Aviation White Paper

Written in collaboration with
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Foreword

The Alliance for Clean Hydrogen Energy Systems (ARCHES) is California's initiative to accelerate renewable, clean hydrogen projects and infrastructure. California has a pivotal opportunity to decarbonize important sectors of the state's economy, towards achieving the State's ambitious greenhouse gas reduction goals. Through ARCHES, California can play a decisive role in realizing the US Department of Energy's Hydrogen Earthshot target of lowering clean hydrogen production costs five-fold to $1 per kilogram ($1/kg) within a decade.

New technology and large-scale deployment will be needed to achieve these goals. Clean hydrogen made from renewable sources, ranging from renewably powered electrolysis to agricultural biomass, offers enormous promise to advance a zero-carbon economy and to reduce the costs of clean hydrogen. Innovative electrolysis and fuel cell technologies as deployed through ARCHES can help decarbonize sectors like heavy duty freight, shipping, ports, and energy generation and offer the promise of cleaner air for all communities and new good jobs. To this end, in late 2022, ARCHES commissioned a series of white papers spanning multiple thematic working groups meetings convened topically, and across sectors, charged with developing a clean hydrogen roadmap and blueprint to inform, stimulate and scale up clean hydrogen activities across California.

Drawing upon the knowledge and expertise of academic, government, industry, and labor representatives, the ARCHES Clean Hydrogen White Papers are the culmination of over two years of regular meetings between engaged stakeholders from industry, government, academia and community groups, among others. Each White Paper is co-authored by a Working Group Chair from the University of California, with two or more co-chairs, with contributions from working group members. Key recommendations that would support overall development of a clean hydrogen economy include:

- Devise hydrogen pricing programs that ensure **transparency, consistency, longevity, and adaptability**;
- Develop hydrogen **transportation and storage infrastructure for both gas and liquid**;
- Ensure that local, state, and federal agencies that oversee emissions, safety, and permitting generate **aligned and adaptable standards and regulations**; and
- Promote **collaboration and communication among stakeholders**, including communities, industries, regulatory agencies, and workforce development programs.

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Executive Summary

The California aviation industry currently uses hydrogen in small quantities, notably for ground transportation and as an input to produce renewable diesel fuel from hydroprocessed esters and fatty acids. As of January 2023, California indirectly consumed up to 1,600 tonnes of hydrogen annually–representing 0.2% of in-state total hydrogen production capacity. The following summary outlines top findings by the ARCHES Aviation Working Group, identifying the opportunities, challenges, and policy needs to support the transition to clean hydrogen within the aviation industries.

Opportunities

Current Uses

Hydrogen use in aircraft is still in the early stages of development, with several prototypes undergoing testing in recent years. Future market demand for hydrogen fuel as a power source for aviation varies widely, as it is still unclear what the payload and range capabilities of hydrogen-powered aircraft will be, when commercial aircraft will be available, and how quickly such aircraft can be delivered to customers. In 2035, airport ground support equipment and ground fleets could require 14 metric tonnes per day (MTPD) of hydrogen statewide. Projections for hydrogen demand for direct use in aircraft vary from 11 metric tonnes per day to power 32 aircraft across 10 California airports to 47 MTPD to power 132 aircraft across 26 California airports by 2035.

Versatility of Zero-Emission Jet Fuel

Due to its high energy density, hydrogen could be well-suited to the demands of aviation. Hydrogen can power aircraft in various ways. It can be used directly in fuel cells to generate electricity, providing a clean and efficient power source. Additionally, hydrogen can be utilized as a key ingredient in the production of synthetic e-fuels, which can be used in existing jet engines with minimal modifications. When produced via renewable pathways, hydrogen has the potential to offer a zero-emission alternative to kerosene-based fossil jet fuel. Hydrogen-powered aviation could improve air quality and reduce noise pollution, benefitting surrounding communities. Furthermore, hydrogen has the potential to provide airports with an avenue for both energy resilience as a backup power generating source including as mobile charging units for electric vehicles and reduced emissions from fuel-cell powered ground support equipment (GSE) and other ground transportation. Hydrogen production could be located at airports, and may prove to be a less costly and carbon-free alternative to conventional fossil jet fuel and biomass-derived sustainable aviation fuel (SAF).

Challenges and How to Address Them

Broader use of hydrogen in airports faces several challenges, including the current high production costs of hydrogen, current lack of production, distribution, and storage infrastructure and standards, and safety standards that may vary according to the use case. In the near term, the state could encourage the development of hydrogen clusters at select airports such as Long Beach to fuel ground-support equipment, public transportation, and off-highway ground transportation with infrastructure to produce and store hydrogen fuel on-site. Such clusters could expand to fuel hydrogen powered aircraft as they become commercially viable in the coming years. Other supportive actions that could catalyze investment in hydrogen for aviation include:

- Incentivizing the use of low-carbon hydrogen as an input to liquid SAF production or other chemical/industrial processes, as well as for direct consumption by aircraft;
- Collaboration with federal and international standards organizations to develop and adopt relevant standards and policies for aircraft and ground support equipment;
- State-level leadership to encourage all California airports to include a focus on hydrogen infrastructure in their planning processes and coordination to pursue federal funding via existing grant programs like the Federal Aviation Administration's Fueling Aviation's Sustainable Transition via Sustainable Aviation Fuels (FAST-SAF) and Low-Emission Aviation Technologies (FAST-Tech) grants;
- Collaboration among airports and airport equipment manufacturers with airport-proximal enterprises and transit agencies that have an interest in hydrogen offtake, developing regional entities of sufficient scale to achieve enough demand to enable at-pump cost of $3/kg of hydrogen; and
- Taking a cross-sectoral approach to standardization and regulations, especially in the context of hydrogen at airports.

Section 1: Sector Overview

ARCHES aims to facilitate the market entry of hydrogen into California's aviation sector as a decarbonization pathway. California's aviation sector is an essential backbone for domestic and international travel and trade in the United States, acting as a gateway to the Asia-Pacific. This sector includes airports, aircraft stock, passengers, and cargo. However, burning jet fuel releases carbon dioxide (CO_2), water vapor, methane (CH_4), nitrogen oxides (NO_x), sulfur oxides (SO_x) and non-volatile particulate matter (nvPM).[1] These emissions could lead to premature deaths by negatively impacting air quality at the ground level, particularly impacting vulnerable airport-adjacent communities.[2] Additionally, the atmospheric interactions between the emissions and the environment result in secondary climate pollutants, such as contrail cirrus, which have warming impacts that likely exceed those from CO_2 alone.[3] Although aviation represents a relatively small percentage of global emissions today, 2.4 percent, that could rise to 22% by 2050[4], as more people fly and other sectors decarbonize more quickly.[5] The ARCHES Aviation Working Group reviewed the current state of the sector by assessing existing demand, fuel pathways, and research and development efforts.

1.1 Market Size

Airports, Passengers and Aircraft Stock

California is home to the fifth and sixteenth busiest airports (Los Angeles International Airport and San Francisco International Airport, respectively). The state has 27 commercial service airports fulfilling scheduled air services for passengers and freight as well as non-scheduled air transport (e.g., Air Charter).

In 2021, California airports served as major hubs for air travel, accommodating 138 million passengers—12.9% of all enplanements in the United States (this report focuses on commercial airports because they feature consistent routes that make the adoption of hydrogen fuel more economical and therefore more likely to occur first).[6] The state's

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[1] Barrett, S., et al, , *Guidance on the use of AEDT Gridded Aircraft Emissions in Atmospheric Models,* 2010, https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=aae3bd04f264b1d0d584c5480e3b31d70fb92c39

[2] Yim, et al, *Global, regional and local health impacts of civil aviation emissions. Environmental Research Letters, 10(3), 034001, 2015,* https://doi.org/2020031315113099

[3] Lee, et al, *The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834, 2021,* https://doi.org/10.1016/j.atmosenv.2020.117834

[4] European Parliament, Directorate General for international policies, *Emission Reduction Targets for International Aviation and Shipping*. https://www.europarl.europa.eu/thinktank/en/document.html?reference=IPOL_STU%282015%29569964

[5] World Economic Forum, *Aviation's flight path to a net-zero future,* available at https://www.weforum.org/agenda/2021/09/aviation-flight-path-to-net-zero-future/

[6] Tavares, Tony, "Caltrans Mission, Vision and Goals." Caltrans, 2022, available at https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/caltrans-fact-booklets/2022-caltrans-facts-a11y.pdf.

aviation market is largely driven by narrowbody aircrafts, which dominate domestic passenger operations. Looking ahead, analysts project the domestic passenger aviation sector to expand significantly, with an estimated 83% growth between 2019 and 2045.

Cargo Equipment Demand

It is still unclear whether airport ground-support equipment will trend towards more electrified or hydrogen-powered technologies. However, the Aviation Working Group conducted a preliminary assessment of potential hydrogen demand for such equipment. Assuming the ground fleet grows at the same rate as the aircraft fleet at 1.8% annual growth rate, and that the fleet is gradually replaced to be 25%, 50%, and then 100% hydrogen powered in 2027, 2030 and 2035, respectively,[7] then projected statewide demand would equal the values shown below in Table 1.

Table 1. Projected statewide hydrogen demand from ground support vehicles and airport fleets.[8]

Year	Hydrogen demand per year (MTPY)	Hydrogen demand per day (MTPD)
2027	1,600	4.4
2030	3,400	9.3
2035	7,500	20.4

1.2 Current Role of Hydrogen in Aviation

Airports are already serving as test beds for hydrogen adoption across a variety of ground fleets, while in parallel researchers are evaluating, planning, and preparing for hydrogen as both an aviation fuel and power source. Overall, hydrogen ground fleets have the potential to play a significant role in reducing greenhouse gas emissions and improving air quality at airports, contributing to the overall sustainability of aviation operations. Deploying hydrogen ground fleets requires infrastructure for hydrogen production, storage, and refueling. Airports interested in adopting hydrogen ground fleets are actively developing investment strategies to prepare for the necessary infrastructure, including hydrogen refueling stations.

[7] The 1.8% growth rate is based on Boeing's Commercial Market Outlook for North America, which suggests a fleet growth rate of 1.8%.

[8] Calculated based on the conversion of California's six busiest airports' ground fleet to hydrogen vehicles with a total annual hydrogen demand of 5,900 MTPY, or 16 metric tonnes per day of hydrogen.

1.4 State Fuel Production and Consumption

Of the four major SAF pathways –hydroprocessed esters and fatty acids (HEFA), alcohol-to-jet (ATJ), gasification with Fischer-Tropsch (FT), and power-to-liquid (PtL)—biofuel production through HEFA is the most technologically mature, with a technology readiness level (TRL) of 9. Feedstocks for this pathway include lipids such as waste cooking oil, residues from food processing or other processes, and purposely grown plant oils, with roughly 0.03-0.08 kg of hydrogen required for hydroprocessing per kg of HEFA output.[9] HEFA biofuel is the only SAF currently produced and consumed at commercial scale.

As part of California's greenhouse gas (GHG) emission inventory, the California Air Resources Board (CARB) tracks and reports the quantities of fuel consumed in all sectors of the economy.[10] Jet fuel use peaked in 2017 at 4.9 billion gallons, reducing to 4.3 billion gallons in 2019.[11] Included in the reported numbers are the 1.8 and 4.6 million gallons of alternative jet fuel consumed in 2019 and 2020, which are three orders of magnitude less than statewide fossil jet fuel use. Notably, California uses more jet fuel than any other U.S. state, consuming 14% of the national total in 2021.[12] Statewide jet fuel production has exceeded consumption in 9 of the 16 years between 2005 and 2020, per state data tracking weekly fuel production across its refineries.[13]

Hydrogen Volumes Used for Aviation in California

Hydrogen is currently only used indirectly in small quantities in the aviation sector today, for ground fleets/transportation (demonstrations) and as an input for HEFA. In the U.S., the aviation sector consumed 15.8 million gallons of HEFA in 2022 (shown in Figure 1), primarily in California due to low carbon fuel standard (LCFS) benefits. California alone consumed 7.6 million gallons of HEFA SAF in 2021, requiring roughly 1,300 tonnes of hydrogen. This total indicates that California's aviation market is currently indirectly consuming up to 2,700 tonnes of hydrogen, or 0.3% of in-state hydrogen production capacity at refineries.[14]

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[9] Pipitone, Giuseppe, Giulia Zoppi, Raffaele Pirone, and Samir Bensaid. "Sustainable Aviation Fuel Production Using In-Situ Hydrogen Supply via Aqueous Phase Reforming: A Techno-Economic and Life-Cycle Greenhouse Gas Emissions Assessment." *Journal of Cleaner Production* 418 (September 15, 2023): 138141. https://doi.org/10.1016/j.jclepro.2023.138141.

[10] CARB, *Current California GHG Emission Inventory Data | California Air Resources Board*, available at https://ww2.arb.ca.gov/ghg-inventory-data

[11] 1 gallon of jet fuel has roughly the same energy content as 1.1 kg of hydrogen

[12] U.S. EIA, *Independent Statistics and Analysis*., available at https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_fuel/html/fuel_jf.html

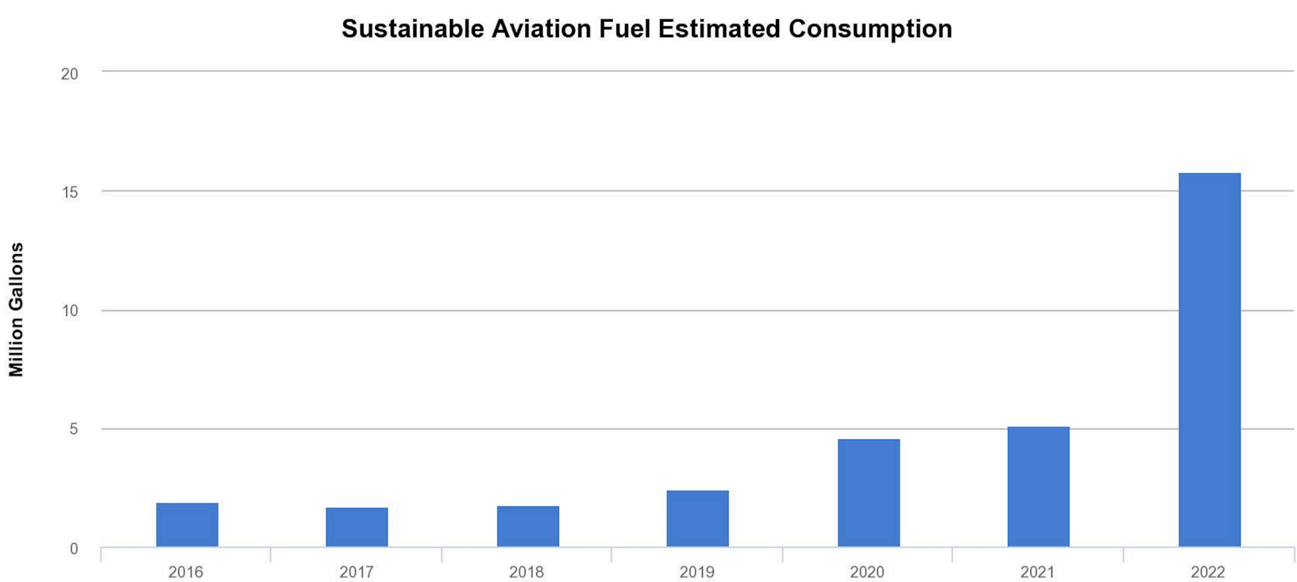
[13] CEC. , *Refinery Inputs and Production,* May 2023, available at https://www.energy.ca.gov/data-reports/reports/weekly-fuels-watch/refinery-inputs-and-production

[14] U.S. EIA, *Production Capacity of Operable Petroleum Refineries,* available at https://www.eia.gov/dnav/pet/PET_PNP_CAPPROD_A_(NA)_8PH_MMCFD_A.htm

Regarding future hydrogen volumes required for announced HEFA production, assuming World Energy's Paramount facility produces 250 million gallons by 2025, and 50% of the 730 million gallons from the Martinez refinery is HEFA jet, aviation sector demand in California for hydrogen would increase by nearly 40 times to around 100,000 tonnes, or 12% of current in-state refinery production capacity. To put this number in perspective, this volume of SAF (and inherent hydrogen demand) would equate to 20% of the White House's 2030 SAF Grand Challenge US-wide production target of 3 billion gallons per year by 2030.

By 2050, the DOE forecasts that 'If the U.S. replaces all jet fuel consumption with SAF, approximately 2-6 MMT/year of hydrogen could be required to produce 35 billion gallons of SAF from biofuels.'[15] Assuming California jet fuel consumption as a percentage of US consumption remains at the 2021 level of 14%,[16] approximately 280-850 thousand tonnes of hydrogen would be required per year to produce the requisite amount of SAF.

Figure 2. US SAF (HEFA) consumption [17]



The imminent commercialization of hydrogen-powered aircraft in 2027-2030 is poised to significantly impact the annual demand for hydrogen in California's aviation sector. In

[15] U.S. DOE, *National Clean Hydrogen Strategy and Roadmap,* November 2022, available at www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf

[16] *U.S.* EIA, *Independent Statistics and Analysis,* available at https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_fuel/html/fuel_jf.html

[17] U.S. EPA, *RIN Generation and Renewable Fuel Volume Production by Fuel Type for the Renewable Fuel Standard, June 2023,* available at https://www.epa.gov/fuels-registration-reporting-and-compliance-help/spreadsheet-rin-generation-and-renewable-fuel-0

addition to the increase in amount of hydrogen consumed by aviation, direct-hydrogen aviation will also prompt a reassessment of optimal locations for hydrogen production.

Table 2. SAE AIR8466, Hydrogen storage ranges for scheduled service operators by aircraft type [18]

Aircraft Type	Earliest Entry In Service (estimated)	Passengers	Range (SAE AIR 8466)	Hydrogen Tank Size (SAE AIR 8466)	In-State Takeoff Ops 2023[19]
Commuter	2027	19	300 nm	100 kg	14,200
Regional	2030	75	750 nm	700-2000 kg	138,500
Narrowbody	2035	150	2400 nm	6000-12000 kg	419,000

Using the capacities in Table 2, a regional airport (e.g. LGB) can expect direct use aircraft demand of 300 kg/day or less in 2027, scaling up to 50 tonnes/day in 2035.[20] Hydrogen demand for a given target year necessarily depends on market adoption rates.

1.5 Policy: Quotas, Mandates, Targets, and Incentives

California has ambitious climate targets, with statutory mandates to reduce greenhouse gas emissions 40% below 1990 levels by 2030 and achieve carbon neutrality by 2045, including via 85% emission reductions.[21] CARB released the roadmap to meet these targets last year with the 2022 Scoping Plan, which outlined a detailed sector-level pathway to 2045 net-zero and going beyond statutory requirements with a plan for 48% reduction in emissions by 2030.[22]

Aviation Emissions Targets

Within the Scoping Plan, CARB proposed achieving decarbonization for in-scope aviation emissions (i.e., from intrastate flights) via hydrogen and electricity to meet 10% of energy demand and the remaining 90% by SAF. In 2022, GovernorNewsom requested

[18] SAE AIR 8466 "Hydrogen Fueling Stations for Airports, in both gaseous and liquid form" projections of hydrogen aircraft size ranges
[19] Bureau of Transportation Statistics T100 Segment Data (All Carriers), available at https://transtats.bts.gov/DL_SelectFields.aspx?gnoyr_VQ=FMG&QO_fu146_anzr=Nv4%20Pn44vr45
[20] Vertical Flight Society, H2-Aero, "Multimodal Hydrogen Airport Hub", available at https://vtol.org/files/dmfile/h2-aero-whitepaper--multimodal-h2-airport-hub-2022_public-final.pdf
[21] *AB-1279 The California Climate Crisis Act,* September 2022, available at https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220AB1279
[22] CARB,2022 Scoping Plan for Achieving Carbon Neutrality, 2022, available at https://ww2.arb.ca.gov/sites/default/files/2023-04/2022-sp.pdf

that CARB raise its clean fuels target to 20% and strengthen the Low Carbon Fuel Standard (LCFS) to boost SAF adoption. LCFS amendments in 2019 helped make California a premium market for SAF, driving in-state production up over 6x from just under 2 million gallons in 2019 to 12 million gallons in 2022.[23] In October 2024, CARB and Airlines for America, an industry trade organization representing nearly a dozen major airlines, committed to a goal of increasing the availability of SAF for use within California to 200 million gallons by 2035, an amount that would meet about 40% of intrastate travel demand – a more than tenfold increase from current levels. Meanwhile, the federal goal announced by the Biden Administration is more ambitious — 3 billion gallons by 2030 and 100% of domestic aviation fuel demand by 2050. In this context, California's target of 200 million gallons represents just 6.7% of the national goal, which is a relatively modest contribution.[24] Additionally, California's SAF production volume only met around 0.3% of total jet-fuel consumption in 2021, highlighting the long path ahead to transition the aviation sector away from conventional fossil-based fuels.[25]

Renewable Diesel and SAF Incentives

HEFA renewable diesel, made from the same feedstocks as SAF, has seen rapid growth due to existing incentives. Stronger SAF support could shift production toward aviation fuel, especially as ground transport electrifies. Policymakers must navigate trade-offs among fuel markets, air quality, and GHG policies. A SAF aircraft manufacturing credit—similar to California's ZEV Program—could also spur hydrogen aviation.[26]

Federal Support

Beyond state policy in California, federal targets and incentives are also boosting alternative aviation fuel markets. In 2021, the U.S Department of Energy announced the SAF Grand Challenge, proposing a 2030 US-wide SAF production target of 3 billion gallons, rising to 35 billion gallons by 2050.[27] Furthermore, the Inflation Reduction Act (IRA) included a tax credit incentive of up to $1.75 per gallon for SAF through 2027, which can be combined with incentives from the Renewable Fuel Standard and

[23] CARB, *LCFS Data Dashboard*, available at https://ww2.arb.ca.gov/resources/documents/lcfs-data-dashboard
[24] CARB, CARB and nation's leading airlines announce landmark partnership for a sustainable aviation future (Oct 2024), available at https://ww2.arb.ca.gov/news/carb-and-nations-leading-airlines-announce-landmark-partnership-sustainable-aviation-future; U.S. Department of Energy, Federal Agencies Publish SAF Grand Challenge Progress Report Highlighting Historic Efforts to Grow America's SAF Industry, available at https://www.energy.gov/eere/bioenergy/articles/federal-agencies-publish-saf-grand-challenge-progress-report-highlighting?nrg_redirect=471761
[25] *U.S. EIA, Independent Statistics and Analysis*, available at https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_fuel/html/fuel_jf.html&sid=CA
[26] CARB, Zero-Emission Vehicle Program, https://ww2.arb.ca.gov/our-work/programs/zero-emission-vehicle-program
[27] U.S. DOE, *Memorandum of Understanding - Sustainable Aviation Fuel Grand Challenge*, September 2021, available at https://www.energy.gov/sites/default/files/2021-09/S1-Signed-SAF-MOU-9-08-21_0.pdf

California's LCFS.[28] As of August 2024, the Federal Aviation Administration (FAA) has announced $291 million from the Inflation Reduction Act for projects that will help achieve the goal of net-zero greenhouse gas emissions from aviation by 2050. It includes $244.5 million for 22 projects that produce, transport, blend or store sustainable aviation fuel (SAF) and for scoping studies related to SAF infrastructure needs. It also includes $46.5 million for 14 projects that develop, demonstrate or apply low-emission aviation technologies.[29]

Ground Equipment and Shuttles

CARB is aiming not only to catalyze decarbonization of in-state aircraft operations but also airport ground equipment and shuttle emissions through requirements such as the Zero-Emission Airport Ground Support Equipment (GSE) and Zero-Emission Shuttle Bus mandates.[30] CARB adopted the latter as a regulation in 2019, mandating that all fixed-route airport shuttle fleets transition to 100% zero-emission by 2035, with operators beginning to add zero-emission shuttles to their fleets by 2027 and any shuttle replacements from 2023 on being replaced by new ZEVs.[31] As some airports begin to adopt hydrogen for energy resilience reasons and to prepare for hydrogen-powered aircraft, California could expect these airports to also potentially adopt hydrogen fuel cell GSE and shuttles, which would add to the demand for hydrogen production at or near these airports.

1.6 Research and Development and Industry Action

In 2023, there were successful prototype demonstrations of hydrogen-powered aircraft utilizing a fuel cell electric powertrain. In March 2023, Universal Hydrogen, a Los Angeles-based startup (now no longer in business), flew a 40-passenger aircraft for 15 minutes using primarily hydrogen as fuel. This demonstration followed a successful 10-minute test-flight of a 19-seater aircraft by Hollister-based startup ZeroAvia, which then completed a 10-flight test cycle. In June 2023, Airbus announced the successful test campaign of a hydrogen fuel cell system, which reached its full-power level of 1.2MW— the most powerful test ever achieved in aviation of a fuel cell designed for large-scale aircraft.[32] German startup H2Fly, acquired by California-based Joby Aviation

[28] Mukhopadhaya, J., & Pavlenko, N, *A roadmap for decarbonizing California in-state aviation emissions*, January 2023, available at, https://theicct.org/wp-content/uploads/2023/01/ca-aviation-decarbonization-jan23.pdf

[29] U.S. Department of Transportation, 'Biden Harris Administration Announces Nearly $300 Million in Awards for Sustainable Aviation Fuel and Technologies as part of Investing in America Agenda' (Aug 2024), available at https://www.transportation.gov/briefing-room/biden-harris-administration-announces-nearly-300-million-awards-sustainable-aviation

[30] CARB, *Aircraft & Airports,* available at https://ww2.arb.ca.gov/our-work/topics/aircraft-airports

[31] CARB, *Zero-Emission Airport Shuttle Regulation Factsheet*, October 2019, available at ww2.arb.ca.gov/sites/default/files/2019-10/asb_reg_factsheet.pdf

[32] Airbus, "First ZEROe Engine Fuel Cell Successfully Powers on," January 2024, available at https://www.airbus.com/en/newsroom/stories/2024-01-first-zeroe-engine-fuel-cell-successfully-powers-on

in 2021, successfully flight-tested a liquid hydrogen system in September 2023 and completed a 523-mile flight on its eVTOL aircraft with a hydrogen-electric propulsion system in June 2024.[33] In February 2024, Airbus announced that its ZEROe program remains on track and will develop both hydrogen combustion and hydrogen fuel cell propulsion with anticipated entry-into-service in 2035. Beyond Aero, an aviation start-up based in France, is developing a clean-sheet hydrogen fuel cell aircraft, designed to carry 6 to 8 passengers over a range of 1500 km, with entry into service targeted around 2030. The aircraft uses gaseous hydrogen and is fully electric, powered by a fuel cell system.[34] In 2024, the company successfully completed the first flight of its hydrogen-electric demonstrator, Blériot—a retrofitted two-seat ultralight aircraft featuring an 85 kW powertrain.[35]

In addition to fuel cell technology, large aircraft engine manufacturers such as Pratt & Whitney, GE Aerospace, and Rolls Royce are exploring the potential for direct combustion of liquid hydrogen (LH2). In September of 2023, Rolls Royce successfully ground tested a hydrogen combustion engine, and is now working on testing a cryogenic liquid hydrogen pumping system.[36] LH2 carries more energy per unit volume than gaseous H_2 and may therefore be better suited to longer-haul flights.

Beyond the use of hydrogen to power aircraft, companies have launched hydrogen to fuel stationary equipment, like the U.S. Department of Energy-funded light stand demonstration project at San Francisco International Airport, as well as airport ground support equipment and fleets. The 2013-18 deployment of fifteen LH2 fueled cargo tractors at Memphis airport, Tennessee, represents another example. To that end, the impact from the use of these fuels is currently limited. However, airports, airlines, and ground handlers across California are actively integrating hydrogen into their fleets and are gaining comfort with the equipment, technology, supply chain and beyond during this first generation of use. This also includes possibilities for mobile hydrogen-powered fuel cell generators to help recharge battery-driven ground equipment.

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[33] Joby Aviation. "Joby Completes Landmark 523-Mile Hydrogen-Electric Flight | Joby." Accessed October 4, 2024, available at https://www.jobyaviation.com/news/joby-demonstrates-potential-regional-journeys-landmark-hydrogen-electric-flight/; Businesswire, *Joby Subsidiary H2FLY Completes World's First Piloted Flight of Liquid Hydrogen Powered Electric Aircraft*, available at https://www.businesswire.com/news/home/20230907159821/en/Joby-Subsidiary-H2FLY-Completes-World%E2%80%99s-First-Piloted-Flight-of-Liquid-Hydrogen-Powered-Electric-Aircraft

[34] Beyond Aero, One, available at https://www.beyond-aero.com/one

[35] Beyond Aero, Blériot, available at https://www.beyond-aero.com/prototypes

[36] Rolls Royce, "Rolls-Royce Starts New Set of Ground-Breaking Hydrogen Research Tests," December 2023, available at https://www.rolls-royce.com/media/our-stories/discover/2023/rolls-royce-starts-new-set-of-ground-breaking-hydrogen-research-tests.aspx

Section 2: Future Vision for Hydrogen in Aviation

2.1 Hydrogen Demand from Aviation

As discussed in Section 1, there are four use cases for hydrogen demand from the aviation industry:

1. Powering ground support equipment and airport fleet vehicles
2. Direct use in hydrogen-powered aircraft
3. As a feedstock for SAF production
4. Use for Auxiliary Power Units (APU) as backup power for instance

Each use case has a unique demand growth and maximum demand based on the current state of technology and future projection.

Projected Hydrogen Demand for Aircraft

Based on 2019 airline route data for domestic flights departing California airports, and estimated aircraft performance outlined in Table 3, hydrogen-powered aircraft could be used on 76% of the departures or 46% of the available seat kilometers.[37][38]

The demand for hydrogen to power airplanes directly is dependent upon the payload and range capabilities of the hydrogen-powered aircraft as well as their market entry dates and delivery rates. To encapsulate the range of projected hydrogen demand numbers, this paper presents two scenarios: a "measured rollout," which forms the lower bound of our hydrogen demand estimates, and an "accelerated rollout," which forms the upper bound. Table 3 lists the aircraft performance and entry dates for the two scenarios.

Fuel cell retrofit aircraft are likely to enter the market the earliest. Incorporating feedback from ZeroAvia on expected certification timelines, this analysis estimated an entry date of 2027 for a commuter-sized fuel cell retrofit aircraft. Based upon the routes flown from California airports, an LH_2-powered 50-passenger aircraft would have the

[37] The difference in departure and available seat kilometer (ASK) coverage is owed to the fact that shorter flights, which are better suited for hydrogen aircraft, happen more often and account for a larger portion of departures rather than ASK.

[38] Mukhopadhaya, J., & Graver, B, *Performance analysis of regional electric aircraft. International Council on Clean Transportation*, 2022, available at https://theicct.org/publication/global-aviation-performance-analysis-regional-electric-aircraft-jul22/; Graver, B., Rutherford, D., & Zheng, S.CO2 emissions from commercial aviation: 2013, 2018, and 2019. International Council on Clean Transportation, 2020, available at https://theicct.org/publication/co2-emissions-from-commercial-aviation-2013-2018-and-2019/; Mukhopadhaya, Jayant. "Performance Analysis of Fuel Cell Retrofit Aircraft," International Council on Clean Transportation, August 2023, available at https://theicct.org/publication/fuel-cell-retrofit-aug23/

biggest impact with an estimated maximum range of 1330 km and hydrogen consumption of 200-400kg.[39] Based upon Airbus' recent successes in fuel cell demonstration, they may first introduce a clean-sheet fuel cell-powered regional aircraft as part of their ZEROe program in 2035.[40] Such an aircraft could have a passenger capacity of 75 with a range of 800 nautical miles.[41] As mentioned earlier, Beyond Aero expects to enter into service in 2030 the clean-sheet hydrogen fuel aircraft One, with a range of 1500 km.

Table 3. Estimated payload and range capability, entry dates, and delivery rates for hydrogen powered aircraft

Scenario	Aircraft	Seating capacity	Range (km)	Entry year	In-State Takeoffs 2023[42]
Measured Rollout	Fuel cell retrofit (turboprop)	50	1250	2030	18,000
	Clean-sheet fuel cell (turboprop)	75	1500	2035	37,000
	Hydrogen combustion narrowbody	150-192		2040	37,000
Accelerated Rollout	Fuel cell retrofit	9-19	500	2027	9,200
	Fuel cell retrofit (turboprop)	72	1400	2030	36,000
	Fuel cell retrofit (jet)	75-150	1400	2035	40,000

With Joby's successful hydrogen-electric vertical take-off and landing (eVTOL) demonstrator aircraft completing the aforementioned 523-mile flight, as well as other

[39] Ibid.
[40] Airbus, *At Airbus, hydrogen power gathers pace,* June 2023, available at https://www.airbus.com/en/newsroom/stories/2023-06-at-airbus-hydrogen-power-gathers-pace
[41] Debney, D., et al, *Zero-Carbon Emission Aircraft Concepts (FZO-AIN-REP-0007). Aerospace Technology Institute*, 2022, available at https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf
[42] Bureau of Transportation Statistics T100 Segment Data (All Carriers), available at https://transtats.bts.gov/DL_SelectFields.aspx?gnoyr_VQ=FMG&QO_fu146_anzr=Nv4%20Pn44vr45

companies like Archer having goals to deploy 6,000 eVTOLs by 2030,[43] this technology could be in commercial service by that year. Companies could also introduce a family of more traditional aircraft with varying payload-range capabilities. While timelines for entry into service are uncertain and would depend on the success of the preceding hydrogen-powered aircraft, they could potentially enter service by 2040. The analysis in this report uses a combination of a 150-, 168-, and 192-passenger aircraft.[44] The measured rollout scenario uses a delivery rate of 1 aircraft per airport for regional aircraft. The delivery rate for the narrowbody is doubled compared to the regional aircraft because they have a larger market potential and therefore a potentially higher manufacturing capability. However, aircraft deliveries for all aircraft will be bound by the maximum demand for total aircraft at each airport. The analysis used 2019 airline route data to quantify the demand between airports.[45]

Hydrogen Infrastructure

The use of hydrogen-powered aircraft will initially be limited to airports with hydrogen infrastructure. To develop a realistic scenario of how hydrogen could power California's aviation ecosystem, the Measured Rollout scenario considered the concurrent development of hydrogen infrastructure at six airports in California: Oakland (OAK), Sacramento (SMF), San Jose (SJC), Ontario (ONT), Palm Springs (PSP), and Long Beach (LGB).[46] After industry leaders demonstrate hydrogen-powered aviation at these airports, infrastructure development could begin at Los Angeles (LAX) and San Francisco (SFO) airports by 2035. In line with the DOE's plan to develop ten regional hydrogen hubs, the analysis also assumed that industry develops hydrogen infrastructure at six out-of-state airports: Seattle (SEA), Denver (DEN), Dallas-Fort Worth (DFW), Phoenix (PHX), Chicago O'Hare (ORD), and Salt Lake City (SLC); these out-of-state airports have the most connectivity with the chosen in-state airports. Although DOE selected only seven hubs and excluded the regions where PHX, DEN, and SLC are located, industry analysts continue to expect hydrogen infrastructure development at these airports.

Advanced Air Mobility (AAM) refers to a new class of aircraft—typically electric, highly automated, and capable of vertical takeoff and landing (VTOL). Initial AAM operations

[43] Builtin, 'What Are eVTOLs? Are They the Future of Aviation?', available at https://builtin.com/articles/evtol-aircraft

[44] Mukhopadhaya, J., & Rutherford, D, *Performance analysis of evolutionary hydrogen-powered aircraft*, International Council on Clean Transportation, 2022, available at https://theicct.org/publication/aviation-global-evo-hydrogen-aircraft-jan22/

[45] A growth rate of 2.35% per year is assumed from 2019 – 2045. This is the average between the predicted growth rates for domestic aviation in the U.S. from Airbus (2.2%) and Boeing (2.5%).

[46] Schneider, J. et. al, Multimodal Hydrogen Airport Hub. Vertical Flight Society, 2023, available at https://vtol.org/files/dmfile/h2-aero-whitepaper--multimodal-h2-airport-hub-2022_public-final.pdf

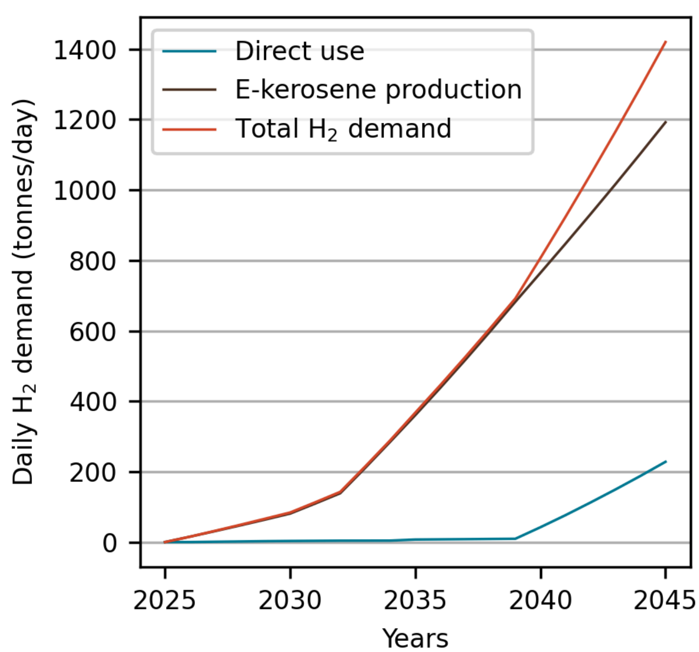
will utilize modified existing infrastructure (airports and heliports), with future expansion supported by dedicated facilities such as vertiports and vertistops.[47]

E-Kerosene

Fuel providers will also require hydrogen to make e-kerosene. For the purpose of this study, the report assumed that e-kerosene production scale-up mirrors the mandates set in the ReFuelEU Aviation regulation, increasing from 1.2% in 2030 to 15% in 2045.[48] This analysis assumed that 1.37 MJ of hydrogen is required to produce 1 MJ of e-kerosene.[49]

Figure 3 shows the projected daily demand for hydrogen for direct use in hydrogen-powered aircraft in the measured rollout scenario and for e-kerosene production and the resulting total daily hydrogen demand. Experts estimate that the demand for hydrogen from aviation could be 84 metric tonnes per day (MTPD) in 2030, increasing to about 1400 MTPD in 2045.

Figure 3. Projected daily hydrogen demand in California under the measured rollout scenario



[47] Federal Aviation Administration "Advanced Air Mobility Infrastructure", available at https://www.faa.gov/airports/new_entrants/aam_infrastructure

[48] European Commission, *European Green Deal: New law agreed to cut aviation emissions by promoting sustainable aviation fuels*, April 2023, available at https://ec.europa.eu/commission/presscorner/detail/en/ip_23_2389

[49] Argonne National Laboratory, *The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET)*, 2022, available at https://greet.es.anl.gov/index.php

Table 4 presents the expected hydrogen demand, number of hydrogen-powered aircraft, and number of airports assumed to develop hydrogen infrastructure in California. Depending on the rollout of hydrogen aircraft, the demand for direct hydrogen use in aviation could range from 11 MTPD to 47 MTPD in 2035. Table 5 shows the progression of the demand in 2027, 2030, and 2035 under the two scenarios. This demand is also placed in the context of the potential demand from e-kerosene production, which could be more than 6 times higher in 2035.

Table 4. Expected hydrogen demand for 'Measured Rollout' and 'Accelerated Rollout' scenarios.

Year 2035	Measured rollout	Accelerated Rollout
Hydrogen demand	11.0 MTPD	46.7 MTPD
Operational aircraft	24 fuel cell retrofit turboprops 8 fuel cell clean-sheet designs	109 commuter turboprop retrofit 3 regional turboprop retrofit 20 regional jet aircraft retrofit
In-state airports with H2 support	8	27
Out-of-state airports with H2 support	6	N/A

Table 5. Expected hydrogen demand in 2027, 2030 and 2035.

Year	Direct-use hydrogen demand (MTPD) Measured Rollout	Direct-use hydrogen demand (MTPD) Accelerated Rollout	Hydrogen demand from e-kerosene production (MTPD)
2027	1.4	0.9	31.0
2030	3.3	3.0	80.9
2035	11.0	46.7	360

2.4 Hydrogen Cost Analysis

Renewable Power Constraints and Capital Costs

Based on the above assumptions, 2045 hydrogen demand for direct use by aircraft and as an input for synthetic fuel production is estimated at 1439 tonnes/day, over 525,000 tonnes per year. To meet this demand with optimized California solar PV and wind resources, the state will need to build approximately 16-19 gigawatts (GW) of renewable energy to support zero-emission renewable hydrogen production.[50] This deployment amounts to nearly all of the existing utility-scale PV and onshore wind assets currently installed in California.

Between 2010-2020, California built an average of 1 GW of utility solar PV and 300 MW of wind per year.[51] To meet 2045 hydrogen demand for aviation, approximately 0.9-1.1 GW of renewable energy will need to be built on average per year between 2023-2045. This deployment is in addition to the nearly 2.5 GW of annual build out required to meet California's 2045 goal of powering all retail and state agency electricity needs with renewable and zero-carbon resources.[52]

To meet 2045 hydrogen demand for direct use by aircraft and as an input for synthetic fuel production using in-state resources, state leaders will need approximately $14 to $16.7 billion dollars of capital investment in renewable energy assets. Additionally, they will need approximately $3.3 to $3.9 billion of direct and indirect capital investment in electrolyzers.

Hydrogen Volume Supply Gap

Estimated annual hydrogen production in California totals 1.05 million tonnes.[53] [54] Produced by both merchant hydrogen plants and petroleum refiners, nearly all production in the state uses fossil fuels as a feedstock. To meet 2045 direct-use hydrogen and input hydrogen for synthetic fuel production demand for aviation alone, California hydrogen production capacity will need to increase by approximately 50%. For

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[50] Two centralized California production locations to meet the 2045 estimated aviation hydrogen demand were modeled separately for this analysis; a northern location (Chico, CA) and a southern location (Lancaster, CA). Chico would require about 8.5 GW of solar PV and 7.5 GW of wind for a total of 16 GW. Lancaster would require about 8.8 GW of solar PV and 10.2. GW of wind for a total of 19 GW.

[51] CEC, *SB 100 Joint Agency Report: Charting a path to a 100% Clean Energy Future*, March 2021, https://www.energy.ca.gov/news/2021-03/california-releases-report-charting-path-100-percent-clean-electricity

[52] CEC, *SB 100 Joint Agency Report: Charting a path to a 100% Clean Energy Future*, March 2021, https://www.energy.ca.gov/news/2021-03/california-releases-report-charting-path-100-percent-clean-electricity

[53] CEC, Adopted 2022 Integrated Energy Policy Report Update, 2022, https://www.energy.ca.gov/data-reports/reports/integrated-energy-policy-report/2022-integrated-energy-policy-report-update

[54] CEC staff calculation. Used Documentation of California's 2000–2019 GHG Inventory, https://ww2.arb.ca.gov/applications/california-ghg-inventory-documentation, files for 2–Industrial Processes and Product Use, 2H–Other, 2H3–Hydrogen Production.

context, between 1982 and 2019 California petroleum refinery-produced hydrogen increased 1.1% per year on average.[55] Additionally, considering approximately 97% of industrial gas company hydrogen produced via steam methane reforming is consumed by refining processes,[56] industry leaders will need significant investment in clean hydrogen production pathways to meet 2045 aviation demand.

In addition to the 1.05 million tonnes per year of existing hydrogen production capacity in California, experts have forecasted over 3 million tonnes to come online by 2027, primarily all clean and renewable derived.[57] [58] Projected aviation hydrogen demand (excluding ground-support equipment applications) by 2027 accounts for less than 1% of forecasted additional capacity by 2027. This forecast indicates that planned capacity for renewable hydrogen production should be sufficient to meet near-term aviation demand. However, as hydrogen demand for aviation and other sectors increases over time, planned near term capacity will likely become insufficient to meet it.

Hydrogen Production–Optimizing for Cost

This report identified the levelized cost of hydrogen (LCOH), as well as the LCOH including section 45V clean hydrogen production tax credits introduced by the 2022 Inflation Reduction Act (as of report publication, this credit is targeted for elimination by the 2025 federal tax bill), for each location, as seen in Table 7 below.[59] Given the need for low carbon intensity derived hydrogen, the analysis applies the full tax credit of $3/kg of hydrogen produced via processes achieving less than .45 kg CO2 per kg of hydrogen. Accounting for the total estimated capital and operating costs over the lifespan of the assets, the analysis applies the total tax credit over ten years and divides

[55] U.S. EIA, California Refinery Hydrogen Production Capacity , available at https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=8_NA_8PH_SCA_6&f=A

[56] Hydrogen Tools, North American Merchant Hydrogen Plants 2016, available at https://h2tools.org/hyarc/hydrogen-data/merchant-hydrogen-plant-capacities-north-america

[57] U.S. DOE, Office of Energy Efficiency and Renewable Energy, Hydrogen and Fuel Cell Technologies Office, *H2 Matchmaker*, available at https://www.energy.gov/eere/fuelcells/h2-matchmaker

[58] Element Resources, Delivering a Meaningful, Sustainable Source of Clean Energy for Lancaster, California, and the Western U.S., 2023, Production value included based on 2025 production of ~21,000 Mt per year, available at https://www.elementresources.com/element-resources-to-build-one-of-californias-largest-renewable-hydrogen-production-facilities-in-the-city-of-lancaster-ca/

[59]Assumptions: To assess optimized cost for the production and storage of hydrogen to meet California aviation demand by 2045, this analysis assumed production equipment investment in 2030 comparing various locations. The cost of renewable hydrogen production is dependent on various factors including technology type, renewable energy resources available, and storage type. The analysts modeled eight production locations, two within California and six out of state. They assumed each location would use proton exchange membrane (PEM) electrolyzer production technology with direct CAPEX costs of $400 per kilowatt.[#] Additionally, the analysts applied solar PV CAPEX costs of $750 per kilowatt and onshore wind CAPEX costs of $1000 per kilowatt to each scenario.[#] Last, the researchers applied pipeline storage and transport of gaseous hydrogen at an assumed pressure of 100 Bar with CAPEX costs of $516 per kg. This estimate factored in the likelihood of centralized production of hydrogen, as opposed to on-site production occurring at each airport, which would require distribution to the California airports included in this analysis for direct use in aircraft as well as centralized synthetic fuel production facilities within the state.

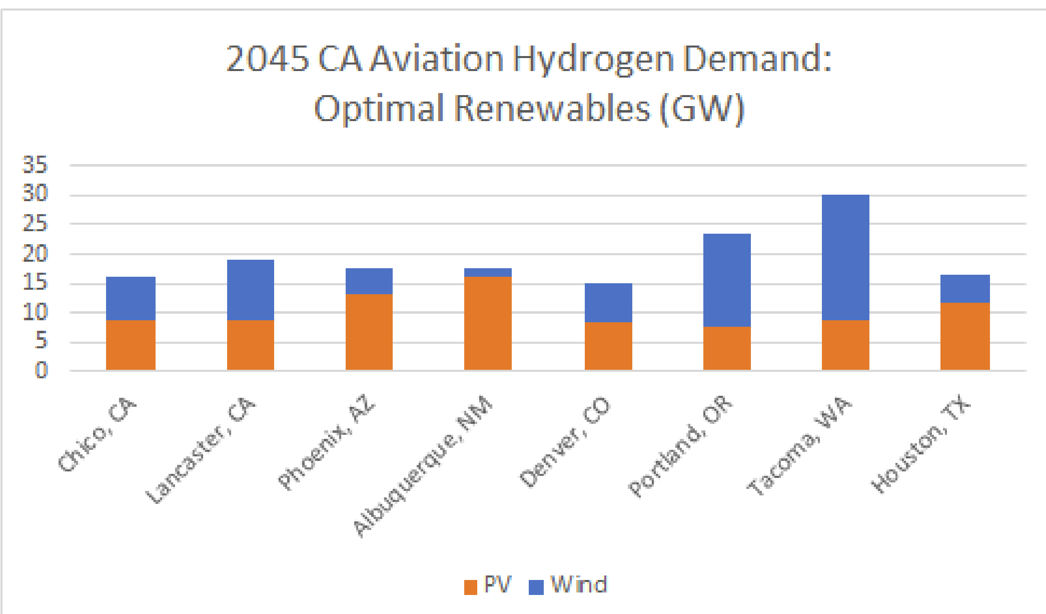
it by the amount of hydrogen produced over the lifespan of the production assets to identify the difference between the LCOH with and without 45V production credits. LCOH values are represented in 2023 dollars. Additionally, Figure 4 depicts the optimal renewable energy resource mix per location.

Table 7. Levelized cost of hydrogen (LCOH) at various locations

Location	LCOH	LCOH w/ 45V
Albuquerque, NM	2.71	1.14
Chico, CA	3.18	1.61
Houston, TX	3.19	1.61
Denver, CO	3.20	1.62
Phoenix, AZ	3.41	1.83
Lancaster, CA	3.95	2.37
Tacoma, WA	4.86	3.28
Portland, OR	5.98	4.40

*LCOH values represent 2023 dollars

Figure 4. 2045 California aviation hydrogen demand: optimal renewables (GW)



As seen in Table 7, production based in Albuquerque, New Mexico resulted in the lowest LCOH of $2.71 ($1.14 with 45V) per kg, due both to favorable solar resources and the cost of solar PV per kilowatt compared to onshore wind. Chico, California has the next lowest LCOH of $3.18 ($1.61 with 45V). Compared to Lancaster, California, which has an LCOH of $3.95 ($2.37 with 45V) per kg, Chico's optimal wind resources resulted in fewer renewable energy assets required to meet production demand.

Houston, Texas- and Denver, Colorado-produced hydrogen is also comparable to Chico, resulting in LCOH values of $3.19 ($1.61 with 45V) and $3.20 ($1.62 with 45V) per kg, respectively. Notably, the cost of hydrogen produced in the Pacific Northwest states of Washington and Oregon was relatively high given reduced solar resources that would necessitate additional, more expensive onshore wind assets. Although analysts expect announced hydrogen production projects in California to meet anticipated demand, hydrogen sourced from outside CA may provide additional cost-effective sources of supply.

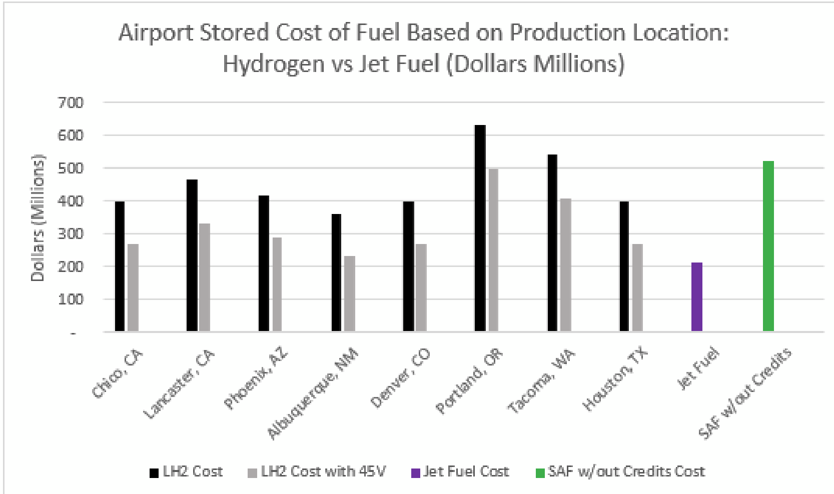
Hydrogen Cost Premiums Versus Conventional Jet Fuel

Experts expect hydrogen to come at a premium cost on a dollar per tonne basis compared to SAF without credits and conventional jet fuel, where the latter benefits from deeply rooted economies of scale and decades of technological and market development. This analysis compared the cost of estimated California 2045 direct use hydrogen demand to the equivalent energy amount of jet fuel and SAF. The per tonne costs are adjusted by the energy content of each fuel and presented in Figure 5.[60]

Even when considering 45V production tax credits, total hydrogen costs to meet 2045 demand ranged from 10-140% higher than that of jet fuel. Specific to the California locations evaluated, hydrogen production in Chico and Lancaster resulted in an airport-dispensed cost premium of approximately 30% and 60% respectively, compared to conventional jet fuel. It should be noted, however, that the cost gap between jet fuel and hydrogen could be reduced further in the future considering potential fuel taxes or other emissions policies. Interestingly, when compared to SAF without credits, in most locations evaluated, the total cost of hydrogen without tax credits to meet California 2045 demand was estimated to be lower than the cost of the energy equivalent amount of SAF without credits. However, SAF production is currently supported by various policies and credits at federal and state levels and costs are expected to decrease overtime as production economies of scale are achieved.

Figure 5. Airport Stored Cost of Fuel Based on Production Location (*Represented in 2023 dollars)

[60] Researchers considered production, delivery, liquefaction (as applicable to hydrogen), and storage costs of each fuel type. This analysis calculated the cost per tonne of 2045 direct-use hydrogen produced at the various locations and delivered via pipeline based on the respective modeled LCOH in 2023 dollars. Next, it identified the cost of liquefaction and storage per tonne of hydrogen and then added that cost to the cost per ton produced and delivered. Researchers then calculated the total cost per tonne of hydrogen ready to be dispensed at the airport both with and without section 45V tax credits.



2.5. Multimodal Hydrogen-Airport Hub Ecosystem

Policy makers could accelerate and scale the adoption of hydrogen technologies in the aviation sector by developing a multimodal hydrogen airport hub ecosystem that combines demand from ground vehicle traffic outside the airport with the aircraft and ground support equipment within an airport as well as demand from energy resilience requirements. Initial investments in infrastructure to service existing ground transportation demand (cars, trucks, buses) can be expanded to eventually service the higher demand from hydrogen-powered aircraft.

The VFS H2-Aero whitepaper, Multimodal Hydrogen Airport Hub,[61] outlines hydrogen demand projections for converting aircraft and ground transport to hydrogen at airports, emphasizing the creation of large hydrogen hubs. Using Long Beach Airport as a case study, it estimates hydrogen demand starting with 8 metric tonnes per day (MTPD) for ground vehicles by 2025, scaling to 60 MTPD for aircraft by 2035. The paper explores three hydrogen supply scenarios—off-site production and delivery, pipeline supply with on-site liquefaction, and local production—and highlights the need for energy availability, land, and gradual scaling. It calls for interconnected hydrogen airport networks to align with ARCHES' hydrogen ecosystem vision, enabling decarbonization across multiple transportation modes.

2.6. Fuel Supply Infrastructure Readiness

The infrastructure needed to supply hydrogen to airports and deliver to aircraft consists of:

[61] Vertical Flight Society, H2-Aero, “Multimodal Hydrogen Airport Hub,” available at: https://vtol.org/files/dmfile/h2-aero-whitepaper--multimodal-h2-airport-hub-2022_public-final.pdf

- Hydrogen production and storage facilities
- Hydrogen distribution and transportation from the production facility to airports
- Hydrogen fueling infrastructure for supply from airport storage to aircraft

Hydrogen Production and Storage Facilities

Currently a few large hydrogen producers located in California produce hydrogen from fossil fuels using steam methane reforming of natural gas. The off-takers generally use it for refining petroleum and processing foods. For the hydrogen production and storage industry to be ready to support the aviation sector, industry will need investment in infrastructure to produce clean hydrogen using renewable energy sources or perhaps carbon capture and storage (CCS) if from biogenic sources. Companies have already announced a number of large clean renewable hydrogen production projects in California,[62] which means that supply could potentially be in place by the time demand materializes.

Liquid Hydrogen

Although the announced projects do not mention the inclusion of liquefaction as part of the infrastructure investment, the production of liquid hydrogen will be critical for the operation of hydrogen powered aircraft. If the distribution of liquid hydrogen by truck is the most economical mode of hydrogen transport between the production facility and an airport, these facilities may therefore require additional investment in liquefaction at the production site. However, if transportation of hydrogen by truck or pipeline is economically the preferred option then the liquefaction would need to take place at or near the airport. Depending upon the most economical mode of hydrogen transport, these facilities may therefore require additional investment in liquefaction at the production site or the airport. These types of facilities are currently only found in industrial settings, and they can have a capital cost of up to $70M for a 30 tonne per day production rate (which would be sufficient to refuel about 10 narrow body aircraft).[63] They would require a footprint of approximately 20,000 sq ft for a 30 tonne per day facility. They also need to operate 24/7 and consume about 11 to 14 MW of power.

Methods of Hydrogen Distribution/Transportation

In the early stages of deployment in the aviation sector, transporting gaseous or liquid hydrogen by truck is the most likely method of delivering hydrogen to airports across

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[62] Linde, *Linde to Increase Green Hydrogen Production in California*, January 2023, available at https://www.linde.com/news-media/press-releases/2023/linde-to-increase-green-hydrogen-production-in-california; SGH2 Energy Projects, https://www.sgh2energy.com/projects/#proheader; Lancaster Clean Energy Center, https://www.elementresources.com/our-projects/lancaster-energy-center/

[63] Office of Energy Efficiency & Renewable Energy, DOE Technical Targets for Hydrogen Delivery, available at https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-delivery

the state. The technology for trucking gaseous and liquid hydrogen is well-developed. The trucks can cost up to $1M each, while depending on the demand level at an airport and the distribution distance, a fleet of 10s or 100s might be required. These will also generate operational costs for maintenance and workforce.

For larger airports that are close to urban centers, this transport will become impractical as demand for hydrogen increases. In this case, the options are to:

- deliver gaseous hydrogen to airports by pipeline
- produce clean hydrogen at or adjacent to the airport

Both options require liquefaction at or near the airport.

Pipeline Delivery

Developers often favor gaseous hydrogen pipelines over liquid hydrogen delivery for cost-effectiveness, scalability, and operational simplicity. Gaseous hydrogen pipelines operate at high pressure but do not require cryogenic temperatures, making them more practical for continuous delivery over long distances. The distribution of hydrogen gas by pipeline is a standard technology, with approximately 1,600 miles of hydrogen pipelines currently operating in the United States (including 30 miles in California). In the case of supplying hydrogen gas by pipeline to airports, the feasibility will depend upon an airport being able to install a low pressure distribution gas pipeline to link into a local high pressure transmission pipeline. These pipelines do not currently exist in California, although SoCalGas is currently planning Angeles Link, which is an open access pipeline system dedicated to public use that would transport clean renewable hydrogen to Central and Southern California.[64] Similar projects would be needed in Northern and Central California for airports in these regions to be able to connect to a reliable source of gaseous hydrogen.

Production of Hydrogen by Electrolysis at the Airport

In the case of producing hydrogen at an airport with electrolysis, the supply infrastructure will consist of electricity and water. Producing the hydrogen required to fuel 10 metric tonnes per day (at 1.2MW/MT) would be approximately 12 MW. Hydrogen liquefaction would also add energy to this equation with an additional 2MW needed (assuming 13 kwh/kg H2). This may require a significant increase in electric capacity allocation to airports (the permitting process for on-site hydrogen production at airports is beyond the scope of this report but likely to be complex and an important topic for further research).

[64] SoCalGas, *Angeles Link: Shaping the future with Clean Renewable Hydrogen*, available at https://www.socalgas.com/sustainability/hydrogen/angeles-link

Pyrolysis, another means of hydrogen production

There are other means to produce hydrogen with low carbon intensity, but low energy usage such as with a process called pyrolysis. In the pyrolysis process, methane (CH_4) is separated directly into hydrogen and solid carbon at very high temperatures in the absence of oxygen–the latter is much easier to handle than the gaseous CO_2 produced in steam reforming. It can be used in its solid form in various production processes or safely deposited.

The pyrolysis of biomethane, biomass, waste or wastewater with subsequent storage of the solid carbon is a negative emission technology, since the carbon dioxide previously removed from the atmosphere and neutralized in the biomethane is not released again during the pyrolysis reaction and the use of the hydrogen produced, and thus no climate-damaging greenhouse gas effects are produced. The solid carbon black that results in the pyrolysis process may need to be transported away from the site and/or changed into a new product onsite.

2.7 Milestones for Hydrogen and Hydrogen-Derived SAF Adoption

Market Entry & Aircraft Technology

Several companies, including Airbus, ZeroAvia, and Beyond Aero, are advancing hydrogen-powered aircraft, with certification efforts underway in the U.S. and U.K. Initial models will retrofit smaller airframes (<100 passengers) with hydrogen fuel cells, with ZeroAvia's Cessna Caravan targeted for 2027 and ATR-72-sized powertrains by 2030. Airbus aims to introduce a hydrogen-powered commercial aircraft by 2035, while Boeing continues hydrogen propulsion demonstrations but has not announced specific plans.

Achieving these timelines requires advancements in key subsystems:

- Hydrogen Fuel Cells: A 70+ passenger aircraft will require fuel cells with a 2 MW+ output, needing development by 2024-2026.
- Hydrogen Storage: Liquid hydrogen, preferred for aviation due to efficiency, must be demonstrated in flight by 2027 for mid-2030s deployment.
- Hydrogen Combustion Engines: Essential for extended range, these must undergo flight demonstrations before 2030 to meet a 2035 entry into service.

The FlyZero project, funded by the UK government, has developed longer-term technology roadmaps on these subsystems out to 2050.[65]

Infrastructure & Operations

The planning and implementation of hydrogen infrastructure at airports in California will need to be aligned with the timelines for the availability of:

- hydrogen-fueled aircraft from aircraft manufacturers and their introduction into operation by airlines; and
- sufficient quantities of low- or zero-carbon liquid or gaseous hydrogen that can be supplied to airports.

In addition to these key milestones, which are largely outside the control of airports, other areas of development that will need to be undertaken and completed in parallel include:

- **Fixed & Mobile Equipment:** Large-scale liquid hydrogen storage (1,000+ tons), refueling vehicles, and hydrant systems. The California Energy Commission (CEC) has funded ZeroAvia's mobile hydrogen refueling project at Livermore Airport.
- **Standardization & Safety:** Industry-wide refueling standards, safety codes, and regulatory frameworks are under development by organizations such as SAE International and ASTM.
- **Operational Considerations:** Workforce training, airline operational adjustments, and refueling management systems will be critical.

Stakeholder Engagement & Business Development

Successful adoption will require collaboration among policymakers, regulatory agencies (FAA, CARB, CEC, Caltrans, CalSTA, and GO-Biz), airports, airlines, hydrogen suppliers, and affected communities. Multi-party agreements will be needed to finance and deploy infrastructure efficiently.

Infrastructure Implementation Strategy:

The following factors need to be considered when planning the implementation of hydrogen infrastructure at airports:

- Demonstration Projects: Small-scale hydrogen installations, including fuel cell ground support equipment and buses, should be introduced early.
- Incremental Expansion: Hydrogen supply options and infrastructure should scale with aircraft deployment while minimizing stranded capital.

[65] Aerospace Technology Institute, *Flyzero*, available at https://www.ati.org.uk/flyzero/

- Long-Lead Item Procurement: Key components such as compressors, storage tanks, and electrolyzers should be ordered well in advance.
- Alignment with ARCHES Hydrogen Hubs: Infrastructure rollout should synchronize with regional hydrogen production and distribution networks.

The complexity of aligning all of these timelines is significant. If hydrogen-powered aircraft at the regional and narrow body level of size enter into service in the late 2020s and early 2030s, then many of the tasks identified above should commence in the next few years, particularly the introduction of hydrogen powered ground support equipment and buses, and the development of technical areas of the infrastructure system, such as refueling vehicles and hydrant networks/dispensing vehicles.

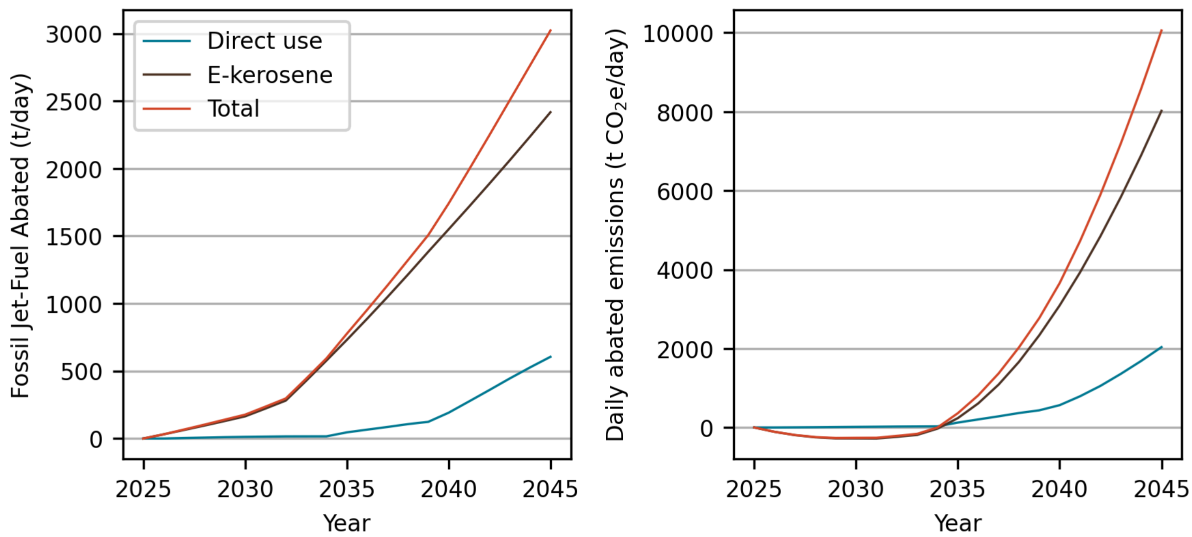
Section 3: Expected Impact of Hydrogen Uptake in Aviation

3.1. Fossil Jet-Fuel and CO_2 Emissions Abated

The deployment of hydrogen infrastructure at eight California airports could propel a notable reduction in fossil jet-fuel use and associated carbon emissions. Flights of hydrogen aircraft on replaceable routes and the acceleration of e-kerosene use would allow for lowered jet-fuel consumption across these airports.

To assess these impacts, contributors to this report considered the net fossil jet-fuel and carbon emission abatement resulting from the introduction of hydrogen aircraft, increased hydrogen production, and e-kerosene use and production. The resulting abatement trajectory can be seen below in Figure 6, growing to a combined abatement of over 3,000 tonnes of fossil jet-fuel abated per day in 2045.

Figure 6. Projected Fossil Jet-Fuel and CO_2 Emissions Abated from California Airport Hydrogen Infrastructure from 2025-2045



The CO_2 emissions abated from this shift in fuel usage are characterized as the net sum of the emissions abated from fossil jet-fuel and emissions released during the production of liquid hydrogen and e-kerosene. The production is assumed to be from California's grid electricity, which in 2020 had a carbon intensity of 83 gCO_2e/MJ and is expected to be fully decarbonized by 2045.[66] The researchers projected the total abated CO_2 emissions to be over 10,000 tonnes CO_2e/day in 2045.[67] As the electricity grid decarbonizes, these production emissions will decrease while abated emissions will increase.

3.2. Technical and Operational

As referenced previously, experts expect liquid hydrogen to be the preferred state of hydrogen to fuel aircraft due to its higher energy density. Most operational aspects, from fuel delivery to the airport to the refueling process at the gate, will therefore require significant changes to existing airport operations to accommodate hydrogen-powered aircraft.

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[66] CARB, *California Average Grid Electricity Used as a transportation fuel in California*, 2020, available at https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/comments/tier2/elec_update.pdf; Reference for 2045 fully renewable target

[67] Mukhopadhaya, J., & Pavlenko, Ni, *Life Cycle Emissions of the Decarbonization Options for Aviation, EM Magazine-pg 20* (2023), available at https://online.1stflip.com/dsup/3m93/; For simplicity, this analysis assumed the energy mix in 2045 to be 50% wind energy and 50% solar energy, resulting in a grid carbon intensity of 8.1 g CO_2e/MJ. The carbon intensity is assumed to vary linearly in the years in-between. The production intensity of liquid hydrogen and e-kerosene was assumed to be 122 gCO_2e/MJ and 180 gCO_2e/MJ respectively in 2025 and, through linear improvements in conversion efficiency and decarbonization of the electricity grid, 12 gCO_2e/MJ and 13 gCO_2e/MJ respectively in 2045. Moomaw, W., et al, *Annex II: Methodology. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, IPCC, 2011, available at https://www.ipcc.ch/site/assets/uploads/2018/03/Annex-II-Methodology-1.pdf

Refueling Aircraft

Initial refueling of hydrogen aircraft will likely be carried out using mobile refueling trucks, similar to how conventional refueling occurs today. To meet the turnaround times of conventional aircraft, the refueling hoses will need to be significantly larger in diameter and heavier. This larger diameter is due to the higher volume, reducing heat transfer and to insulate from the cryogenic temperatures of liquid hydrogen, which require larger diameter and insulated hoses. This change will in turn necessitate the automation of the refueling process (e.g. articulated arm), as industry will require refueling flow rates of up to 84 kg/minute for regional aircraft, and up to 200 kg/min for narrowbody-sized aircraft as described in AIR8466.[68] Even with larger hoses, bigger aircraft will likely need two or more hose attachments to meet the flow-rate requirements and the 20-30 minute refueling times.

Safety

Safety procedures and quantitative risk assessment around hydrogen handling will determine if ground operations, such as passenger loading and unloading, can happen concurrently with refueling. If safety concerns prevent parallel operations, the turnaround times for the aircraft could be significantly increased.[69] This delay would likely reduce the flights that are possible per day and adversely impact revenue for the aircraft operator.

3.3. Water and Energy Advantages

According to a study by Staples, the amount of water used in the production of hydrogen (approximately 10 L/kg) is less than that used in the production of conventional jet fuel or rainfed biomass-derived SAF (via Fischer-Tropsch), despite perceptions to the contrary. The lifecycle freshwater consumption is up to 0.217 L water/MJ for jet fuel and 0.523 L water/MJ for HEFA SAF respectively, while hydrogen uses 0.117 L water/MJ.[70] Hydrogen offers further environmental advantages over drop-in fuels, particularly when used in fuel cells, as discussed in Section 2. PtL production will likely require 3x the energy needed to produce LH_2.

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[68] SAE AIR 8466, Hydrogen Fueling Stations for Airports, in both gaseous and liquid form, 2024 https://www.sae.org/standards/content/air8466/

[69] McKinsey & Company, *Hydrogen-powered aviation A fact-based study of hydrogen technology, economics, and climate impact by 2050*, Clean Skys 2 JU, 2020, https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf

[70] MIT, *Water consumption footprint and land requirements of alternative diesel and jet fuel*, https://dspace.mit.edu/handle/1721.1/81130

3.4. Community and Social Impacts

Environmental Benefits

The introduction of hydrogen aircraft and hydrogen-derived SAF in California could have both positive and negative community and social impacts. One of the significant benefits will be the potential for global warming abatement. Hydrogen aircraft produce zero carbon emissions during flight, while SAFs can produce net-zero carbon emissions, both of which will help reduce the state's overall greenhouse gas footprint and contribute to California's ambitious climate goals.

The use of hydrogen can also help mitigate pollutants and air quality concerns across all aircraft operations including taxi, takeoff, initial climb and during the approach and landing. Traditional fossil jet fuel combustion emits pollutants such as nitrogen oxides (NO_x) and particulate matter, contributing to local air pollution. Hydrogen fuel cells by contrast emit only water vapor, eliminating these harmful emissions. They also offer significant noise reduction for airport-adjacent communities. Hydrogen combustion could reduce particulate matter emissions across the flight cycle with approximately 90 percent of aircraft emissions occurring higher than 3,000 feet above the ground. This reduction can result in improved air quality near airports and surrounding communities, leading to better respiratory health and a higher quality of life for residents.

Infrastructure and Land Use Changes

Yet the introduction of hydrogen aircraft could also have infrastructure impacts on communities. Establishing the necessary infrastructure for hydrogen production, storage, refueling at airports and production capacity for SAF will require significant investment and land use changes. This deployment could potentially impact nearby communities by necessitating land acquisition, increased truck transport, and/or construction activities. Under the California Environmental Quality Act (CEQA), such projects would likely require environmental review to assess potential impacts on air quality, noise, traffic, land use, and public health and mitigate them where feasible.[71]

Policy makers will therefore need to engage in transparent and inclusive dialogue with affected frontline communities to address concerns, mitigate potential disruptions, and ensure that the infrastructure development process takes into account community needs and preferences. Developers will also need to build this infrastructure to high standards to manage leakage of hydrogen.

[71] Governor's Office of Land Use and Climate Innovation, "CEQA: The California Environmental Quality Act", available at https://lci.ca.gov/ceqa/

Economic and Workforce Opportunities

At the same time, the introduction of hydrogen aircraft or development of a SAF industry could bring economic opportunities to local communities, including jobs in the construction, manufacturing, and maintenance sectors of hydrogen infrastructure. Additionally, California has been at the forefront of hydrogen technology and innovation, which can attract investment and research opportunities, contributing to local economic growth and technological advancement. Hydrogen fuel cell powertrains offer the additional benefit of reduced noise during takeoff and landing—another compelling factor for communities situated near airports.

Section 4: Challenges

4.1. Technical

Transporting Liquid Hydrogen

In the initial phases of hydrogen adoption, long-distance transport of liquid hydrogen will play a critical role due to a lack of local hydrogen production facilities. However, this approach presents significant challenges. Liquid hydrogen trailers, while commercially available today and capable of transporting 4.5 tons per load, require specialized infrastructure and careful handling due to the cryogenic temperatures involved. Additionally, airport fuel suppliers will need dedicated dispensing vehicles to transfer liquid hydrogen from the supply trailers to aircraft fuel tanks, adding complexity and cost to the refueling process. Scaling this system will depend heavily on overcoming these logistical and infrastructure hurdles.

Liquid Hydrogen Storage Tanks

The provision of liquid hydrogen storage at the volumes needed at airports is technically feasible today. The NASA sphere at Kennedy Space Center in Florida currently holds 330 Metric tonnes today. As a comparison, a relatively small $10m^2$ footprint (108 ft^2) would hold 30 tonnes of hydrogen. These examples however are not widespread and CAPEX is still significant. However, when the majority of aircraft are hydrogen (especially at larger airports) the size of liquid hydrogen storage may need to increase significantly to accommodate a few days of storage, (e.g. 1400-2800 metric tonnes) as described in the VFS Multimodal Hydrogen Airport Hub.

Airframe Integration of Hydrogen Storage

Existing tube-and-wing airframe designs rely on integrated fuel tanks within the wings of the aircraft, which serve the dual purpose of relieving the bending moments experienced at the fuselage-wing empennage and maximizing the fuselage volume available for the passenger cabin. Hydrogen, on account of requiring compressed or cryogenic storage, necessitates bulky storage tanks, which preclude storage within the wing. Instead, it will need to be stored within the fuselage, which reduces the volume available for the passenger cabin and results in a lower passenger capacity than conventional jet-fueled aircraft.

A number of companies are currently working on retrofit designs for hydrogen fuel cell propulsion systems with integrated Hydrogen storage and management systems to be put on existing airframes. This includes hydrogen in both gaseous and liquid forms.

Hydrogen Propulsion Technology

The two propulsion technologies of hydrogen fuel cells and hydrogen combustion each have their set of challenges. Proton Exchange Membrane (PEM) fuel cell propulsion is more efficient and mature than hydrogen combustion, but it provides a lower specific power and peak power output. Contrary to hydrogen combustion engines that can expel the heat generated in the form of exhaust gasses, fuel cells have additional cooling challenges. However, in 2023, deployment of High-Temperature PEM (HTPEM) fuel cells emerged as a likely solution, as indicated by recent industry, NASA and DOE investments. Future developments in high temperature PEM or HTPEM projects are just starting to be demonstrated in aviation. HTPEM holds the promise of both high efficiency and power, with less cooling requirements and a concept is planned to be demonstrated by 2025[72].

Hydrogen combustion engines can leverage decades of gas-turbine technology development to power bigger aircraft–the principles of operation are like those of conventional jet-fueled turbine engines. However, they require a redesign of the fuel-injection system and the combustion chamber. By burning hotter than jet fuel and causing embrittlement in certain materials, the engines will also require revisiting the materials used to construct them. They still have NOx emissions however.

Currently, no hydrogen combustion turbine engines exist that can fly. This lack of deployment means a long timeline path through research and development until flight certification for this technology becomes available. Airbus is working in partnership with engine OEMs on the development of a hydrogen combustion engine.[73] Several engine OEMs, including GE Aerospace, Pratt & Whitney, and Rolls Royce, are also developing hydrogen combustion engines but with unannounced entry-into-service targets.

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[72] Piasecki targets first crewed flight of hydrogen-powered helicopter this fall https://verticalmag.com/news/piasecki-targets-first-crewed-flight-of-hydrogen-powered-helicopter-this-fall/

[73] Airbus, Airbus reveals hydrogen-powered zero-emission engine, November 2022, https://www.airbus.com/en/newsroom/press-releases/2022-11-airbus-reveals-hydrogen-powered-zero-emission-engine

4.3. Siting and Safety Considerations

Infrastructure Siting/Operation

The siting and operation of the above-referenced infrastructure deployment implicates airport operational procedures and how the “license to operate” is given by regulators and the public.

As is the case for existing fuels currently available for airports, delivery, liquefaction, and storage infrastructure will be located far from airport areas where passengers and airport staff are present. Industry leaders will need to design these infrastructure elements to comply with codes and standards relating to clearances, boundary walls and operating procedures. A number of existing H2 standards exist for the key infrastructure elements and are identified in Appendix A and could be used. Also any gaps in existing standards need to be identified. A number of groups such as SAE and ASTM are actively working on these guidelines to address some of the gaps in existing standards such as LH2 refueling /couplings and H2 quality standards for aviation use. Research into these topics is ongoing and could have implications for the design and operation of these facilities and systems at airports. In the meantime, however, local permitting latitude will be necessary to launch demonstration projects.

Public Perception and Consumer Education

Hydrogen is a relatively new technology and is not well-understood by the public. Stakeholders may be apprehensive and skeptical due to the novelty of hydrogen aircraft and airport technology. This reaction may be particularly true for new aircraft designs (for example, the “Flying-V”) that look radically different from today’s aircraft.

Finally, safety concerns and the perception of hydrogen as a potentially volatile and flammable substance might lead to some reservations among airport workers and the public. Therefore, stakeholders should engage in effective communication and education campaigns to address these concerns, discredit misapprehensions, highlight the safety measures in place, and emphasize the positive environmental benefits of hydrogen aircraft.

Equity and Research and Development, System Development and Operation

Introducing hydrogen aircraft at airports raises important equity considerations. Access to this technology should be inclusive, ensuring that the benefits are not limited to a select few. At the same time, the clearest air quality beneficiaries of hydrogen aviation will be airport-adjacent communities, many of which are at a socioeconomic disadvantage and have suffered negative health and quality of life impacts from airport activity.

The scale of hydrogen for aviation should also mean job creation for the state, with careful attention needed to ensure equitable access to those economic benefits. By prioritizing equity in the implementation of hydrogen aircraft, policy makers can strive for a more just and inclusive aviation system.

Safety Risks

The introduction of hydrogen aircraft at airports should necessitate a comprehensive assessment of health and safety considerations. While hydrogen itself is a clean and non-toxic fuel, airports will need to ensure safety measures are in place to address potential risks associated with hydrogen storage, handling, and refueling infrastructure and operations.

The risks related to storing, distributing and refueling with liquid hydrogen in industrial and aerospace settings are well known, with available mitigation measures that can manage them. The difference in the use of liquid hydrogen at airports is the potential proximity of passengers and airport staff to a risk event. This proximity is likely to mean that safety regulations and the expectations of safety regulators should reference the SAE and NFPA Standards work being developed for this application.

4.4. Workforce

California's aerospace and aviation sector currently employs 64,200 people in non-management occupations, across the roles highlighted in Figure 9. This total represents roughly 14% of employment in these occupations across the United States, and 0.4% of all in-state employment.

Figure 7. Aerospace and aviation sector employment in CA, in 1,000s of people[74]

[74] U.S. Bureau of Labor Statistics, *May 2022 State Occupational Employment and Wage Estimates*, 2022, https://www.bls.gov/oes/current/oes_ca.htm#49-0000

Upskilling is essential to support the development, operation, and maintenance of hydrogen- and SAF-powered aircraft, alongside upstream fuel infrastructure. This transition will require training, safety procedures, educational programs, and supply-chain collaboration.

Skills and Training

Due to their 'drop-in' nature, increased uptake of HEFA and PtL synfuels will not require any changes to incumbent jet-propulsion aircraft or to much of the fuel supply and dispensing technologies. While a future increase in SAF blend percentages and upstream production capacities may require new technology development (and therefore expertise), the workforce transition requirement for SAF will be far less than for hydrogen-based propulsion. As a result, the focus of these recommendations will be solely on skills and training requirements for hydrogen use in aviation. A transition to hydrogen-powered aviation will require training and upskilling for two main workforce groups:

- **Upstream:** The personnel focused on building, operating, and maintaining the upstream hydrogen infrastructure including production facilities, distribution networks, storage systems, and refueling
- **Aircraft:** The personnel tasked with developing, operating and servicing the aircraft themselves

To meet the requirements for a workforce to deliver, operate and maintain hydrogen powered aircraft,[75] and assuming that liquid hydrogen will be the dominant future

[75] Upstream workforce challenges and considerations will be covered in the ARCHES Production working group whitepaper (TBC)

hydrogen-fuel pathway (due to energy density advantages), the industry will need new skills and training across areas, such as propulsion (hydrogen-gas turbines and fuel cells), aircraft systems and structures.[76]

In the short-term (i.e., next 5 years), novel skill development will be required in the earlier stages of the hydrogen aircraft product lifecycle, namely new materials development and assessment and design and validation of systems, sub-systems, and components. This process will require highly skilled engineers and researchers with the capability and knowledge in three disciplines combined together — Cryogenics (LH2 Physics), LH2 system design, and Fluid & Thermodynamics— to develop new design methods, specify the LH2 equipment and component, and to design the next generation of hydrogen fuel cells, electrical systems, gas turbines, cryogenic fuel distribution and storage systems, hydrogen heat exchangers, and hydrogen detection and safety systems. The workforce will also need to be able to integrate these subsystems and components onto aircraft and carry out rigorous testing protocols to ensure material and component integrity and consistent optimal and safe operation.

In the longer term (5+ years), a workforce with new skills will be required for manufacturing and maintenance of hydrogen aircraft. This workforce will need to include not only engineers and researchers, but also technicians, engineers, and operators with the capabilities to produce and maintain hydrogen fuel cells, combustor components, integrated sensors and wider hydrogen aircraft sub-systems and structures (e.g., integrated systems, liquid hydrogen storage, etc.).

Beyond development and maintenance of the aircraft, industry leaders will also need upskilling and retraining across a number of crucial roles, including the pilots that operate the aircraft, the ground support staff that fuel and service the aircraft, the airfield operations staff and air traffic controllers, and the workers that handle cargo. Furthermore, cross-cutting skills, capabilities and knowledge will be required in the wider workforce to enable successful delivery of hydrogen aircraft, including sustainability practices (life cycle analysis and end-of life management), digital skills (for development of tools to support design, production and maintenance), safety certification knowledge, and automation and robotics for production.

Workforce Safety

While many sectors use hydrogen, its unique properties pose safety risks in aviation. Without proper management at all product lifecycle stages, safety incidents could

[76] Aerospace Technology Institute, *Workforce to Devliver Liquid Hydrogen Powered Aircraft,* March 2022, www.ati.org.uk/wp-content/uploads/2022/03/FZO-IST-PPL-0053-Workforce-to-Deliver-Liquid-Hydrogen-Powered-Aircraft.pdf

hinder the hydrogen economy. However, with careful design and planning, hydrogen systems can achieve safety levels comparable to traditional fuels.

Gaseous hydrogen is stable but highly flammable, with risks of fire and explosion, especially at high altitudes. It can safely be stored at ambient temperatures, but concerns arise from its low ignition energy and rapid combustion. Adequate ventilation and detection systems are crucial to prevent hazards from leaks. Additionally, transporting hydrogen under high pressure or in cryogenic form introduces further safety risks.

Section 5: Recommendations

5.1. Policy Recommendations

Federal

Several state and federal policies can help nurture a nascent hydrogen aviation sector. Initially at the federal level, a set of policies that level the playing field with SAF will help advance hydrogen as a direct aviation fuel, whether for combustion or in fuel cell electric powertrains. As Congress pursues a reauthorization of the FAA, it can open a clearer pathway for hydrogen, and both the House bill that passed overwhelmingly on July 20, 2023 and the Senate bill that emerged unanimously from committee take steps in that direction.[77] In May 2024, President Biden signed the bipartisan Securing Growth and Robust Leadership in American Aviation Act to advance the development of hydrogen fuel for aviation into law.[78] It requires the agency to research hydrogen fuel for aviation, consult with industry, and establish an advisory committee to develop recommendations on the adoption of hydrogen fuel in aviation. The new law directed the FAA to open its Aviation Sustainability Center (ASCENT) R&D program to hydrogen research projects and its Continuous Lower Energy, Emissions, and Noise (CLEEN) research program to new entrants. Further, it opened the FAA's Airport Improvement Program (AIP) to airport energy improvements, including hydrogen projects. Finally, it directed the FAA to work with other federal agencies on a strategy to integrate hydrogen aviation into the national airspace and to then implement that strategy.

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[77] Key U.S. Senate Committee Passes Sen. Ossoff, Rep. Johnson's Bipartisan Bill to Advance Adoption of Hydrogen Energy for Aviation, available at https://www.ossoff.senate.gov/press-releases/news-key-u-s-senate-committee-passes-sen-ossoff-rep-johnsons-bipartisan-bill-to-advance-adoption-of-hydrogen-energy-for-aviation/

[78] Atlanta Journal-Constitution, 'Bill backed by Georgia lawmakers to boost hydrogen aviation fuel now law' (June 2024), available at: https://www.ajc.com/news/business/faa-bill-includes-hydrogen-fuel-measure-proposed-by-ossoff-and-johnson/2422ARBDNBFYHE643OKGETJHOM/#

The FAA Reauthorization Act of 2024 mandates the development of airworthiness standards for hydrogen-fueled propulsion systems, including both combustion and fuel cell technologies. This directive aims to prevent the prolonged certification processes experienced by electric vertical takeoff and landing (eVTOL) aircraft, which have previously hindered industry scaling. The Act emphasizes the need for an efficient certification process and directs the FAA to enhance its workforce's expertise in hydrogen technologies. Specifically, the FAA is tasked with advancing certification efforts for hydrogen technologies and exploring grants and loan guarantees to facilitate their adoption.

Stakeholders, including California's governor, congressional delegation, and other state leaders could help lead the advocacy for a certification process that neither caters toward the nascent hydrogen aviation industry nor blocks its entry into service.

California State

California has explored policy avenues to promote hydrogen and sustainable aviation fuel (SAF) through recent legislation. Assembly Bill 1322 (2022), which Governor Newsom vetoed, sought to create an incentives-based plan for SAF adoption. Second, SB 1291 (Archuleta), signed into law in 2022, streamlined permitting for hydrogen fueling stations but only for "vehicles," leaving aircraft refueling in a legal gray area. Policymakers could clarify or expand this protection, especially as airport ground support equipment is already covered. Below are the tech maturation and greenhouse gas reduction policy recommendations:

Technology Maturation Policy Recommendations

To help accelerate the technology development, state leaders could consider adopting the following policies:

1. **State legislative and agency leaders could collaborate with industry organizations and other stakeholders to develop and adopt relevant standards and policies** for airport hydrogen storage, distribution, and refueling infrastructure, along with aircraft and ground support equipment.
2. **CEC leaders, with support from CARB and relevant safety and planning agencies, could promote the deployment of commercial low-carbon hydrogen infrastructure** to allow the technology to mature. Airports in particular may be good candidates as local hydrogen industry centers. In the context of California, specific airports recommended in this whitepaper are found in Section 3.2. These airports not only handle substantial air traffic but also play pivotal roles in the state's transportation and economic landscape, making them strategic choices for advancing low-carbon hydrogen infrastructure.

3. **The California Infrastructure and Economic Development Bank (IBank), and other investment-focused state agencies could de-risk capital investments in novel technology at commercial scale**, including through loan guarantees, contracts-for-difference, advance market commitments, and project insurance, among others. For example, IBank's Climate Catalyst Fund aims to bridge financial gaps that prevent advanced technologies from scaling into the marketplace, and to accelerate the speed and scale at which technologically proven, critical climate solutions are deployed.[79]

Greenhouse Gas Reduction Policy Recommendations

To ensure maximal reductions in greenhouse gas emissions from hydrogen-based aviation fuel policies, state leaders could consider the following actions:

1. **CARB could adopt a stronger life-cycle analysis methodology for low-carbon fuels** with strict additionality tests and consideration of indirect effects. The low carbon fuel standard is likely to be the primary forum in which issues relating to greenhouse gas assessment evolve. At present, the low carbon fuel standard recognizes zero-carbon electricity by requiring the retirement of Renewable Energy Certificates (RECs) into an account created for this purpose. This accounting helps minimize the risk of double-counting. However, it is insufficient to adequately ensure that processes using the zero-carbon electricity live up to claimed carbon reductions. Adding phased-in requirements for time-matched supply, deliverability, and additionality (i.e. ensuring that RECs from projects developed for RPS or other policy compliance are not double-counted as providing zero-carbon electricity to a hydrogen project) would help.
2. **CARB could incentivize the use of low-carbon hydrogen as an input to liquid SAF production** (HEFA, power to liquid or PtL, etc.) or other chemical/industrial processes, as well as for direct hydrogen consumption by aircrafts. Hydrogen production and distribution will benefit from increased demand regardless of the specific sector, given that it will lead to critical economies of scale and technological efficiencies. To the extent that SAF policy can incentivize or require the use of low-carbon hydrogen, it can help begin the development of these economies of scale and move associated technologies towards maturation.
3. **California State Transportation Agency (CalSTA) and metropolitan planning organizations (MPOs) could consider the contribution of hydrogen-powered aircraft in long-term inter-regional transportation planning** (e.g. California Corridor). Additional research is required to understand likely long-term travel behavior for long-distance (e.g. Northern California to Southern California) travel.

[79] IBank, *Climate Catalyst Program*, https://www.ibank.ca.gov/climate-financing/climate-catalyst-program/

If low-carbon hydrogen aviation displaces conventional petroleum aviation along these routes, it can help reduce in-state emissions from transportation and meet long-term climate goals.

5.2. Finance and Investment Recommendations

In the pursuit of advancing hydrogen technology within the aviation sector in California, policy makers could consider not only the technological advancements but also the financial and investment aspects that underpin its success. The recommendations outlined below present a comprehensive strategy for fostering the growth of hydrogen-powered aircraft and propulsion systems, as well as for creating a robust infrastructure to support this paradigm shift:

1. **CARB and CEC leaders could consider inclusion of aviation in California's low emissions programs**, such as the CEC's Clean Transportation Program, in order to accelerate hydrogen aircraft and propulsion timelines and help de-risk investment.[80] This program provides funding to support innovation and accelerate the development and deployment of zero-emission transportation and fuel technologies.
2. **CEC leaders could increase support for research, development and deployment and prioritize development of hydrogen aircraft and propulsion certification.**
3. **GO-Biz could facilitate hydrogen infrastructure network rollout** by working with California airports and local authorities to assess total infrastructure capital needs to meet hydrogen aviation demand.
4. **CARB could create a green-premium voucher program** like HVIP for aviation fleet renewal with hydrogen-fueled aircraft powertrains to encourage adoption of hydrogen-powered and other low-carbon aviation technologies. Such a program could be technology-agnostic and base its voucher percentages based on carbon-reduction, thereby reducing opposition that might be based on the State "picking winners."
5. **GO-Biz and industry leaders could leverage ARCHES funding** to help build capacity and accelerate private capital investment, including through targeted outreach, which could increase awareness of available incentives among industry leaders and investors, as well as of their 'stackability' to investors and developers for both PtL and hydrogen.
6. **GO-Biz and ARCHES could consider funding pilot airports with pilot routes between them** to demonstrate the viability of– and increase the visibility of–

[80] CEC, *Clean Transportation Program*, https://www.energy.ca.gov/programs-and-topics/programs/clean-transportation-program

hydrogen aviation. Beginning with flights aboard experimental certificated aircraft and evolving to certified aircraft as industry obtains those certifications. This would also help familiarize the public with the prospect of hydrogen-enabled airports and hydrogen-powered air travel, about which there will likely be both curiosity and concern.

7. **State, airport and industry leaders could pursue federal funding via existing grant programs** like the Federal Aviation Administration's Fueling Aviation's Sustainable Transition via Sustainable Aviation Fuels (FAST-SAF) and Low-Emission Aviation Technologies (FAST-Tech) Grant Programs, and encourage all California airports to include a focus on hydrogen infrastructure in their planning processes.

5.3. Industry Action and Collaboration Recommendations

Stakeholders and policy leaders will need to coordinate to implement the demonstration projects discussed earlier in this document. Without federal or state incentives or leadership, hydrogen aviation in California will likely need to begin with first movers from the hydrogen demand side. These might include airports considering adoption of hydrogen technology for ground services equipment or airlines/operators considering hydrogen aviation routes, the earliest of which will likely be fueled by gaseous hydrogen. Below are some recommendations for industry action and collaboration:

1. **Airport leaders could empower forward-thinking executive teams to recruit producers based on price, proximity, and availability of zero-emission hydrogen to meet the needs of their operator-customers.** If airports are unwilling to take the lead based on cost and complexity, a key airline/operator could help encourage a less-than-enthusiastic airport into a coalition to move forward, as well as potentially recruit hydrogen infrastructure experts to connect them with hydrogen production.
2. **Hydrogen-engaged manufacturers like Airbus, Joby, and ZeroAvia could help facilitate coordination across the industry**, including by helping to de-risk investments by otherwise reluctant operators, providing a new market for hydrogen availability at airports favored by their target customer-operators. As an example, aviation manufacturers were engaged in DOE Hydrogen Hub applicant consortia across the country, from Maine to Hawaii.
3. **Airports and aircraft manufacturers could collaborate with airport-proximal enterprises and transit agencies with an interest in hydrogen offtake**, developing regional entities of sufficient scale to achieve enough demand (particularly as the

aircraft segment continues to develop) to enable price-competitive hydrogen supply.

4. **Industry partners with standards groups, like SAE, could address any gaps that exist in existing H2 codes and standards**. Initial demonstration projects will otherwise require more than the usual cooperation to achieve the success necessary to demonstrate hydrogen aviation going forward. These partners can also work together to ensure affordable airside access to hydrogen.
5. **Industry partners could collaborate to help develop the requisite skilled workforce,** as described in this paper. This will require working with community colleges, trade schools, and union training centers to plan and implement the necessary training programs and safety courses.

Similarly, industry partners, along with key agency and airport leaders, could plan, coordinate, and execute a community relations effort to address public concerns about local hydrogen use. While hydrogen aviation, as discussed previously in this paper, offers many benefits to neighboring communities, including reduced NOx, particulates, and noise, the novelty of hydrogen will require a considerable educational effort. If the partnership includes a willing airport, the airport's history with the community will play an important role in determining public relations outcomes.

5.4. Codes and Standards Recommendations

Policy makers can repurpose existing hydrogen safety codes and standards for airport use, but industry will need additional guidelines to fill gaps and facilitate the acceptance of hydrogen infrastructure and fuel cell aircraft. Federal regulators, like the FAA, may align with these certification requirements by adopting or coordinating their regulations with industry-developed safety and performance standards for hydrogen infrastructure and fuel cell aircraft, just as they currently do for conventional aviation fuels.

The certification reference for U.S. airports is 14 CFR Part 139, which outlines requirements for airports serving air carrier passenger operations. FAA Advisory Circulars provide compliance guidance, which refer to widely accepted standards (e.g., NFPA 407) for certification.

Key aerospace standards under development require support from industry and government. SAE International, in collaboration with EUROCAE, is producing standards for onboard hydrogen storage and fuel cell systems. They are also developing fueling standards for liquid hydrogen refueling, with an initial focus on small and regional aircraft.

While gaseous hydrogen (GH2) may be used for some small aircraft, industry leaders prefer liquid hydrogen (LH2) due to its energy density. The SAE/EUROCAE standards aim to achieve fast fueling times comparable to kerosene—about 100 kg in 10 minutes for small aircraft and 2,000 kg in 25 minutes for regional aircraft, potentially requiring new interface hardware.

Key recommendations include:

- FAA regulators, with industry support, could standardize hydrogen fueling codes for liquid hydrogen, evaluating it with the same safety distances as conventional fuels.
- The US Department of Transportation and FAA could consider a cross-sectoral approach to standardization at hydrogen hubs in airports.
- SAE International and government agencies could further develop key standards in ISO, SAE, and ASTM related to LH2 refueling, hydrogen quality, Aircraft Rescue and Fire Fighting (ARFF), and Ground Support Equipment, as detailed in the appendix.
- The National Fire Protection Association (NFPA) and International Civil Aviation Organization (ICAO) could use NFPA 2 as a general hydrogen technology code until NFPA 407 is updated with hydrogen-specific safety information, as the aeronautical community has recognized the need for such updates based on ongoing hydrogen tests at airports.

5.5. Technical Recommendations

Liquid Hydrogen Storage Tanks

The provision of liquid hydrogen storage at the volumes needed at airports is technically feasible today. However, when the majority of aircraft are hydrogen (especially at larger airports) the size of liquid hydrogen storage may need to increase significantly to accommodate a few days of storage. To address this challenge:

- **Industry leaders could increase the capacity of the current size of liquid hydrogen storage spheres** to build ultra-large spheres at large airports. Companies such as CB&I and Kawasaki have concept designs for tanks of this magnitude. However, their further development may require a government grant or a public-private partnership and is likely to take 5 to 7 years to complete.

Airframe Integration of Hydrogen Storage

Hydrogen's storage requirements necessitate fuselage tanks instead of wing tanks, reducing passenger cabin space and capacity compared to conventional jet-fueled aircraft.

- **build hydrogen-powered blended wing-body aircraft** to account for the volume constraint on future aircraft designs. There is one application for a blended wing aircraft starting in 2030 with SAF and upgraded thereafter to hydrogen.
- **Policy makers could encourage tank manufacturers to adopt lightweight construction of storage tanks** that can handle tens of thousands of duty cycles. Cryogenic tanks will need to be designed to handle certain levels of hydrogen boil-off without venting the gaseous hydrogen into the aircraft or atmosphere and potentially re-using it in on-board fuel cells. Designing the tank to handle higher pressures and not completely filling the tank with liquid hydrogen would solve this problem.

5.6 Siting and Safety Recommendations

Hydrogen Aerospace Codes and Standards

The large number of standards from multiple organizations highlights the critical need for harmonizing them and/or deciding on the most relevant standards/guidelines for airport applications.[81] (See Appendix A).

- **Airport authorities and standards organizations could harmonize hydrogen-related standards** across sectors (e.g., heavy-duty vehicles, power, maritime) to simplify collaboration and reduce administrative burdens for industries adopting hydrogen technologies.
- **Public-private partnerships could facilitate airport demonstrations** to generate data that can validate and refine hydrogen standards, as suggested in the VFS Whitepaper “Multimodal H2 Airport Hub.”
- **Federal Aviation Administration (FAA) could adapt or develop new aircraft regulations** specific to hydrogen-powered aircraft to enable their certification and integration into commercial aviation.

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[81] This section contains the status of key codes and standards relevant to airports and aerospace. A more complete list can be found in Appendix A. Established standards for ground vehicles from the Society of Automotive Engineers (SAE) and International Organization for Standardization (ISO) could also be applicable to specific ground applications for hydrogen at airports. Some fuel cell and hydrogen standards exist for aerospace such as SAE AIR8466 and there are a number in development for hydrogen aerospace applications from standards organizations (such as the SAE International and European Organization for Civil Aviation Equipment [EUROCAE] efforts).

Infrastructure Siting/Operation

The deployment of hydrogen infrastructure at airports raises challenges related to operational procedures, regulatory approvals, and public acceptance, requiring careful adherence to existing codes and standards for safety and operation.

- **Airport authorities could develop robust systems to manage key operational areas** including:
    - Airport security and hydrogen supply chain security.
    - Hydrogen leak detection systems and LH2 boil-off/flash gas management.
    - Designation of diversion airports for emergencies.
    - Emergency response preparedness, including rescue and firefighting, de-icing, and emergency response equipment and training.
    - Maintenance protocols, safety management procedures, and training programs for personnel.
- **Airlines could extend turnaround times to comply with potential safety constraints during hydrogen refueling**. Airlines may need this flexibility if safety regulators determine that risk events that could occur during the stages of hydrogen refueling are likely and would be more severe than the equivalent risks from refueling with kerosene.
- **Airlines could consider operational strategies to accommodate clearance distances for refueling**, including the potential use of dedicated remote stands if required by safety regulators. However, these outcomes are not certain at this stage, and with further research on refueling risks and the development of safety equipment and protocols, the impact of refueling on airline operations may not be significant.
- **Policymakers and hydrogen suppliers could define clear terms and conditions for contracts** for hydrogen procurement, including requirements for hydrogen quality, traceability, and inventory management to meet impending demand.

Public Perception and Consumer Education

Proactive education and communication tailored to specific audiences and communities can help address any concerns and improve public perception.

- **Policy makers could communicate the positive impacts of hydrogen use in aviation**, namely mitigating the climate impact of the sector and improving air quality at airports and in surrounding communities.Policy makers could anticipate a mixed public perception to the introduction of hydrogen aircraft at airports.

- Agency leaders could ensure t**ransparency and clear communication with the public** about the rigorous safety and approvals process necessary to build public support for hydrogen aircraft.
- **Industry leaders could engage in effective communication and education campaigns** to address these concerns, discredit misapprehensions, highlight the safety measures in place, and emphasize the positive environmental benefits of hydrogen aircraft.

Equity and Research and Development, System Development and Operation

Introducing hydrogen aircraft raises equity considerations, including ensuring broad access to benefits, minimizing cost burdens on consumers, addressing the needs of airport-adjacent disadvantaged communities, and preventing disproportionate impacts from hydrogen infrastructure.

- **Federal and state leaders, plus industry, could seek to minimize the potential cost burden on consumers** and ensure that air travel remains accessible to a wide range of socioeconomic groups, particularly because hydrogen aircraft may initially be more expensive to develop than conventional aircraft.
- **Policy makers could plan for a transition within the existing aviation workforce**, offering necessary training and skills development to workers to allow them to be part of the transition to hydrogen aviation.
- **Policy makers could consider the impact on communities surrounding airports**, particularly those already disproportionately affected by aviation-related noise and pollution. Any transition to hydrogen aircraft should be accompanied by robust community engagement, taking into account the concerns and needs of impacted communities.
- **Policy makers could consider the concerns around the movement of hydrogen through communities** – whether by pipeline or truck – and/or the siting of new hydrogen storage infrastructure or electrolyzers for production, which may increase the footprint of airports and, as further discussed below, raise safety questions in neighboring communities that policy makers and industry leaders will need to address.

Safety Recommendations

The introduction of hydrogen aircraft at airports necessitates a thorough assessment of health and safety considerations to address risks associated with hydrogen storage, handling, and refueling infrastructure and operations, particularly given the proximity of passengers and staff.

- **Federal and state leaders could develop stringent safety protocols and regulations** to ensure that industry minimizes hydrogen leaks, fire hazards, and other safety incidents.
- **Federal and state officials, as well as industry leaders, could develop** t**raining programs and certifications** for pilots, ground crew, and maintenance personnel to ensure they have the necessary expertise and knowledge to handle hydrogen aircraft safely.
- **Industry leaders could continue to adhere to robust safety standards and foster a culture of safety** to manage the health and safety risks associated with hydrogen aircraft and provide a secure operating environment for both aviation professionals and passengers. By contrast, the use of hydrogen-derived zero emission fuels will not necessitate such an extensive review of health and safety measures. Designed as a "drop-in-fuel," ZEFs are compatible with existing fuelling infrastructure at airports and the robust health and safety practices already in place.

Policymakers will need to consider safety risks in the design of the infrastructure and how to manage these risks. Key risks include: :

- **Liquid hydrogen tank rupture**: highly unlikely due to low-pressure operation and stable cryogenic temperatures, with decades of incident-free storage experience.
- **Refueling spills**: leaked hydrogen evaporates quickly in open air, but cryogenic burns from connectors remain a concern. Designing safer refueling systems and funding research through national labs could help mitigate these risks.

SAE standards, such as SAE AIR8466, provide a more comprehensive hazard analysis and mitigation strategies.

5.7 Workforce Recommendations

Skills and Training

Given the broad set of novel workforce skills and knowledge required to ensure timely transition to hydrogen in general (and for relevant aviation market segments), below are a set of recommendations to accelerate training and upskilling of the workforce in California:[82]

- **California state government leaders could prioritize the skills agenda in California for hydrogen use in aviation**, along with recognition of the necessity

[82] Taking a similar approach as the recommended actions on workforce skills as laid out in FlyZero's 'Workforce to Deliver Liquid Hydrogen Powered Aircraft,' 2022, available at https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-IST-PPL-0053-Workforce-to-Deliver-Liquid-Hydrogen-Powered-Aircraft.pdf

and potential of hydrogen-powered aircraft. The DOE highlighted US-wide hydrogen workforce expansion as a priority in its *Pathways to Commercial Liftoff* report.[83] However, this need was mostly in reference to upstream manufacturing for hydrogen production, transport, and storage technologies. The workforce transition and training agenda for downstream use technologies will be equally as crucial to enable development of a fully functioning hydrogen economy.

- **Industry leaders (e.g., aviation manufacturers, airlines, hydrogen technology providers) could conduct a workforce skills requirement and gap assessment** to understand short-term and long-term skills and training priorities for a workforce that is able to deliver, operate and maintain hydrogen powered aircraft technologies.
- **Industry leaders could develop a hydrogen skills framework specific to aviation**, outlining required competencies, qualifications, and training standards. This framework can be modeled after FlyZero's UK workforce study to address workforce needs across product lifecycle areas.[84]
- **Industry and workforce leaders could partner with educational institutions** to establish targeted training and upskilling programs, such as on-the-job training, short courses, apprenticeships, and higher education, to address immediate skill gaps.
- **Federal agencies could support California's hydrogen aviation workforce agenda** by providing funding for workforce development initiatives, including training and research programs. This goal can be enabled through research and development investment (for example in novel propulsion systems and aircraft materials), emphasis on innovation and collaboration (with world-leading research institutions and industry players) in training program development, and facilitation of US-entry for international experts via work visa programs.

Workforce Safety

Considering the properties of hydrogen along with potential hydrogen supply models and use technologies for the aviation sector, a set of practical, industry and policy leaders can develop and implement interlinked solutions to ensure the safety of the workforce:

1. **Industry leaders could implement fire prevention, suppression, and control measures** to minimize the risk of fire and explosion:

[83] U.S. DOE Pathways to Commercial Liftoff: Clean Hydrogen, March 2023, https://liftoff.energy.gov/wp-content/uploads/2023/05/20230523-Pathways-to-Commercial-Liftoff-Clean-Hydrogen.pdf

[84] Aerospace Technology Institute, Fly Zero, March 2022, www.ati.org.uk/wp-content/uploads/2022/03/FZO-IST-PPL-0053-Workforce-to-Deliver-Liquid-Hydrogen-Powered-Aircraft.pdf

- Installing adequate ventilation systems in spaces where hydrogen is stored and used, including emergency venting and dilution systems that can quickly release or lower the concentration of hydrogen in the event of build up
- Identification and elimination of potential ignition sources in close proximity to hydrogen storage or use
- Using flame-resistant materials for the construction of hydrogen systems and infrastructure
- Designing fire suppression systems and equipment such as infrared sensors, cooling systems and extinguishers

2. **Industry leaders could deploy leak detection and mitigation systems** to prevent hydrogen leakage and quickly identify and contain any leaks that do occur:
    - Leak avoidance through regular visual inspection of components such as piping, valves, and connectors, with replacement of anything worn or faulty
    - Leak detection systems such as hydrogen sensors integrated with alarms installed at strategic locations
    - Leak mitigation and containment including prompt repairs and leak-resistant enclosures
3. **Industry leaders could ensure safe handling of high pressure systems** by:
    - Designing pressure vessels (including cryogenic) to withstand maximum operating pressures, accounting for wear and embrittlement.
    - Installing pressure relief and venting systems and components installed at system bottlenecks such as relief valves
    - Using pressure monitoring and control systems such as gauges and sensors that relay live data to operators, and pressure regulators to maintain acceptable system conditions
4. **Industry leaders could develop systems** for managing cryogenic temperatures and boil-off gas during storage and transfer of liquid hydrogen to ensure safety and efficiency
5. **Policymakers (e.g., Federal Aviation Administration, Occupational Safety and Health Administration) could establish and enforce regulatory guidelines** for hydrogen safety, including fire prevention, leak detection, pressure handling, and cryogenic management in aviation applications.
6. **Industry leaders and educational institutions could develop and deliver training programs to the workforce** to provide the required awareness and knowledge of the characteristics of hydrogen, along with the numerous potential hazards and their respective prevention and crisis-response protocols.

Section 6: Conclusion

This white paper provides a guideline for the integration of hydrogen in California's aviation sector. Hydrogen, as a potential green aviation fuel, holds promise in addressing the industry's environmental challenges, especially in reducing carbon emissions and moving toward a sustainable future. While the adoption of hydrogen-powered aircraft and fuels in California's aviation sector presents various challenges, it also offers numerous environmental, economic, and societal benefits.

The significance of this endeavor lies in its potential to reshape the aviation industry by promoting a transition to more sustainable and environmentally friendly practices. The recommendations outlined in this report, spanning policy, finance, industry collaboration, and codes and standards, offer a holistic approach to overcoming the hurdles of hydrogen adoption. Collaboration and synergy among various stakeholders, including government bodies, industry players, and financial institutions, will be essential in realizing the vision of a hydrogen-powered aviation sector. The active involvement of airports and state agencies in developing hydrogen infrastructure will also be crucial for success.

Furthermore, as California moves toward hydrogen adoption, it must do so with an equitable, inclusive, and community-centered approach, taking into consideration the potential impacts on various frontline communities. The transition to hydrogen should not only bring environmental benefits but also create job opportunities and enhance air quality in these communities. Ultimately, the adoption of hydrogen in California's aviation sector is a transformative step that can significantly reduce the industry's carbon footprint and contribute to a more sustainable future. By implementing the recommendations provided in this report, California can become a leader in green aviation and set a positive example for the rest of the world.

Appendix A: List of Codes and Standards and Regulations

In this appendix, there are a number of codes, standards and regulations which are to be used as guidance also for hydrogen applications. There is still collaborative work to be done on behalf of Standards and Codes Development Organizations to update related to hydrogen safety for aerospace and aircraft applications. However, there are decades of published codes and standards from the ground transportation industry NFPA and SAE for example which could be used as reference in the interim. Many are listed herein.

Key Airport Fuel and Operations Standards and Regulations

While a guideline from the FAA for Aircraft Fuel Storage, Handling, and Dispensing on Airports (150/5230-4C) exists, it is not mandatory. However, airports can demonstrate consistency with it as one method of compliance with 14 CFR Part 139 – Certification of Airports. To receive government funding, airports may need to demonstrate compliance. This chapter contains standards and guidance for the training of personnel conducting aviation fuel-related activities.

With regards to the handling, storage and dispensing of aircraft fuel, this guideline mainly references National Fire Protection Association (NFPA 407), which not all airports necessarily follow. Each airport may have different local fire code regulations and operating procedures different from what NFPA 407 describes. While the requirements specified in NFPA 407 are not directly applicable to hydrogen, the topics covered and considered within the document are potentially worth adapting to enable the safe adoption of hydrogen as an aviation fuel.

Most of the existing airport standards are focused on liquid hydrocarbon fuels. However, the topics they cover need to be updated for the use of hydrogen as an aviation fuel. Below is an overview of some of the existing standards.

Table 5: Standards for operational procedures and quality assurance for airports.[85]

Standard	Title

[85] Vertical Flight Society, H2-Aero Team, "Multimodal Hydrogen Airport Hub," 2023 https://vtol.org/files/dmfile/h2-aero-whitepaper--multimodal-h2-airport-hub-2022_public-final.pdf

FAA ARFF 105 Series[86]	Aircraft Rescue and Fire Fighting (ARFF) First Responder and Aircraft Safety Standards (needs to be updated for hydrogen)
NFPA 407	Standard for Aircraft Fuel Servicing (needs to be updated for hydrogen)
Air Transport Association (ATA) 103	Standard for Jet Fuel Quality Controls at Airports
Joint Inspection Group (JIG) 1	Aviation Fuel Quality Controls and Operating Standards for Into-Plane Fueling Services (needs to be updated for hydrogen)
JIG 2	Aviation Fuel Quality Controls and Operating Standards for Airport Depots and Hydrants (needs to be updated for hydrogen)
JIG 4	Aviation Fuel Quality Control and Operating Standards for Smaller Airports (needs to be updated for hydrogen)
Energy Institute (EI)/JIG 1530	Quality Assurance Requirements for the Manufacture, Storage and Distribution of Aviation Fuels to Airports (needs to be updated for hydrogen)

[86] FAA, *Aircraft Rescue and Fire Fighting (ARFF) ARFF-Related Advisory Circulars*, https://www.faa.gov/airports/airport_safety/aircraft_rescue_fire_fighting

FAA 150/5230-4C	Aircraft Fuel Storage, Handling, and Dispensing on Airports (needs to be updated for hydrogen)

Reference Ground Vehicle Codes and Standards

Below is a list of key ground vehicle published codes and standards which could be used as reference for ground support equipment and also for use in the interim before aerospace C&S are complete.

NFPA 2	Hydrogen Technologies Code
SAE J2719	Hydrogen Fuel Quality for Fuel Cell Vehicles
ISO 19880-1	Hydrogen Fueling Station Standard- General Requirements
ISO 14687	Hydrogen Fuel Quality
ASTM D7941/7941M-14 Standard Test Method for Hydrogen Purity	Standard Test Method for Hydrogen Purity
SAE J2799	Hydrogen Surface Vehicle to Station Communications Hardware-Software
SAE J2601	Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles

SAE J2601-2	Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles
SAE J2601-5	High-Flow Prescriptive Fueling Protocols for Gaseous Hydrogen Powered Medium and Heavy-Duty Vehicles

Aircraft Hydrogen and Fuel Cell Standards

The jointEUROCAE WG-80/SAE AE-7F group develops guidelines to support the use of hydrogen (GH2/LH2) and fuel cell systems onboard aircraft.In addition, the SAE AE-5H Hydrogen Airport Committee was created to develop guidance on hydrogen fueling of aircraft at the airport. SAE AE-5H also works together on publishing joint standards documents EUROCAE WG-80..

Table 6: Key SAE/ EUROCAE aircraft hydrogen standardization.[87]

Name of Standard	Standard	Aircraft Application	Applicable Gaseous Hydrogen
Aircraft Fuel Cell Safety Guidelines	AIR6464/ ED-219	Definitions, Safety H2-Aircraft Integration (Auxiliary Power)	**GH2/LH2**
Installation of Fuel Cell Systems on Large Civil Aircraft	AS6858/ED-245	Integration of Fuel Cell Systems (Auxiliary Power)	**GH2**
Considerations for Hydrogen Fuel Cells in Airborne Applications	AIR7765/ ER-20	General Properties, Hazard Mitigation, (Auxiliary Power)	**GH2/LH2**

[87] Vertical Flight Society, H2-Aero Team, "Multimodal Hydrogen Airport Hub," 2023, https://vtol.org/files/dmfile/h2-aero-whitepaper--multimodal-h2-airport-hub-2022_public-final.pdf

Hydrogen Fuel Cells for Propulsion	AS7141	Usage of hydrogen PEM fuel cells for generation of electrical power for aircraft propulsion systems	**GH2**
Liquid Hydrogen Storage for Aviation	AS6679	LH2 General Properties, Requirements, Onboard Storage	**LH2**
Gaseous Hydrogen Storage for General Aviation	AS7373	GH2 General Properties, Requirements, Onboard Storage	**GH2**
Airport Hydrogen Stations- Gaseous and Liquid Guideline	SAE AIR8466	Hydrogen Airport Guideline	**GH2/LH2**
High Flow LH2 Process and Couplings for Aerospace	SAE AIR8999 (DRAFT)	Liquid Hydrogen Fueling Process & Coupling	**LH2**

Appendix B: SFO Hydrogen Adoption

The San Francisco International Airport (SFO) sees a role for hydrogen as a primary or auxiliary fuel and is piloting various hydrogen technologies to that end. Working with Sandia National Laboratories and others, SFO currently operates a clean, quiet hydrogen mobile light tower, replacing a high-emission, aging diesel unit. The airport has also incorporated light duty hydrogen vehicles into its fleet.[88] Other opportunities for hydrogen power / fuel may include extending the range of electric vehicles, or powering a variety of auxiliary units, including chargers. The opportunities are significant, given the quantity of vehicles used at airports. A detail of SFO's ground fleets are offered below to illustrate this further.

Ground Support Equipment (GSE) - At the airport, 1,008 pieces of equipment out of 1,949 motorized vehicles could be fuel-switched (currently biodiesel, CNG, diesel, gasoline, propane, etc). This number excludes vans, pick up trucks, SUVs, and sedans. Among total ground support equipment (GSE), 1,495 pieces of equipment out of 2,437 motorized vehicles could be fuel switched (currently biodiesel, CNG, diesel, gasoline, propane, etc). These "traditional" GSE include airfield vans, pick-up trucks, SUVs and sedans.

Fuel - In 2022, SFO used approximately 1 million gallons of fuel (gas, diesel, biodiesel, propane) for GSE. Based upon the conversion factor set by the Department of Energy Alternative Fuels Data Center,[89] SFO's GSE would demand over 1000 metric tonnes per year (MTPY) of hydrogen.

Fleet - For fleet vehicles, 429 out of 486 are estimated to be possible for conversion to alternative fuels (64 are hybrid so conversion may involve going to electric, while 365 can be "fully" converted to H2). Below is SFO's estimated fuel consumption in gallons, which equates to an additional 533 MTPY of hydrogen demanded on-airport for fleet vehicles.

[88] https://www.flysfo.com/sites/default/files/sfo-clean-vehicle-policy_0.pdf
[89] Alternative Fuels Data Center, Hydrogen Basics, available at https://afdc.energy.gov/fuels/hydrogen_basics.html

Appendix C: RPK flown by each market segment

Analysts quantify the passenger aviation market by the number of revenue passenger kilometers (RPK) flown.[90] In 2019, California's domestic aviation market was 184 billion RPK, of which intrastate flights, which are all <600 miles long, made up 16 billion RPK or 9%.[91] California's domestic aviation market can be segmented by flight distance and aircraft type. Table 1 represents a matrix of the segments, with distance increasing from left to right, while aircraft size increases down the rows. The number in each cell is the percentage of the overall RPK in that market segment. Narrowbody aircraft dominate the market, responsible for 87% of total RPK in 2019. Given the domestic scope of the flights, the medium-haul market dominates on the distance axis.[92] The domestic passenger aviation market could grow by 83% between 2019 and 2045.[93] The traffic growth is assumed to be the same across all the different market segments.

Table 1. Percentage of RPK flown by each market segment.

	Commuter (<500 km)	**Short-Haul (500-1500 km)**	**Medium-Haul (1500-4000 km)**	**Long-Haul (>4000 km)**
Commuter (<19 seats)	0.0%	0.0%	0.0%	0.0%
Regional (20-100 seats)	0.6%	3.2%	1.7%	0.0%
Narrowbody (Single-aisle)	1.5%	16.2%	55.8%	13.5%
Widebody (Twin aisle)	0.0%	0.1%	5.2%	2.2%

[90] The RPK is a product of the number of passengers on a flight and the distance of the flight. For example, 200 passengers aboard an aircraft flying 2000 km represent 400,000 RPK

[91] Graver, B., Rutherford, D., & Zheng, S., International Council on Clean Transportation, *CO2 emissions from commercial aviation: 2013, 2018, and 2019,* 2020, https://theicct.org/publication/co2-emissions-from-commercial-aviation-2013-2018-and-2019/

[92] A limited number of routes, to Hawaii and the East coast of the U.S., qualify into the long-haul category and represent a smaller fraction of the RPK than is generally the case globally.

[93] In their commercial market outlook for 2019-2041, Airbus and Boeing predict that domestic US aviation will have a cumulative average growth rate (CAGR) of 2.2% and 2.5%, respectively. Averaging the two, this work uses a CAGR of 2.35%.

Appendix D: Hydrogen Fuel Pathways and Use Technology

Hydrogen can be used directly in novel propulsion aircraft via Hydrogen Electric propulsion (via fuel cells) or hydrogen combustion in the production of SAFs, which are two of the five main aviation decarbonization levers (the others are demand reduction, market-based measures, operational efficiency improvements (air traffic management solutions and ground operations), and carbon dioxide removal solutions).[94]

Novel Propulsion Aircraft

Hydrogen as an aviation fuel can eliminate direct carbon emissions via combustion in a gas turbine jet engine or conversion through a fuel cell to power electric aircraft. Fuel cell aircraft would only emit water vapor while hydrogen combustion aircraft would emit water vapor, NOx, and particulates. So, while both emit water vapor, the absence of particulate emissions from fuel cell propulsion systems and their first use for regional aircraft that cruise at lower altitudes will likely result in a lower non-CO_2 climate impact than hydrogen combustion propulsion systems. However, as discussed, no published data currently exist that measure the climate impact from hydrogen-induced contrails although test campaigns of hydrogen combustion are being carried out by Airbus in Nevada.[95]

Aircraft Retrofitting and New Designs

Whilst hydrogen electric propulsion is being considered for retrofit into existing smaller regional aircraft, both hydrogen combustion and fuel cell applications in subsequent generations may require new aircraft designs in the form of new or upgraded propulsion systems and airframe configuration for larger aircraft. The high energy per unit mass makes hydrogen an advantageous zero-emission fuel for longer-distance applications compared to battery-electric aircraft.[96] But the low energy density by volume of hydrogen necessitates either compression in the case of gaseous hydrogen or liquefaction in the case of liquid hydrogen to allow the carriage of enough hydrogen to power a flight. As a comparison, compressing hydrogen to a pressure of 700 bar results in a volumetric energy density that is 14% the density of kerosene. The compressed gas

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[94] Mission Possible Partnership, *Making Net Zero Aviation Possible: An industry-backed, 1.5°C-aligned transition strategy*, July 2022, https://missionpossiblepartnership.org/wp-content/uploads/2023/01/Making-Net-Zero-Aviation-possible.pdf

[95] Airbus, "Contrail-Chasing Blue Condor Makes Airbus' First Full Hydrogen-Powered Flight" November 2023, https://www.airbus.com/en/newsroom/stories/2023-11-contrail-chasing-blue-condor-makes-airbus-first-full-hydrogen-powered

[96] Mukhopadhaya, Jayant, and Brandon Graver, July 2022, *Performance Analysis of Regional Electric Aircraft*. Washington, D.C.: International Council on Clean Transportation. https://theicct.org/publication/global-aviation-performance-analysis-regional-electric-aircraft-jul22/.

requires heavy storage tanks that create a challengingly low ratio of fuel mass to fuel system weight (Gravimetric Indices).

Storing Hydrogen as Liquid

Storing hydrogen in liquid form increases the volumetric energy density to 25% of Jet A fuel, unlocking longer-haul applications (estimated up to 3,400km for a narrow-body aircraft carrying 165 pax).[97] However, this liquid form entails additional challenges around energy use from cryogenic liquefaction of hydrogen (which can consume 35-45% as much energy as is contained in the final product), as well as the subsequent storage and potential boil-off (natural evaporation), which must be further studied and ultimately managed.[98] Managing boil-off is particularly important as the warming impact of 1 kg of hydrogen emissions (measured in the 100-year global warming potential) is estimated to be between 5 and 13 kg of carbon dioxide equivalent (CO_2e).[99] However, advanced management schemes including re-condensing and using the boil off for electrical loads are currently being developed. A recent International Council on Clean Transportation (ICCT) study estimated that fuel efficiency (comparing MJ/RPK) for a liquid H_2 turboprop and narrowbody aircraft will be 10-20% and 5-26% lower than conventional aircraft using Jet-A1, respectively, for hydrogen combustion. [100] A follow-up study found that using liquid hydrogen and fuel cell propulsion would yield fuel efficiency improvements of ~30% relative to the fossil fueled baseline.[101] The relative economics ($/RPK) of hydrogen compared with the use of conventional jet fuel depend on the future price and availability of JetA, SAF, PtL, and H_2.

Status of Development in California

Hydrogen aircraft are still in early stages of development, with the International Energy Agency (IEA) indicating a technology readiness level (TRL) of 7 out of 9,[102] and long lead times remaining to commercial availability.[103] Start-ups such as ZeroAvia (headquartered in California) are targeting commercial flights for turboprop aircraft

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[97] Mukhopadhaya, J., & Rutherford, D. January 2022. *Performance Analysis of Evolutionary Hydrogen Powered Aircraft*. https://theicct.org/wp-content/uploads/2022/01/LH2-aircraft-white-paper-A4-v4.pdf

[98] Ghafri, et al. Hydrogen liquefaction: a review of the fundamental physics, engineering practice and future opportunities. *Energy & Environmental Science* **15**, 2690–2731 (2022). https://pubs.rsc.org/en/content/articlehtml/2022/ee/d2ee00099g

[99] Derwent, et al, . "Global Environmental Impacts of the Hydrogen Economy." *International Journal of Nuclear Hydrogen Production and Applications* 1, no. 1 (2006): 57, 2006, https://doi.org/10.1504/IJNHPA.2006.009869. Hauglustaine, et al, "Climate Benefit of a Future Hydrogen Economy," *Communications Earth & Environment* 3, no. 1 : 1–14, November 2022, https://doi.org/10.1038/s43247-022-00626-z

[100] Ibid.

[101] Mukhopadhaya, Jayant,. "Performance Analysis of Fuel Cell Retrofit Aircraft." Washington, D.C.: International Council on Clean Transportation, August 2023, https://theicct.org/publication/fuel-cell-retrofit-aug23/.

[102] For more information on this readiness scale, visit: https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

[103] U.S. EIA, *ETP Clean Energy Technology Guide – Data Tools,* https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide?selectedSector=Aviation

retrofit with fuel cell propulsion as early as 2026. This deployment will likely be followed by bigger retrofit aircraft before reaching clean-sheet, fuel cell narrow-body jet aircraft. ZeroAvia has targeted 2032 for long-haul narrowbody aircraft, while Airbus indicated that the hydrogen-powered aircraft that they will bring to market in 2035 will be smaller and will not compete with their existing aircraft.[104]

SAF: Hydroprocessed Esters and Fatty Acids (HEFA)

Of the four major SAF pathways (HEFA, Alcohol-to-jet, gasification + Fischer-Tropsch, Power-to-Liquid),[105] production of biofuel in the form of hydroprocessed esters and fatty acids (HEFA) is the most technologically mature (TRL 9). Feedstocks for this pathway include lipids such as waste cooking oil, residues from food processing or other processes, and purposely grown plant oils, with roughly 0.03-0.08 kg of hydrogen required for hydroprocessing per kg of HEFA output.[106] HEFA biofuel is the only SAF currently produced and consumed at commercial scale. California alone consumed 7.6 million gallons of HEFA SAF in 2021, requiring roughly 1,300 tonnes of hydrogen.

HEFA Emissions

While HEFA is the most commercially mature SAF pathway, emissions from HEFA vary widely depending on feedstock (e.g., waste fats, oils, and greases versus dedicated crops), energy sources for feedstock hydrogen production, and conversion processes at the biorefinery. The International Civil Aviation Organization estimated the range of life cycle emissions for HEFA SAF at 15-120 gCO_2e/MJ, with used cooking oil as the input feedstock at the bottom of the range and palm oil at the top end. This compares to petroleum jet fuel carbon intensities typically around 85-95 gCO_2e/MJ.[107] Much of the wide range in lifecycle emissions for HEFA SAF is due to indirect land use change emissions from feedstocks such as soy oil and palm oil. In some cases HEFA fuel emits more carbon than conventional petroleum fuel on a lifecycle basis.

HEFA Production in California

California hosts the world's first commercial-scale HEFA jet fuel production plant, run by World Energy in Paramount. Originally developed by AltAir Fuels, the plant has produced SAF since 2016 with a current capacity of around 6 million gallons per year. World Energy is targeting production ramp-up to 30 million gallons by the end of 2024, with a

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[104] Kaminski-Morrow, David, "Airbus Aiming Hydrogen-Fuelled Aircraft at 'Low End' of Market," Flight Global, February 2024, https://www.flightglobal.com/aerospace/airbus-aiming-hydrogen-fuelled-aircraft-at-low-end-of-market/156945.article
[105] HEFA, Alcohol-to-jet, gasification + Fischer-Tropsch, Power-to-Liquid
[106] Pipitone, Giuseppe, Giulia Zoppi, Raffaele Pirone, and Samir Bensaid. "Sustainable Aviation Fuel Production Using In-Situ Hydrogen Supply via Aqueous Phase Reforming: A Techno-Economic and Life-Cycle Greenhouse Gas Emissions Assessment." *Journal of Cleaner Production* 418 (September 15, 2023): 138141. https://doi.org/10.1016/j.jclepro.2023.138141.
[107] Pavlenko, N., & Searle, *Assessing the sustainability implications of alternative aviation fuels*, March 2021, https://theicct.org/wp-content/uploads/2021/06/Alt-aviation-fuel-sustainability-mar2021.pdf

goal of 250 million gallons by 2025 once a $2.5B conversion is complete. Beyond production in Paramount, further SAF volumes are also expected later this year from a joint venture between Neste and Marathon Petroleum Corporation in Martinez, California. By the end of 2023, they expected the facility to be capable of producing 730 million gallons of renewable fuel products (renewable diesel, HEFA and renewable feedstock for polymers and chemicals) annually; however, no update has been provided in 2024 yet.[108] Such a large facility would require 124,000 tonnes of hydrogen per year. Start-ups and incumbent refining companies at other sites across California, including Aemetis (Riverbank, CA), Chevron (El Segundo, CA) and Indaba Renewable Fuels (Southern California), are all planning further SAF production.

SAF: Power-to-Liquids (PtL) via Hydrogen

PtL fuels are synthetic fuels (e.g., e-kerosene) produced by upgrading synthetic gas[109] formed via conversion of CO_2 using renewable hydrogen, at a production ratio of roughly 2 tonnes PtL jet fuel per tonne of hydrogen input.[110] The fuel includes hydrogen produced through electrolysis using water, carbon obtained by splitting CO_2, and renewable power inputs.

Cost and Feasibility of PtL

With a TRL of 5-6 out of 9, PtL ranks the lowest of all drop-in SAF. The industry will need further technological development and demonstration to prove feasibility of fuel synthesis utilizing steady-state renewables and integrating direct air capture. Cost represents one of the main hurdles impeding the transition of PtL from demonstration to commercial deployment phases, with PtL projected to cost 3-9x average historical jet fuel prices in 2025.[111] This cost premium is mostly driven by the price of renewable electricity used to power energy-intensive CO_2 capture technology, energy losses through waste heat or unwanted byproducts, and the levelized cost of hydrogen production (which is a function of electricity prices and electrolyser CAPEX). These factors combined account for 85% of projected PtL costs.[112] However, experts predict

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[108] Neste in North America, *Neste finalizes transaction to establish a joint venture for production of renewable fuels with Marathon Petroleum in the United States*, September 2022, https://www.neste.us/releases-and-news/renewable-solutions/neste-finalizes-transaction-establish-joint-venture-production-re newable-fuels-marathon-petroleum

[109] Via Fischer-Tropsch or methanol-synthesis

[110] Assuming energy density (LHV) of 44.14 MJ/kg and 120 MJ/kg for PtL-kerosene and hydrogen respectively, and a conversion efficiency of 71.8%, source: Fasihi, M., Bogdanov, D., & Breyer, C. (2016). Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants. *Energy Procedia*, *99*, 243–268. https://doi.org/10.1016/j.egypro.2016.10.115

[111] Mission Possible Partnership,, *Making Net Zero Aviation Possible: An industry-backed, 1.5°C-aligned transition strategy*, July 2022, https://missionpossiblepartnership.org/wp-content/uploads/2023/01/Making-Net-Zero-Aviation-possible.pdf

[112] Clean Skies for Tomorrow Initiative (CST), World Economic Forum, and McKinsey & Company, *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation,* November 2020, https://www3.weforum.org/docs/WEF_Clean_Skies_Tomorrow_SAF_Analytics_2020.pdf

these costs to decrease by 2030, while biomass-derived SAF (i.e., biofuels) has a lower cost decline potential due to constrained sustainable feedstock costs and CAPEX-heavy production facilities. Furthermore, unlike biofuels, PtL is not constrained by finite sustainable feedstock volumes, due to theoretically abundant renewable electricity generation and CO_2 capture potential, and can be distributed and scaled from small to large plants.

Carbon Intensity of PtL

The carbon intensity of PtL fuels is largely tied to that of the power grid where they are produced, meaning that when produced with electricity from a grid that has a significant amount of fossil-fueled generation, the resulting fuels have less greenhouse gas benefits than those made from a decarbonized grid. For example, PtL made on a decarbonized grid can be over 90% less carbon intensive during its life cycle compared with fossil jet fuel.[113] However, using for example the EU average grid would lead to lifecycle emissions at about 130 gCO2e/MJ, worse than conventional jet fuel.[114] Some researchers noted that while PtL producers could procure clean renewable electricity for their process, or even build renewable generation as part of the PtL project, in most cases using the new renewable generation capacity to displace fossil generation from the grid would likely yield greater greenhouse gas benefits than using it to produce PtL fuels. This opportunity cost means that while PtL fuels may have a significant role to play in long-run decarbonization of transport, their value as a carbon reduction measure is tied to the carbon intensity of the electrical energy servicing the production facility. It is important to note that PtL production will likely require 3x the energy needed to produce liquid hydrogen or LH_2 (Figure 1).[115] More detailed cost assessment of LH_2 production is included in Section 3.4.

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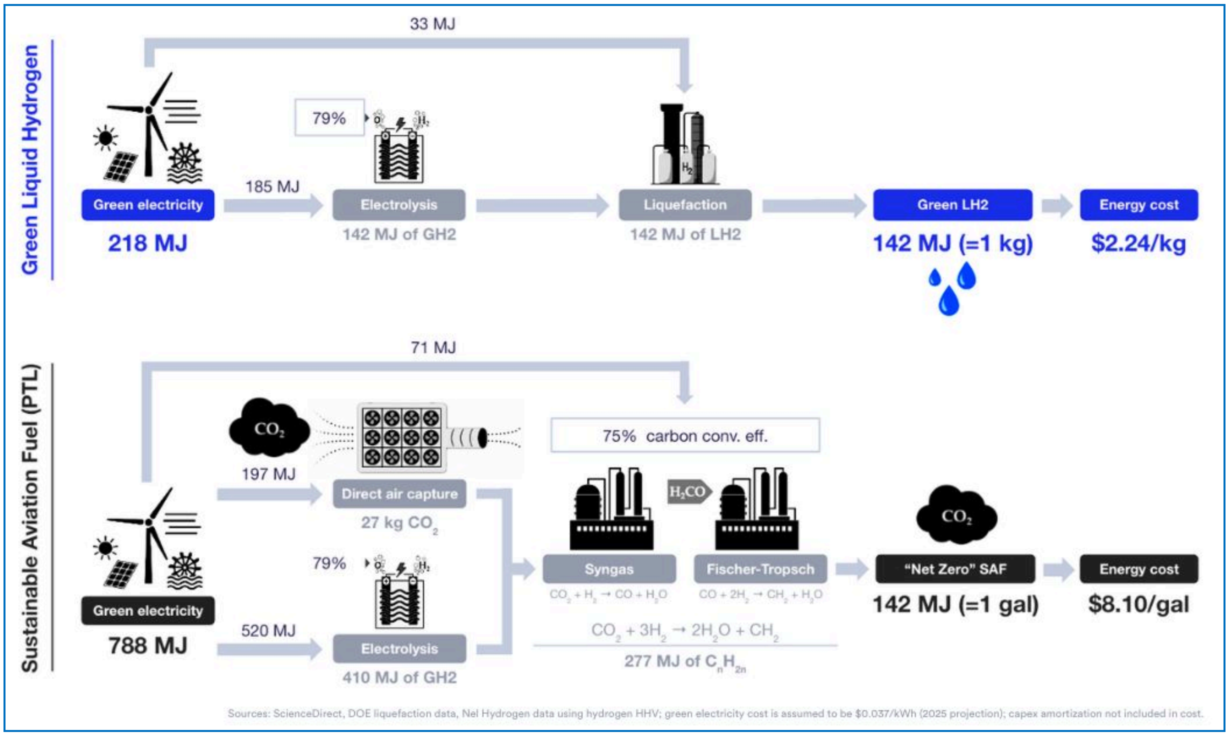
[113] KPMG, *Sustainable Aviation Fuel: Ready for lift off?*, November 2022, https://assets.kpmg.com/content/dam/kpmg/ie/pdf/2022/11/ie-sustainable-aviation-fuel.pdf

[114] Nikita Pavlenko, Stephanie Searle, "Assessing the sustainability implications of alternative aviation fuels," *International Council on Clean Transportation*, March 2021, https://theicct.org/wp-content/uploads/2021/06/Alt-aviation-fuel-sustainability-mar2021.pdf

[115] *Multimodal Hydrogen Airport Hub*, Vertical Flight Society, 2023, https://vtol.org/files/dmfile/h2-aero-whitepaper--multimodal-h2-airport-hub-2022_public-final.pdf

Figure 8: Energy and cost comparison of liquid hydrogen to SAF power to liquid[116]



Advantages of PtL

PtL SAF is widely referred to as 'drop-in' fuel due to its chemical resemblance with conventional based jet-fuel, meaning it is compatible for use in current airport infrastructure and aircraft engines. This chemical likeness implies a TRL of 9 for the aircraft technology that can use PtL synfuel (up to certified percentage blending caps), along with an almost identical fuel energy density, highlighting one of the key advantages of using PtL (or other similar SAF) versus electricity or hydrogen in generating the power required for longer-distance applications. PtL jet fuel has yet to be produced commercially anywhere around the globe. However, multiple facilities are in development, and analysts expect approximately 100,000 tonnes per year of commercial capacity to be available globally by 2025,[117] requiring around 50,000 tonnes of hydrogen. This supply is enough to fuel 15 narrowbody aircraft flying transcontinental flights (between the east and west coast of the US) for 1 year. In North America, the

[116] Vertical Flight Society, H2-Aero, "Multimodal Hydrogen Airport Hub," available at: https://vtol.org/files/dmfile/h2-aero-whitepaper--multimodal-h2-airport-hub-2022_public-final.pdf

[117] Clean Skies for Tomorrow Initiative (CST), World Economic Forum, and McKinsey & Company. *Clean Skies for Tomorrow: Delivering on the Global Power-to-Liquid Ambition*, May 2022, www.mckinsey.com/~/media/mckinsey/industries/aerospace%20and%20defense/our%20insights/clean%20skies%20for%20tomorrow%20delivering%20on%20the%20global%20power%20to%20liquid%20ambition/clean-skies-for-tomorrow-delivering-on-the-global-power-to-liquid-ambition.pdf

SAF+ Consortium announced the first PtL production plant on the continent at its pilot facility in Montreal, with planned commercial volumes available by 2025-26.[118]

In the National Clean Hydrogen Strategy Roadmap, the DOE estimated that if industry used all 44 million tonnes of concentrated CO_2 available from ethanol plants in the US today to generate PtL fuels, producers could make four billion gallons, requiring six million tonnes of hydrogen. This amount would be enough PtL to replace one fifth of 2021 jet fuel consumption in the US, or 135% of California's consumption.

[118] SAF+ Consortium, *The first production of SAF sustainable aviation fuel developed in North America, 2021*, https://safplusconsortium.com/blog/the-first-production-of-saf-sustainable-aviation-fuel-developed-in-canada/

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