require new infrastructure—and potentially even hydrogen-dedicated pipelines that travel offshore to skirt population centers. The need for new, short-range, hydrogen-dedicated pipelines will not be unique to LAX. Due to the urban characteristics of almost every major airport, the limitations of existing hydrogen connectivity, and substantial LH_2 demands from flights, H_2-capable airports will likely require new short-haul pipelines that connect to local production, other end users, or both.

In addition to new pipeline connections, airports will likely require massive new storage facilities to house liquid hydrogen onsite. Storage requirements at airports could be quite substantial if hydrogen adoption accelerates. Carnegie Mellon researchers found that a single Airbus ZeroE JFK-to-Heathrow flight of about 3,440 miles would require more than 47,000 gallons of liquid hydrogen (versus about 10,800 gallons of A-1 jet fuel).[26] While H_2 may not be suitable for very long-distance flights (such as a JFK-to-Heathrow flight) due to liquid H_2's massive onboard volume requirements, the fuel may be ideal for medium-range flights. Therefore, if H_2 technology reaches maturity, major airports would almost certainly expect to operate several dozen or even hundred short- and medium-range H_2 flights every day. Over time, H_2-capable airports may, therefore, require the capability to safely store and process hundreds of thousands of gallons, or even millions of gallons, of LH_2 throughput. Indeed, a study by the Aerospace Technology Institute found that a large airport could require about one million gallons of LH_2 storage by 2035 and 13.2 million gallons of storage by 2050.[27]

There is no precedent for this level of liquid-hydrogen storage, or the amount of daily throughput a storage sphere would need to process. To put these storage requirements in perspective, NASA is building the world's largest, 1.25-million-gallon liquid-storage sphere to support space operations at the Kennedy Space Center. The new storage sphere will mark the first construction of a liquid-hydrogen storage facility in North America in nearly two decades; it will also be nearly 50 percent larger than a comparable 1966 facility.[28] Finally, NASA's storage spheres are used for discrete launches, whereas airport operations would require near-continuous discharges. Future requirements for storing liquid hydrogen for jet fuel will likely be orders of magnitude larger and more complex than those seen to date.

Fortunately, the private sector is already making initial strides in creating larger, more efficient hydrogen storage spheres. McDermott's CB&I, the company that is constructing the NASA storage sphere, is also completing designs for storage tanks that are eight times larger than existing facilities.[29] CB&I Storage Solutions—along with Shell International Exploration and Production, NASA's Kennedy Space Center, GenH2, and the University of Houston—have been awarded $6 million by the Department of Energy (DOE) Hydrogen and Fuel Cell Technologies Office to explore the feasibility of liquid-hydrogen storage at massive scale.[30] Because even limited H_2 flight operations will require massive reserves of liquid H_2 in storage, the technical feasibility and economic reliability of these facilities will be of major importance.

While the DOE's funding of a feasibility study for import and export LH_2 terminals will advance the body of knowledge, there are major operational differences between a maritime export/import H_2 facility and an airport running on liquid H_2. Given the frequency of flights and the magnitude of per-flight fuel requirements, airports may require more frequent

25 Thomas Walker, "Why the Future of Long-Haul Heavy Trucking Probably Includes Lots of Hydrogen," Greenbiz, June 15, 2021, https://www.greenbiz.com/article/why-future-long-haul-heavy-trucking-probably-includes-lots-hydrogen.

26 Clare Callahan, et al., "The Future of Hydrogen in Commercial Aviation: An Economic and Emissions Analysis of Jet Fuel Alternatives," Energy Science Technology and Policy, Carnegie Mellon University, 2021, https://www.cmu.edu/energy/news-multimedia/2021/second-place-poster.

27 Anna Postma-Kurlanc, et al., "Hydrogen Infrastructure and Operations: Airports, Airlines and Airspace," Fly Zero, Aerospace Technology Institute, March 2022, https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf.

28 Brandon Mulder, "World's Largest Liquid Hydrogen Storage Sphere Nears Completion for NASA," S&P Global Commodity Insights, February 23, 2022, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/022322-worlds-largest-liquid-hydrogen-storage-sphere-nears-completion-for-nasa.

29 Ibid.

30 Rod Walton, "McDermott, Shell, NASA Demo Liquid Hydrogen Storage at Scale," Power Engineering International, October 22, 2021, https://www.powerengineeringint.com/hydrogen/mcdermott-shell-nasa-explore-liquid-hydrogen-storage-at-scale/.

NASA's Kennedy Space Center in Florida has the world's largest liquid-hydrogen storage spheres. Much larger storage tanks will be needed to commercialize hydrogen aviation.(NASA)

throughput than marine terminals, which could complicate storage-tank maintenance. While the DOE's demonstration project is a good start, it should also consider evaluating liquid-H_2 storage requirements for different contexts (such as airport operations) and funding several more feasibility studies.

Finally, storage requirements will have strict safety guidelines and procedures. Hydrogen for jet fuel must grapple with the legacy of the Hindenburg hydrogen-blimp disaster, which effectively ended hydrogen-fueled air travel for decades. According to some accounts, there was another near miss during the Cold War. The ultra-secret Skunk Works facility in Burbank, California, used to store hundreds of gallons of liquid H_2. When a fire broke out at the base, some accounts claim that it threatened to destroy the facility, the neighboring airport, and large portions of Burbank.[31] Other studies from NASA note, however, that gasoline fires are "an order of magnitude more severe" than hydrogen fires.[32] Still, a safety incident involving a hydrogen storage tank could severely set back the industry, or worse. While safety procedures have come a long way since the Cold War, regulators will still need clarity on how airports can safely store unprecedented volumes of liquid H_2.

REGIONAL HYDROGEN AVIATION CORRIDOR

There is a strong theoretical case for establishing a regional hydrogen aviation-infrastructure corridor. The corridor would limit risks, but also provide a proof of concept for hydrogen aviation in the real world. A hydrogen aviation corridor would include several characteristics. Strong point-to-point demand, for example, would provide important fundamental economic support for the route. Meanwhile, midrange flights are in the "Goldilocks" range. They extend over distances that range-constrained, battery-powered flights cannot cover, but they also do not exceed hydrogen's onboard storage capabilities. Finally, a hydrogen aviation corridor would also need to be sited close to H_2 infrastructure.

Given these core attributes, California and Texas may be uniquely suitable for a hydrogen aviation corridor. Not only are the states the two largest in the country by population, but they may also prove to be the most critical states for the development of hydrogen jet fuel. Both states possess unique renewable-resource endowments and are well positioned for the initial commercialization of LH_2-powered flights.

31 Piesing, "The Epic Attempts to Power Planes with Hydrogen."

32 John L. Sloop, *Liquid Hydrogen as a Propulsion Fuel, 1945–1959* (Washington, DC: National Aeronautics and Space Administration, 1978), chapter 8, https://history.nasa.gov/SP-4404/ch8-6.htm.

Texas and California's advantages exist along hydrogen's entire value chain. Both states already enjoy excellent wind and solar production and, relatedly, green hydrogen potential. New renewables generation capacity and production will help lower the cost of hydrogen, improving the economics of H_2 for jet fuel. California is the country's largest producer of solar electricity, while Texas generates more electricity from wind than any other state.[33] Moreover, both states' renewables generation capacity is set to rise by more than twenty-six gigawatts (GW) through 2024, according to the Energy Information Administration (EIA).[34] Over the medium and long term, both states (especially California) will also likely tap into their offshore wind resources, creating new renewables generation sources and further improving the economics of local hydrogen production.

Both states also have unique advantages in their midstream segments. California possesses nearly all of North America's existing hydrogen-fueling stations for fuel-cell electric vehicles.[35] Moreover, the Golden State is highly receptive to new green technology, and has some of the country's most aggressive decarbonization goals. At a more local level, the Los Angeles natural gas distribution utility has already set a goal of displacing three million gallons of diesel fuel demand per day through hydrogen-fuel-cell trucks.[36]

Texas may enjoy even greater advantages in the hydrogen midstream segment. The nation's hydrogen-dedicated pipelines, which currently supply hydrogen for use by refineries, as well as other industrial uses, are concentrated in the Gulf Coast, while existing natural gas pipelines may be partially, or even fully, repurposed to transport hydrogen. Additionally, Houston's sizable energy workforce presents built-in opportunities for expanding its existing hydrogen ecosystem.

The construction of new LH_2 pipelines in both states faces challenges, however, and could constrain future hydrogen-fuel operations for aviation. As discussed previously, airport operations will likely consume hundreds of thousands—potentially millions—of gallons of H_2 every day if hydrogen-fueled planes become ubiquitous for medium-haul flights. At those demand levels, hydrogen would almost surely need to be piped into the airport, as existing liquid semitrailers tend to have a capacity of 12,000–17,000 gallons.[37] The political economy of hydrogen pipelines to airports presents risks for LH_2 development in both California and Texas, although the risks may be greater in the Golden State.

Texans are famously supportive of the energy industry. Although there may be an emerging rivalry between renewables and natural gas companies in the state, there are signs that the Lone Star State will support whichever fuel source generates the most economic value. Indeed, a statewide fleet of electric-vehicle charging stations is receiving political support from important political actors, including the governor.[38] On current trends, Texas seems unlikely to strangle hydrogen jet fuel in the cradle, and may even regard H_2 development as an opportunity.

In contrast, California might experience pushback against investing in a LH_2 infrastructure from an anti-development constituency. This movement has already influenced the conversation around the potential shutdown of California's zero-emissions Diablo Canyon nuclear energy plant. While H_2 fuel operations at LAX and/or SFO would require massive storage tanks and new hydrogen-dedicated pipelines, it is not clear if these projects would receive local or state-level environmental permits.

These are not static situations, however. California or Texas' political economy could change by the time liquid H_2 for aviation operations becomes viable.

33 "Historical State Data," US Energy Information Administration," October 14, 2022, https://www.eia.gov/electricity/data/state/.

34 "Preliminary Monthly Electric Generator Inventory (Based on Form EIA-860m as a Supplement to Form EIA-860)," US Energy Information Administration, May 24, 2022, https://www.eia.gov/electricity/data/eia860m/.

35 "Hydrogen Fueling Station Locations," Alternative Fuels Data Center, US Department of Energy, last visited November 21, 2022, https://afdc.energy.gov/fuels/hydrogen_locations.html#/find/nearest?fuel=HY.

36 "SoCalGas Proposes to Develop United States' Largest Green Hydrogen Energy Infrastructure System to Help Decarbonize LA Basin and Accelerate California's Climate Goals," SoCalGas, press release, February 17, 2022, https://newsroom.socalgas.com/press-release/socalgas-proposes-to-develop-united-states-largest-green-hydrogen-energy.

37 "Liquid Hydrogen Safetygram," Air Products, last visited November 21, 2022, https://www.airproducts.com/-/media/airproducts/files/en/900/900-13-082-us-liquid-hydrogen-safetygram-9.pdf?la=en&hash=B37612116B8C1FF8932FB2223C1BF2B8.

38 Reese Oxner, "Texas Plans to Place Charging Stations for Electric Cars Every 50 Miles on Most Interstates," *Texas Tribune*, June 20, 2022, https://www.texastribune.org/2022/06/20/texas-electric-vehicle-charging-stations/.

RECOMMENDATIONS FOR POLICYMAKERS

1. **Consider prioritizing green hydrogen in the Federal Aviation Administration's Aviation Climate Action Plan.**

   - On November 9, 2021, the Federal Aviation Administration (FAA) published the United States Aviation Climate Action Plan. The FAA plan accounts for emission pathways reductions, including the development of new, more efficient aircraft and engine technologies; improvements in aircraft operations throughout the National Airspace System; production and use of Sustainable Aviation Fuels (SAF); and, finally, electrification and, potentially hydrogen, as solutions for short-haul aviation.

   - The FAA should consider elevating hydrogen as a potential solution, particularly for medium-haul flights.

2. **Support H_2-capable jet-plane prototyping and studies on storage feasibility studies and contrails.**

   - To spur H_2 development, the Department of Transportation and other federal agencies should consider providing R&D funding to prototype H_2-fueled jet planes and liquid-storage feasibility studies. Because medium- and long-haul trucking and other potential hydrogen use cases could require substantial liquid-storage capacity, examining new storage designs could provide benefits for more than just aviation decarbonization. The federal government should also support studies examining the climate impacts of hydrogen contrails, as well as efforts to mitigate contrail effects more generally.

3. **Create common standards and evaluate storage safety options.**

   - National policymakers should seek to create common standards and formulate best practices, particularly around storage safety options. While NASA has experienced no known safety issues at its liquid hydrogen storage sites, consumers, businesses, local governments, and insurers will demand that new LH2-storage facilities prioritize safety.

4. **Prioritize regional hydrogen aviation-corridor development. Consider Texas and California as test cases.**

   - There is a strong theoretical case for a regional hydrogen aviation corridor that enjoys strong point-to-point demand, midrange flights, and hydrogen infrastructure. The Lone Star and Golden States have strong potential to develop hydrogen infrastructure, and are excellent candidates for early H_2 fuel adoption and commercialization in aviation. National policymakers should consider partnering early with stakeholders in both states and building support for hydrogen.

Hydrogen is a promising aviation decarbonization solution, but the technology faces significant hurdles and will take a long time—at least a decade, and probably longer—before it will become a viable alternative to existing fuels. While hydrogen faces significant hurdles, it's not too soon for policymakers to begin thinking about ways to accelerate the fuel for deployment in aircraft. In addition to setting common rules and standards, policymakers should look at some R&D initiatives that could spur broader efforts. Funding for new LH_2-storage designs could pay dividends for both aviation and ground-transportation decarbonization solutions, while providing R&D funding for H_2-fueled prototypes could provide a high rate of social return at relatively little cost. In addition to providing funding, policymakers should ensure that regulations are decarbonization supportive and standardized, to the greatest extent possible.

The aviation industry, potentially with the encouragement of government, should also definitively determine if ammonia or liquid H_2 will be a more viable fuel for air travel. While the overwhelming majority of technical experts interviewed by the author believe liquid H_2 will prevail over ammonia, this is not a consensus opinion. More research is needed to determine the optimal fuel for at-scale aviation decarbonization.

Hydrogen has developed rapidly over the past five years, moving from an afterthought to a top-of-mind decarbonization solution. In another five or ten years, hydrogen aviation could move from a distant prospect to an emerging reality.

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