



H₂-Aero Vision

Decarbonizing Aerospace with Green Hydrogen

Multimodal Hydrogen Airport Hub



Vertical Flight Society
H₂-Aero Team
Jesse Schneider, Chair
March 2023



Multimodal H₂-Airport Hub



The Vertical Flight Society is the world's oldest and largest technical society dedicated to enhancing the understanding of vertical flight technology. VFS is a non-profit, charitable educational and technical organization. Since it was founded as American Helicopter Society (AHS) in 1943 — just as the first US helicopter was being put into service — the Society has been the primary forum for interchange of information on vertical flight technology.

Since 2013, VFS has been a driving force behind the “Electric Aircraft Revolution,” beginning with the world's first workshop on electric vertical takeoff and landing (eVTOL) technologies in 2014, the first eVTOL newsletter, *The Electric VTOL News*, in 2016; the first website, www.eVTOL.news, in 2017, and the first short course on eVTOL technologies, in 2019. At this time, VFS expanded its remit to also support conventional takeoff and landing (eCTOL) aircraft and took over leadership of the Electric Aircraft Symposium, which was first held in 2007, and is held annually in Oshkosh, Wisconsin, in conjunction with the EAA AirVenture Fly-In every July.

In 2020, VFS started its first hydrogen working group, the H2eVTOL Council, followed by the H2-Aero Team in January 2022. VFS held the first hydrogen aviation workshop in North America in March 2022, followed by the Second Annual H2-Aero Symposium in March 2023.

This whitepaper, “Multimodal Hydrogen Airport Hub,” is a direct output of the H2-Aero Team, kicked off at the first H2-Aero Symposium & Workshop. It was originally published in December 2022 and updated in March 2023. An electronic copy of this whitepaper and other hydrogen-related efforts can be found at www.vtol.org/hydrogen.

VFS is indebted to the H2-Aero Team and all our member volunteers who work together to advance the future of flight. We encourage anyone who shares this vision to join VFS. Learn more at www.vtol.org.



Multimodal H₂-Airport Hub

Table of Contents

Foreword	2
1. Goal and Scope	4
1A. Structure	4
2. Status and Background	5
3. Hydrogen Policy	8
3A. Enabling Policy and Regulation	9
3B. Federal Policy	10
3C. State and Local Policy.....	11
3D. Industry Collaboration	11
3E. VFS H ₂ -Aero Team Recommended Policy Measures.....	12
4. Codes and Standards Status and Gaps	13
4A. Key Airport Fuel and Operations Standards and Regulations.....	13
4B. Ground Vehicle Hydrogen Standards.....	14
4C. Aircraft Hydrogen and Fuel Cell Standards	15
4D. Gaps in Aircraft Fueling Standards.....	16
5. Hydrogen Safety	17
5A. General Description of Hydrogen Storage Systems and Safety	17
5B. Storage and Fuel Cell Safety	18
6. H₂-Aero Fuel Matrix.....	21
6A. Use Case Class vs. H ₂ Storage Type	21
6B. Hydrogen Fuel Capacity vs. Size of Aircraft.....	21
7. H₂-Airport Demo: Public-Private Partnership and Sandbox.....	24
7A. H ₂ -Airport Public-Private Partnership.....	24
7B. Key Outcomes to an H ₂ -Aero Public-Private Partnership.....	25
7C. “Sandbox” Testing Environment	26
8. Multimodal H₂-Airport Hub (Ecosystem)	28
8A. H ₂ Airport Ecosystem Overview.....	29
8B. Airport Hydrogen Supply Scenarios.....	31
9. Conclusion	34
References.....	35
Abbreviations	36

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Multimodal H₂-Airport Hub

Foreword

Aircraft emissions equate to approximately 10% of US transportation greenhouse gas emissions and 3% of overall. By 2050, it is expected that commercial aircraft emissions could increase to over 22%+ of the world's total CO₂ emissions¹! Since the average aircraft life is 30 years, it hastens the need to replace fossil fuels and their propulsion sooner than later. To abate this impending reality, the Vertical Flight Society's (VFS) H₂-Aero Team's aim is to help decarbonize aviation using zero emission propulsion (e.g., fuel cell) fueled by carbon-free hydrogen.

Though sustainable aviation fuels (SAF) are starting to be established as a “drop in fuel” for replacing conventional kerosene, there are many factors indicating that hydrogen is an advantageous follow-on and will be needed in the mix to achieve net zero for hydrogen aerospace. The H₂-Aero Team was formed in 2022 with the goal to decarbonize aviation with carbon-free hydrogen, as a *follow on* to SAF.

The goal of this whitepaper, “Multimodal H₂-Airport Hub,” is to create a repeatable hydrogen hub for the airport, first with a ground vehicle fueling station, and later expanding to an airport-based hub supplying multiple modes of transportation. This whitepaper establishes a blueprint towards creating hydrogen aircraft and fueling demonstrations and proposes creating a public-private partnership to enable demonstrations. The objective is to further prove out the technology and develop confidence in scaling hydrogen hubs at airports. Below is a concept illustration of the H₂-Aero Team's vision for a renewable hydrogen hub at airports, from production to dispensing of both gaseous and liquid hydrogen and accommodating both modes of aircraft and ground transportation. Hydrogen storage is also exemplified as needed for fueling and onsite reserve.

Thank you to the whole VFS H₂-Aero Team to help create this document. Thank you to the Fuel Cell Hydrogen Energy Association for their insightful trade association input. In addition, thank you to the National Renewable Energy Laboratory for their valuable perspective and analysis on hydrogen in transportation².

Jesse Schneider
Chair, VFS H₂-Aero Team

Figure 1: H₂-Aero Vision of a Multimodal Hydrogen Airport Hub (courtesy of ZEV Station).



¹ <https://www.weforum.org/agenda/2021/09/aviation-flight-path-to-net-zero-future/>

² This does not imply an endorsement of a specific policy or technology recommendation from NREL.



Multimodal H₂-Airport Hub

Table 1: H₂-Aero Team chapter leads and co-leads.

Chapter	Lead	Co-Lead
1) Goal and Scope	Joe Rainville (Bell Textron)	Jesse Schneider (ZEV Station)
2) Status, Background	Helen Leadbetter (Consultant)	Liviu Cosacescu (ZEV Station), Monterey Gardiner (Consultant)
3) Hydrogen Policy	Todd Solomon (ZeroAvia)	John Scott, John Piasecki (Piasecki), Hank Krakowski (NEXA Capital Partners)
4) Codes and Standards Status and Gaps	Griffin Valentich (Shell)	Jesse Schneider (ZEV Station), Reid Larson (Chart Industries)
5) Hydrogen Safety	Liviu Cosacescu (ZEV Station)	Monterey Gardiner (Consultant)
6) H ₂ -Aero Fuel Matrix	<u>H₂-Aero Fuel and Aircraft Subteams</u> Amanda Simpson (Airbus), Joe Rainville (Bell Textron), Liviu Cosacescu (ZEV Station), Monterey Gardiner (Consultant), A Chatterjee (ZeroAvia), Reid Larson (Chart Industries), Charlie Myers (Massachusetts Hydrogen Coalition), Jesse Schneider (ZEV Station)	
7) H ₂ -Airport Demonstration, Public-Private Partnership and Sandbox	Helen Leadbetter (Consultant)	A Chatterjee (ZeroAvia), Joe Rainville (Bell), Reid Larson (Chart Ind.), Charlie Myers (Mass. H ₂)
8) Multimodal H ₂ Airport Hub: Ecosystem	Jesse Schneider (ZEV Station)	Griffin Valentich (Shell), Monterey Gardiner (Consultant), Joe Rainville (Bell Textron), Reid Larson (Chart Ind.), Liviu Cosacescu (ZEV Station), Arnab Chatterjee (ZeroAvia)
9) Conclusion	Jesse Schneider (ZEV Station)	Joe Rainville (Bell Textron)



1. Goal and Scope

The H2-Aero whitepaper aims to inform and align industry, government, and academia to start developing a collaborative effort for hydrogen-powered aircraft to help decarbonize aerospace. This could happen in stages with initial small-scale demonstrations, followed by larger hydrogen hubs as the market and demand evolves. H2-Aero proposes creation of a hydrogen-enabled airport for multimodal hydrogen ecosystem using economies of scale to support of three areas of transportation: aircraft, ground support vehicles and adjacent ground vehicle airport uses (such as highway traffic, heavy duty vehicles, rental cars, etc.).

The joint Hydrogen and Aircraft Teams (from H2-Aero) propose a demonstration of the near-term airport fueling hydrogen-powered aircraft. Such a demonstration would partner industry, government, standards organizations, and academia in an effort to develop meaningful data toward establishing a safe, replicable model for a hydrogen-enabled airport. This would be an opportunity to create a public-private partnership towards collective goals for the hydrogen airport hub.

Standards must be developed for hydrogen-fueled aircraft, and a real-world demonstration of hydrogen-aircraft fueling is needed to support development of the hydrogen-enabled airport ecosystem. The whitepaper establishes a baseline status of Codes & Standards, analyze the gaps, and recommend actions needed to close them.

The whitepaper proposes gaining consensus and agreement on safety, developing common fueling infrastructure, interfaces, storage technology and scalability of hydrogen solutions in aerospace. This whitepaper takes the first step at harmonizing and aligning onboard aircraft hydrogen storage by type, quantity and acceptable fill times.

The list below highlights the main points of the whitepaper:

- Establish a baseline for hydrogen aerospace and propose methods toward commercialization.
- Give policy status and recommendations.
- Provide a background in codes, standards and regulations, making recommendations for gaps.
- Harmonization of aircraft hydrogen storage and fuel size (H2-Aero Storage Matrix).
- Support the development of viable H2-Aircraft and demonstration of aircraft and airport ecosystem.
- Create a framework for a public-private partnership to further H2 aerospace and airport standards.
- Establish basic elements for airports and industry members for a “Multimodal H2-Airport Hub.”

1A. Structure

This whitepaper for the Multimodal H2-Airport Hub is authored by a team consisting of aircraft manufacturers, hydrogen providers, regulation authorities and standards representatives from the US and around the world.

The following are the key H2-Aero whitepaper outcomes:

- Industry roadmap to H2 demonstration and airport H2 hubs (whitepaper).
- Overview of key codes and standards (C&S) and identification of gaps.
- Outline for H2 demonstrations required to support and accelerate hydrogen adoption at airports.
- Framework for a H2 hub using the example of small regional airport.



2. Status and Background

Hydrogen is present in hydrocarbons (fossil fuels) and when combusted has different types of exhaust emissions such as volatile organic compounds, particulate matter, and metals formed, as well as greenhouse gas emissions and contrails. When used in a fuel-cell configuration, hydrogen-electric aviation produces only water vapor. Hydrogen combustion is free of carbon emissions, but Nitrogen Oxides (NO_x) and potentially some unburned hydrogen in the exhaust and contrails continue to exist.

Hydrogen offers several benefits to aviation fuel. However, the storage density of gaseous hydrogen due to its properties is less, whereas liquid hydrogen offers comparable energy storage density.

Hydrogen is the widest used industrial gas in the world. The largest use in the US is to refine gasoline. Safe use of hydrogen has been demonstrated by the National Aeronautics and Space Administration (NASA) and industrial gas companies for over 50 years. Hydrogen is now widely used for fuel cell forklift applications across North America and buses in transit applications; and it is beginning to be used in the light duty and heavy-duty sector. There are also over 50 hydrogen stations, mainly in California, for light duty fueling, a figure projected to expand to over 1,000 in the next 10 years³.

While aircraft powered by hydrogen and fuel cells are at an early stage, hydrogen fuel cell ground vehicles have been engineered to the highest safety standards developed by SAE, GTR, ISO and other standards bodies. The hydrogen fueling stations also have several codes and standards including ASTM, CSA, ISO and NFPA, among others. Fuel cell passenger cars and buses are in service around the world transporting passengers safely since the late 1990s. In addition, hydrogen stations have a proven safety track record even in extreme climate environments and based on established codes, standards and risk analysis. It is important for aerospace to build upon the collective body of work already carried out for hydrogen for the automotive industry.

Though it is often perceived as an issue, the amount of water used in the production of hydrogen — approximately 10 L/kg — is significantly less than that used in the production of conventional jet fuel or rainfed biomass-derived SAF (via Fisher-Tropsch). The lifecycle freshwater consumption is up to 0.217 L_{water}/MJ for jet fuel and 0.523 L_{water}/MJ for SAF respectively, while hydrogen has uses 0.117⁴ L_{water}/MJ. This means that hydrogen consumes around two times less water than jet fuel and around four times less water than biomass derived SAF. In addition to freshwater, it is possible to produce hydrogen from desalinated water and wastewater with the opportunity to purify more of this water for drinking water. In fact, a recent study for the hydrogen hub water needs Southern California⁵ indicated the supply far exceeds hub demands. The graph below shows hydrogen water demand where the wastewater supply far exceeds the future hydrogen hub demands.

³ <https://cafc.org/sites/default/files/CAFCR.pdf>

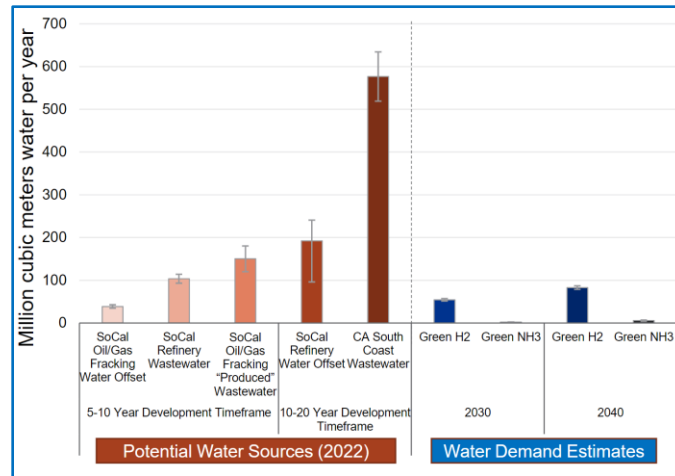
⁴ <https://dspace.mit.edu/handle/1721.1/81130>

⁵ <https://www.ghcoalition.org/hybuild-la>



Multimodal H₂-Airport Hub

Figure 2: Potential water sources vs. usage and H₂ demand (courtesy of PNNL).

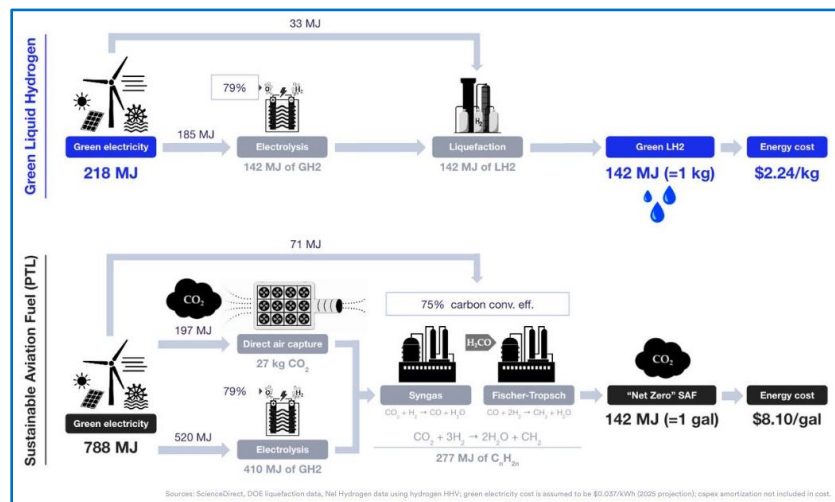


Sustainable aviation fuels offer a near-term drop-in option to help reduce the carbon intensity of aircraft fuel using supply chains similar to those for jet fuel, but, in addition to relative water consumption, hydrogen offer further advantages, particularly when used in fuel-cells. SAFs, either produced by bio or e-fuel methods, cannot abate all emissions such as NO_x and contrails due to fuel combustion, especially in the sensitive upper atmosphere.

Also, as indicated in the diagram below, SAF production requires 3X the energy required to produce LH₂. The renewable Hydrogen used as an aviation fuel has the potential to be 3X less expensive than SAF and substantially less expensive than kerosene today. According to Figure 3, the resulting comparison of liquid hydrogen energy cost is \$0.016 per MJ compared to \$0.057 per MJ for SAF e-fuels (power to liquid).

Using SAFs with existing aircraft engines will not provide enough emissions abatement to achieve net zero emissions by 2050 and the supply of SAFs is not anticipated to meet industry demand. Finally, bio feedstocks needed for SAFs may require challenging decisions between agriculture for food and agriculture for energy in a world where many live in hunger. For these reasons hydrogen should also be considered an alternative to replace jet fuel.

Figure 3: Energy and cost comparison of liquid hydrogen to SAF power to liquid (courtesy of universal hydrogen).





Multimodal H₂-Airport Hub

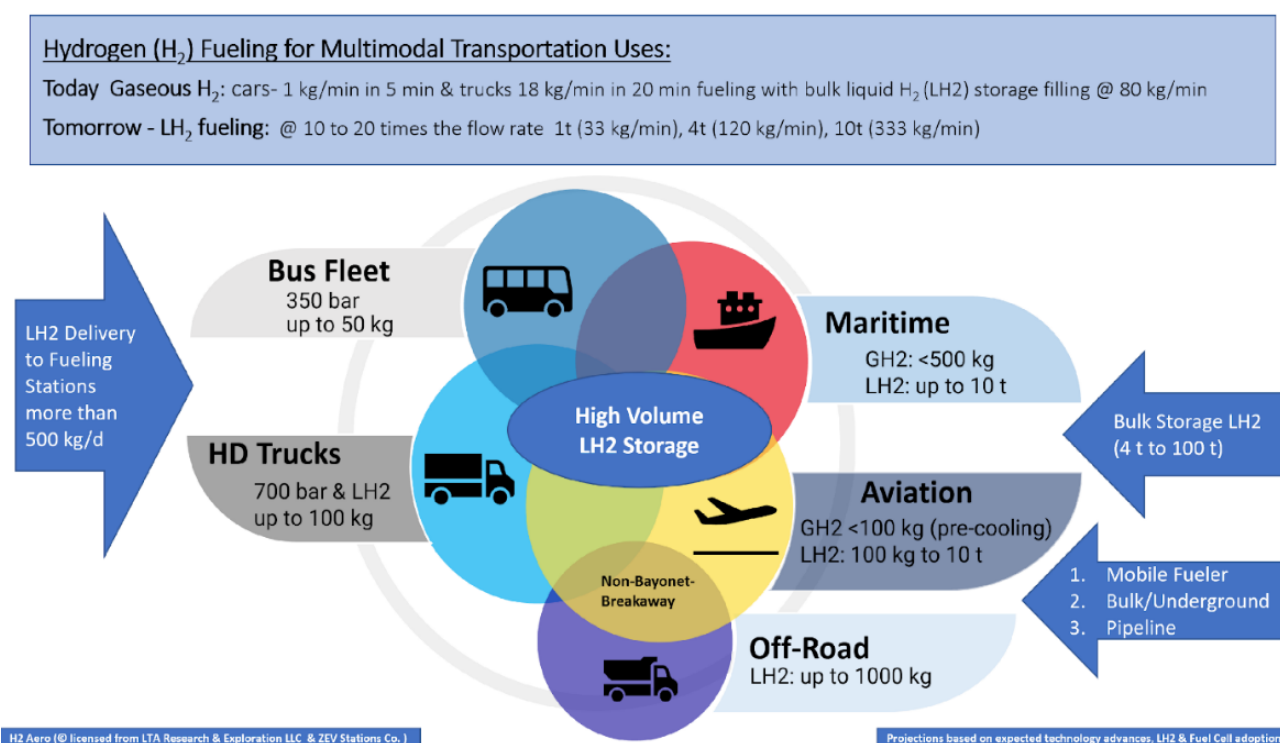
Though this whitepaper is focused on two separate modes of transportation, ground vehicles and aerospace, there is an overlapping multimodal aspect of hydrogen. As hydrogen is introduced and adopted for use by the various transportation and mobility sectors there are opportunities for learning and technology sharing. Many industries such as heavy-duty transportation stand to benefit from the co-development of hydrogen for aerospace purposes. Below is an overview of multimodal transportation uses of hydrogen per onboard storage. There is, for instance, commonality between heavy-duty (HD) ground transportation and small aircraft in hydrogen, as well as fuel cells.

For example, heavy-duty Class 8 trucks will store up to around 100 kg of hydrogen. These trucks have a target fueling time of 10 to 20 minutes. Small aircraft and vertical takeoff and landing (VTOL) aircraft are likely to store similar amounts of hydrogen onboard with a similar fueling time. A second example may be the similarities between regional aircraft hydrogen needs and those of offroad mine haul trucks. Offroad mine haul trucks will store approximately 1,000 kg of hydrogen and target a 20-minute or less fueling time. Regional aircraft (turboprop) or airships (modular tanks) are of a similar capacity in the range of 1,300 kg.

By making use of these opportunities the airport sector can accelerate the adoption of hydrogen technologies (such as hydrogen interfaces), and hydrogen at scale, to realize lower capital and operational costs, and develop a resilient supply chain. Technology sharing may include development of common hydrogen fueling connections, hydrogen storage equipment, safety standards and protocols for hydrogen fueling.

Though gaseous hydrogen is a starting point for most demonstrations, the deployment of larger aircraft or ground vehicles may require bulk liquid hydrogen storage onsite to accommodate the needed volume and fueling requirements.

Figure 4: Hydrogen fueling for multimodal transportation (courtesy of LTA Research and ZEV Station).





3. Hydrogen Policy

Hydrogen aviation is coming and will help meet NetZero. The 2022 Farnborough International Airshow took place during a historic heatwave that beset the UK and Europe. Across the Atlantic, the US endured yet another summer of heat domes, persistent drought and record-high temperatures. These indicators of climate change remind the aviation industry that it contributes 2-3% of the world's carbon emissions and 3-6% of the world's climate changing emissions — in addition to carbon dioxide, NO_x, sulfur dioxide (SO_x), particulates and soot are also released in the upper atmosphere where the deleterious effects are multiplied, resulting in a greater impact on climate change.

This has not gone unnoticed. The widespread emergence of “flygskam” (“flight shaming”) in Europe exposes the industry to a global backlash and adds to the need for positive action. Around the world, individuals and businesses are being called out for private jet use, with an eye to their environmental, social and governance (ESG) footprint. This increases the pressure on aviation to abate its emissions, not only to prevent climate change, but to assure the economic viability of the industry.

NetZero is a campaign by the global air transport industry to achieve net-zero carbon emissions by 2050. It was announced on Oct. 4, 2021, at the 77th Annual General Meeting of the International Air Transport Association (IATA). New national targets have since followed that declaration. In addition, the International Civil Aviation Organization (ICAO, a UN agency) has implemented the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), whereby member states purchase carbon credits to offset their increasing carbon emissions.

The cost of hydrogen production is anticipated to be cheaper than aviation fossil fuels or e-fuels within this decade, boosted considerably by the recent enactment of the Inflation Reduction Act in the US, and other sources of government support. Hydrogen can be electrolyzed wherever there is a source of electricity and water. With renewable electricity generation, the lifecycle carbon intensity of hydrogen production approaches zero and the industry can achieve if not “net” zero, something closer to true zero-emission aviation.

The emerging hydrogen aviation market has an anticipated valuation of \$27B in 2030 and at least \$174B by 2040. The field of hydrogen engine developers ranges from startups to major manufacturers. The field of airframe developers covers a similarly comprehensive range from electric VTOL (eVTOL) startups to established rotorcraft and fixed-wing original equipment manufacturers (OEMs). The range of passenger and cargo operators lined up to adopt hydrogen aviation technologies extends from business charters to sub-regional carriers to global networks.

Hydrogen aviation can also be an economic engine for communities lacking air service. Because hydrogen-powered flight, particularly electric propulsion, will incur lower operating costs, the economics of sub-regional routes will benefit potentially with onsite hydrogen production, increasing resiliency. Airports previously denied service by carriers could gain service. Airports with limited service could see an increase. Formerly isolated communities are expected to attract businesses and workers.

In addition to the hydrogen volume required by aircraft propulsion, airports will have the opportunity to become centralized hydrogen demand hubs. For example, airports with access to hydrogen for aircraft can also support hydrogen fuel cell ground vehicles and hydrogen-powered ground support equipment as well as airport adjacent hydrogen use cases. With demand for hydrogen increasing rapidly, producing hydrogen onsite can also create a valuable revenue stream for airports.

Airports will need support to access the hydrogen economy. There is planning from some manufacturers to have hydrogen-electric powertrains capable of powering 20-seat aircraft approximately starting in 2024, 40-to-80-seat aircraft by 2026, and regional jet aircraft by 2028. In order to prepare for this, select airports would need to begin preparing their infrastructure for hydrogen production, storage and fueling in the near future. However, some airports



Multimodal H₂-Airport Hub

have indicated that they were limited by local, state and federal regulations, as well as by infrastructure challenges and budgets.

From the source or entry point, airports will need to store their hydrogen supply, transport it to the aircraft or ground support equipment or vehicle, and refuel that aircraft, equipment or vehicle.

To implement hydrogen supply at the airport, it will require specially trained personnel, hydrogen management, newly designed and standardized fueling equipment, safety planning, permitting, and more, all of which must be supported by policy. This includes new standards, new regulations or waivers, the modification of existing regulations, and ideally public-private partnerships as proposed in this paper.

3A. Enabling Policy and Regulation

For hydrogen aviation to thrive, a substantial supporting infrastructure is required to service both ground and airborne hydrogen users at airports and vertiports, and perhaps provide mobile supply for off airport and vertiport needs. Aviation infrastructure is heavily regulated by federal and local entities and by the Federal Aviation Administration (FAA).

Additionally, to receive approvals for any infrastructure build, one needs to understand how US airports are governed. Most US commercial airport are owned and operated by public entities which could be local, regional or state authorities with the power to determine operations and funding. Their policy and funding priorities are as critical as any of the regulatory approvals and frequently overlap with federal authorities.

Hydrogen aviation will require enabling policy and regulation across a wide spectrum. The hydrogen aviation community will need to collaborate to promote the benefits of the technology. Together with industry groups, it is possible to collectively lobby and assist regulatory processes across critical feedback enablers. The following is a summary table which documents responsible regulatory agencies and trade organizations and their status as it relates to hydrogen for aerospace.



Multimodal H₂-Airport Hub

Table 2: Roles and responsibilities related to hydrogen for aviation.

Responsible Organization	Status	Analysis, Gap and Applicability
National Aviation Authorities (FAA, Civil Aviation Authority, etc.)	Starting investigations. Currently no existing regulations for use of hydrogen as an aviation fuel.	Gap analysis and Fundamental Hazard Assessments (FHA) need to be carried out with industry to understand new areas of technology that need to be regulated or current regulations that can be amended or adapted. Potential to adopt industry standards (ASTM International, SAE International, etc.) as a means of compliance.
General Aviation Manufacturers Association (GAMA)	Starting investigations. Currently no existing policy for use of hydrogen as an aviation fuel.	GAMA exists to foster and advance safety, interests and activities of the global business and general aviation industry. This includes promoting general aviation manufacturing, maintenance, repair and overhaul and potential economic growth and opportunities. Suggest communicating the published whitepaper to start the conversation with hydrogen in aerospace.
International Civil Aviation Organization (ICAO)	The ICAO CORSIA agreement creates a political commitment to carbon neutrality by 2050. It is in place, no further action needed or expected by ICAO.	ICAO is a United Nations sanctioned aviation treaty and harmonization body across national borders. Most of the ICAO member states have agreed to a carbon neutral goal for commercial aviation by 2050. While hydrogen could be a tool in the toolbox to meet the CORSIA goal, this would not be worked through ICAO. Suggest communicating the published whitepaper to start the conversation with hydrogen in aerospace.
International Air Transport Association (IATA)	IATA membership is made up of each International Airline. It has technical committees to work issues such as hydrogen.	The International Air Transport Association (IATA) supports aviation with global standards for airline safety, security, efficiency, and sustainability. Suggest communicating the published whitepaper to start the conversation with hydrogen in aerospace.

3B. Federal Policy

The current state of hydrogen development in aerospace in the US is at its infancy. The FAA is involved in research, development, and testing at preliminary level. Hydrogen is not yet present in the proposed five-year FAA reauthorization proposals, but it received a mention in the FAA's Climate Action Plan. Without action, this may potentially hamper progress for the certification of hydrogen aircraft. Specifically, the timeline is unknown for the establishment of a regulatory and enabling timeline for on-aircraft and at-airport hydrogen use.

To meet NetZero goals, there is a need for the FAA to craft specific rules (orders) and regulations — CFR-Federal Aviation Regulations (FARs) — for hydrogen flight and the industry will be paced by its progress. Hydrogen for aviation is not just a challenge for the industry; the FAA will need support in the form of data and policy assistance to enable the commercialization of hydrogen.

Below are three recommended paths for the hydrogen aviation community to consider:



Multimodal H₂-Airport Hub

First, adopt hydrogen as another sustainable aviation fuel. Working with the existing SAF political and regulatory ecosystem would be a logical and efficient effort. The FAA and industry have very sophisticated SAF organizations and offices, so hydrogen specific capabilities could be established within these existing organizations and processes.

Second, advocate for specific hydrogen aviation language and funding in the upcoming budgets and requests for information. The FAA and other government agencies need direct cross-industry input for oversight for hydrogen aviation as well as funding mechanisms. The hydrogen aviation community would benefit from advocates and lobbying across many constituencies to encourage Congress to provide both direction and funding as soon as possible, especially for the FAA reauthorization.

Third, advocate across multiple US government agencies. Airports are also subject to other federal regulators that the hydrogen community will need to work with such as the US and California environmental agencies. Because of fuels, lubricants, emissions and de-icing fluids, the Environmental Protection Agency (EPA) is an active regulator around every airport, and they will have an interest in the hydrogen infrastructure build and may determine the need to create airport specific EPA regulation. The Occupational Safety and Health Administration (OSHA) is also an active regulator as airports are an intensely human enterprise; Airports and those who operate on them are mandated to comply with OSHA regulations. This will be no different when establishing hydrogen aviation. The Transportation Security Administration (TSA) regulates the security aspects of the airport and perimeter, including fuel farms and distribution and vehicular access for the delivery of products such as fuel and hydrogen. It will need to be satisfied that the supply-chain is secure and with sufficient vulnerability mitigation. The Department of Homeland Security (DHS) itself also has direct regulations concerning volatile chemicals such as hydrogen peroxide to assure security and assess any threats posed by its possible use. It will likely take an interest in airport hydrogen. The Department of Energy (DOE) is already very active and has been a longtime advocate, and has specific funding for hydrogen projects for generation, hydrogen in transportation and energy sectors. While typically not active at airports unless there are power grid issues, it would be valuable for the hydrogen aviation community to work with DOE to increase their involvement as their participation, perspectives and advocacy would be helpful with the sister regulatory agencies listed above.

3C. State and Local Policy

Airport infrastructure build, funding, approvals, and operations fall upon the governance of these varied airport authorities. In many cases, they impose local regulations above and beyond that of the federal regulators. Working with these authorities can range from straight-forward business protocols to those that are highly partisan which can be difficult. In some cases, powerful labor and trade organizations can also have influence.

3D. Industry Collaboration

The success of SAF approval and commercialization would not have been possible without industry speaking in unison and advocating for the fuel. In the many multi-decade meetings, workshops, advisory and regulatory groups with industry at the table were working toward a common goal. Examples are the aircraft industry, oil industry and SAF development companies, as well as trade organizations and regulators.

The hydrogen aviation industry will need a similar approach if it is to:

- Lobby the FAA with goal of recognizing zero-emission aircraft (e.g., fuel cell) and hydrogen fuel towards achieving NetZero.
- Organize a public-private partnership towards demonstrating, standardizing and commercializing hydrogen as an aviation fuel.

These aforementioned efforts will require substantial resources to be successful. A reliance on a consortium of industry partners and matching government funding will be necessary — particularly for the small companies. Below is an example list of stakeholders, in addition to VFS, who would be needed to drive a similar effort.



Multimodal H₂-Airport Hub

Airport Organizations

- Airports interested in hydrogen aircraft (see Hydrogen Hub Section for example)
- Airport Councils International (ACI)
- American Association of Airport Executives (AAAE)
- National Association of State Aviation Officials (NASAO)

Trade Associations

- Airlines for America (A4A)
- American Institute of Aeronautics and Astronautics (AIAA)
- Air Line Pilots Association (ALPA)
- Commercial Alternative Aviation Fuel Initiative (CAAFI)
- Fuel Cell Hydrogen Energy Association (FCHEA)
- General Aviation Manufacturers Association (GAMA)
- Helicopter Association International (HAI)
- National Business Aviation Association (NBAA)
- Regional Airline Association (RAA)

Academia (some universities in aerospace)

- California State Universities and University of California
- Embry-Riddle Aeronautical University
- Georgia Institute of Technology
- Massachusetts Institute of Technology
- Purdue University
- Pennsylvania State University
- University of Dayton (Ohio)
- University of Maryland
- University of North Dakota
- University of South Carolina
- Washington State University

3E. VFS H₂-Aero Team Recommended Policy Measures

Policy

- Support hydrogen aviation policy as a follow-on to SAF.
- Develop a government and industry roadmap to NetZero airports and aircraft with H₂.
- Develop policy to accelerate permitting, codes and standards (C&S) of H₂-Airports (and public-private partnerships).
- Support large scale carbon-free hydrogen production.

Funding Support

- Support the FAA's Airport Improvement Program and Voluntary Airport Low Emissions Program for hydrogen infrastructure.
- Support H₂-Airports and H₂-Aircraft at the DOE Loan Office and the Department of Transportation's Transportation Infrastructure Finance and Innovation Act.
- Add H₂-Airport to Low Carbon Fuel Standard (LCFS).
- Support H₂-Airport and aircraft technology development programs.



4. Codes and Standards Status and Gaps

This section contains a status and gaps analysis of key standards and regulations with recommendations for new efforts. Presently there are established codes and standards for ground vehicles that could also be applicable to some applications for hydrogen at the airport. While there are some existing fuel cell and hydrogen standards for aerospace — such as the SAE and European Organization for Civil Aviation Equipment (EUROCAE) efforts — there is a need to create new standardization efforts as outlined herein.

Hydrogen aircraft need exponentially more hydrogen in comparison to ground vehicles. It is likely that for small aircraft — such as eCTOL, eRotor and eVTOL — the fueling methodology may be similar to bus and heavy-duty fueling, albeit fueling on the tarmac at 35 MPa. However, large aircraft such as a narrow body or a widebody require up to 100 to 1000 times more hydrogen storage than ground vehicle fueling. With this larger amount for aircraft fueling, there will be an exponentially larger need for hydrogen supply and delivery on site.

Because of this, new standards are needed for both gaseous and liquid hydrogen, as well as for developing mobile fueling. In conjunction with standardization, a public-private partnership would be an excellent route to assist with airport demonstrations to coordinate data generated to help validate standards before any are published. Aircraft regulations need to be adapted or created in order for aircraft to be able to be certified by the FAA. Perhaps a “sandbox” testing environment between the aircraft makers, the FAA and other consortium members is needed to accelerate this activity. Reference the chapter on demonstrations for further recommendations.

4A. Key Airport Fuel and Operations Standards and Regulations

While there is an existing FAA guideline for Aircraft Fuel Storage, Handling, and Dispensing on Airports (150/5230-4C), it is not mandatory. However, demonstration thereof is one way of complying with 14 CFR Part 139 – Certification of Airports. To receive government funding, it may be required to demonstrate compliance. In this chapter there are 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 is not necessarily followed at all airports. Each airport may have different local fire code regulations and operating procedures different than what is described in NFPA 407.

While the requirements specified in NFPA 407 are not directly applicable to hydrogen, the topics covered and considered within the document are worth adapting to enable the safe adoption of hydrogen as an aviation fuel. The main topics covered within NFPA 407 are general fueling requirements, aviation fueling facilities, airport fueling vehicles, rooftop heliports and self-service aircraft fueling.

It would be recommended to update present codes for airports — for example, NFPA 407 — with key topics from NFPA 2, focused on hydrogen in respect to airport environment. NFPA 2, Hydrogen Technologies Code, provides fundamental safety provisions for the generation, installation, storage, piping, use and handling of hydrogen in compressed gas (GH₂) or cryogenic liquid (LH₂) form. This comprehensive resource covers everything from hydrogen industry terminologies and general fire safety practices to deflagration protection, explosion protection and so on. The code is a safety essential for officials reviewing permits and inspecting occupancies containing hydrogen as well as for designers, engineers, installers, contractors and facility managers responsible for applications involving:

- Storage of hydrogen in bulk and non-bulk quantities.
- Use of hydrogen in laboratories.
- Dispensing and fueling of hydrogen for vehicles and vehicle servicing and repair.
- Systems for fuel cell power and generation, such as backup power systems using polymer electrolyte membrane (PEM) fuel cells and forklifts.
- Applications involving combustion processes and special atmospheres, including electrolytic production of hydrogen.



Multimodal H₂-Airport Hub

In the UK, the Control of Major Accident Hazards (COMAH) Regulations aim to prevent and mitigate the effects of major accidents with dangerous substances for storage of hazardous substances including hydrogen up to 50 tons. The lower tier up to five tons requires a Major Accident Prevention Policy (MAPP). The upper tier additionally requires a safety report, emergency response plan, and information to be supplied to local authorities and the public.

Most of the existing airport standards are focused on liquid hydrocarbon fuels, however the topics they cover and the risks they intend to mitigate by outlining such procedures should be adapted to the use of hydrogen as an aviation fuel. Below is an overview of some existing airport standards.

Table 3: Standards for operational procedures and quality assurance for airports.

Standard	Title
NFPA 407	Standard for Aircraft Fuel Servicing
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
JIG 2	Aviation Fuel Quality Controls and Operating Standards for Airport Depots and Hydrants
JIG 4	Aviation Fuel Quality Control and Operating Standards for Smaller Airports
Energy Institute (EI)/JIG 1530	Quality Assurance Requirements for the Manufacture, Storage and Distribution of Aviation Fuels to Airports
FAA 150/5230-4C	Aircraft Fuel Storage, Handling, and Dispensing on Airports

4B. Ground Vehicle Hydrogen Standards

The table below gives a list of key ground vehicle standards and hydrogen flow rates and gaseous versus liquid hydrogen fueling.



Multimodal H₂-Airport Hub

Table 4: Reference of key ground vehicle fueling standards.

Name of Standard	Standard	Applicable Vehicle	Applicable Gaseous Hydrogen Fueling	H ₂ Flow Rate	Customer Required Fueling Time	LH ₂ Cryogenic Hydrogen Fueling
Fueling Protocols for Light Duty (LDV) Gaseous Hydrogen Surface Vehicles	SAE J2601	LDV/ Interim HD	GH₂	LDV 60 g/s HDV 60 g/s	LDV HDV	
Fueling Protocol Gaseous Hydrogen Powered Heavy-Duty Vehicles (HDV)	SAE J2601/2-5	Bus/Truck	GH₂	Bus 120 g/s Truck 300 g/s		
Hydrogen Surface Vehicle to Station Communications Hardware-Software	SAE J2799	IrDA LDV (Bus/ Interim HD)				
Compressed Hydrogen Surface Vehicle Fueling Connection Devices	SAE J2600 ISO 17268	LDV-Bus	GH₂	LDV 60 g/s Bus 120 g/s HD 300 g/s (draft)		
Gaseous hydrogen — Fueling protocols hydrogen-fueled vehicles	ISO 19885	Heavy-Duty	GH₂	HDV 300 g/s (also future J2601/2)	100 kg in 15 min	
Hydrogen Fueling Station Standard	ISO 19880-1	LDV/ Interim HD	GH₂			Liquid H ₂ Storage and Transfer
Hydrogen Fuel Quality — Product Specification	ISO 14687	ICEs, PEM Fuel Cells, Industrial applications, aircraft, spacecraft	Gas, Liquid, Slush	N/A		
Hydrogen Fuel Quality for Fuel Cell Vehicles	SAE2719	All FCEV	GH₂	N/A		

4C. Aircraft Hydrogen and Fuel Cell Standards

SAE/EUROCAE WG-80 is tasked to work as a joint group with SAE AE-7AFC and develop guidelines to support the use of hydrogen (GH₂/LH₂) and fuel cell systems for onboard aircraft applications. Performance requirements such as power and reliability are outside the scope of this working group.

SAE AE-5CH which is already in process has created a hydrogen fueling task group for hydrogen fueling of aircraft and is starting standardization (in process).



Multimodal H₂-Airport Hub

Table 5: Key aircraft hydrogen standardization.

Name of Standard	Standard	Aircraft Application	Applicable Gaseous Hydrogen
Aircraft Fuel Cell Safety Guidelines	AIR6464/ED-219	Definitions, Safe H ₂ -Aircraft Integration	GH ₂ /LH ₂
Installation of Fuel Cell Systems on Large Civil Aircraft	AS6858/ED-245	Integration of Fuel Cell Systems	GH ₂
Considerations for Hydrogen Fuel Cells in Airborne Applications	AIR7765/ER-20	General Properties, Hazard Mitigation,	GH ₂ /LH ₂
Liquid Hydrogen Storage for Aviation	AS6679	LH ₂ General Properties, Requirements, Onboard Storage	LH ₂
Gaseous Hydrogen Storage for General Aviation	AS7373	GH ₂ General Properties, Requirements, Onboard Storage	GH ₂
Airport Hydrogen Fueling- Gaseous and Liquid (SAE AE-5CH)	AIR AIR8466	Hydrogen Fueling	GH ₂ /LH ₂

4D. Gaps in Aircraft Fueling Standards

Below are the key gaps in hydrogen standards which are deemed to be a priority in the creation of a Multimodal H₂-Airport Hub. It is important to note that ground vehicle fueling with dispenser standards are most likely to be significantly different than mobile fueling on the tarmac.

Gaps for hydrogen fueling for gaseous and liquid hydrogen systems:

- Gaseous: Fuel Range 100 kg per 35 MPa within time.
- For small aircraft, gaseous hydrogen fueling should be able to use the connector from bus 35 MPa ground vehicle fueling, to 100 kg at 120 g/s (70 MPa Draft ISO 17268:2022).
- However, a new fueling protocol should be standardized for 35 MPa gaseous hydrogen fueling potentially with a novel protocol for mobile hydrogen fuelers that could be used on the tarmac.

Liquid H₂ fueling status and gaps:

- Liquid hydrogen fueling may necessitate new fueling protocol connectors with a maximum fuel rate up to approximately 11,000 kg per 60 min (widebody). The current status of liquid hydrogen fueling technology with heavy-duty trucks at an LH₂ station is 10 kg per minute. Though a LH₂ trailer is able to dispense 100 kg per min, it is using a bayonet type of connector requiring constant monitoring and only up to 4,000 kg. Therefore, a LH₂ fueling standard should be evaluated.
- There are potential synergies for LH₂ fueling connectors and protocols with mobile fuelers up to 1,000 kg (regional aircraft) with offroad mine trucks. Mobile hydrogen fueller standard GH₂ and LH₂.

Industry standards recommendation:

- Industry trade group standards: Airlines for America
 - Update operational standards for the fueling system and depot. Operational safety standards should be developed in line with appropriate safety levels that are the same or better than today using properties of hydrogen. For example, there is a 3 m separation distance for kerosene, this should be evaluated for both GH₂ and LH₂ through a safety analysis.



5. Hydrogen Safety

5A. General Description of Hydrogen Storage Systems and Safety

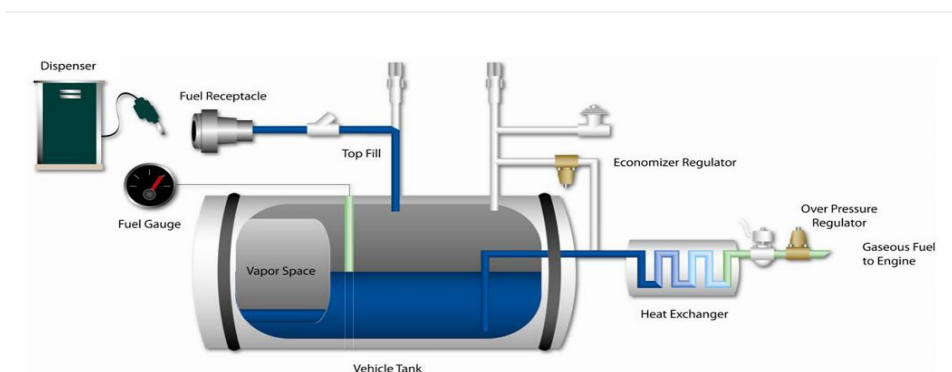
A number of hydrogen's properties⁶ make it as safe or safer to handle and use than the fuels commonly used today. For example, hydrogen is non-toxic. In addition, because hydrogen is much lighter than air, it is highly buoyant and exits rapidly upwards. It also dissipates rapidly when it is released, allowing for relatively rapid dispersal of the fuel in the unlikely case of a leak. Some of hydrogen's properties require additional engineering controls to enable its safe use. Fuel systems design is critical and includes appropriate material selection, redundant pressure relief devices, systems designed to withstand extreme-case conditions, provide hydrogen shutoff(s) for isolation, check and overflow valves, and so on. There are multiple safety systems for hydrogen storage in regards to overpressure and over temperature in the event of a fire or overpressure. For gaseous storage there are Temperature Pressure Relief Devices (T-PRDs) to avoid over temperature and for liquid hydrogen, there is a Pressure Relief Valve (PRV) to avoid overpressure.

There are two main types of hydrogen storage and delivery systems: gaseous hydrogen (GH₂) and liquid hydrogen (LH₂). Liquid hydrogen is much more energy dense than gaseous and as per the fueling matrix in Table 9, both of these types of storage will be used in aerospace applications. The main difference is service pressures to 70 MPa for gaseous stored at ambient temperature and up to 0.1-1.6 MPa for LH₂ to subcooled liquid hydrogen, stored at cryogenic temperature (-253°C).

Gaseous hydrogen storage retains fuel over long periods like conventional fuel. A safety measure utilizes a check valve to insure only one direction of hydrogen flow — for both gaseous and liquid hydrogen. Liquid hydrogen is stored at cryogenic temperatures (-253°C) with an insulative vacuum jacket that has a very small amount of boil off, which is safely mitigated through venting. Vented hydrogen is to be routed through a tube located away and upwards from the vehicle or aircraft. With regards to storage and servicing of hydrogen vehicles and aircraft in an enclosed space, risk is mitigated through a service port.

In the example diagram below, the liquid hydrogen tank has a vapor space above the liquid and is fueled through a coupling. At the start of fueling the connection allows liquid to flow into the tank and gaseous hydrogen to be recovered safely in the fueling apparatus. The fuel cell or internal combustion engine is fed by gaseous hydrogen developed from gasifying the liquid hydrogen through a heat exchanger. The LH₂ storage level is monitored through a fuel gauge using the height of the LH₂ in the tank.

Figure 5: Liquid hydrogen (LH₂) on-board storage diagram (courtesy of Chart Industries)



⁶ <https://www.energy.gov/eere/fuelcells/safe-use-hydrogen>



5B. Storage and Fuel Cell Safety

There are a number of hazards that are mitigated by safety devices and by using the properties of hydrogen. For instance, if there is a fire, a hydrogen explosion is mitigated by the safe release of hydrogen away from the aircraft through a PRD and/or T-PRD. These safety devices work extremely effectively to evacuate hydrogen in the event of a fire.

Several studies and demonstrations have been published to show that hydrogen can be designed to be as safe — or safer — than liquid hydrocarbon fuels such as diesel and gasoline. This safety chapter and appendix lists and describes some of the resources for understanding hydrogen safety such as H2Tools.org, the DOE Introduction to Hydrogen for Code Officials, FAA Final Report Template (faa.gov) and OSHA, among others:

- Hydrogen Tools (h2tools.org) is one of the most complete resources available when it comes to hydrogen safety information. H2 Tools Resources include the following: Center for Hydrogen Safety (US DOE Safety Resource); Hydrogen Safety Panel (safety experts from across the industry, coordinated by the Pacific National Northwest Laboratory, PNNL); codes and standards (a comprehensive list of C&S worldwide); H2FIRST (training materials for first responders); HyRAM (an open-source quantitative risk assessment tool developed by Sandia National Laboratory); and learnings and guidance, papers and references, training materials and videos.
- A study aiming at understanding liquid hydrogen is being performed by the Health and Safety Executive, a UK government agency. The most recent results can be found in the published report: <https://www.hse.gov.uk/research/rrpdf/rr986.pdf>.
- The “Guidebook for Deploying Zero-Emission Transit Buses” (2021), published by the National Academies Press is also a good resource for understanding the safety of deploying a large number of vehicles running on hydrogen, in this case city buses. This would be a useful resource to transfer the knowledge to hydrogen in aviation.
- Even though the resources available are not targeted for aerospace, the website www.FCHEA.org addresses a wide range of hydrogen applications, some of which are definitely applicable to hydrogen on the ground, including facilities and infrastructure. Several hydrogen properties make it safer to handle and use than hydrocarbon-based fuels. Hydrogen is non-toxic, much lighter than air and it diffuses rapidly when released. In fact, hydrogen is 16 times more buoyant than air, making it escape very quickly upwards. Unlike jet fuel, hydrogen does not accumulate when leaked or released in the open.

Hydrogen, however, is combustible and has a wide range of flammable concentrations in air and a lower ignition energy than gasoline and natural gas. Like other combustible gasses in closed spaces, it can be flammable and explosive with the right mixture. To mitigate risks in the hangar, passive safety methods such as a simple service connection to the vent tube (for LH₂) — in addition to adequate ventilation — are recommended. To mitigate risk further, active methods such as hydrogen sensors and/or ultraviolet (UV) detection are used.

It is important that the public, as well as regulatory bodies, aircraft OEMs, emergency responders all understand that hydrogen and fuel cell-powered aircraft can be designed and operated with a very high level of safety, the same as today. This can be done with support from OEMs, fuel cell and hydrogen suppliers, equipment suppliers, service providers, regulatory bodies, and government. Below is an overview of general safety educational needs and recommendations.



Multimodal H₂-Airport Hub

Table 6: General education recommendations.

Education	Needs	Recommendations
Public perception	Understanding H ₂ is the largest used industrial gas that can easily be safely handled in transportation and usage just like kerosene and aviation gasoline (avgas).	Education on hydrogen characteristics (buoyancy and dispersion in air) that are on par or safer than conventional heavier than air fuels.
Industry understanding knowledge (differences)	The industry for decades has implemented safety measures for the complete hydrogen supply chain, from H ₂ production to storage, fueling and operation. It is also beneficial to communicate to the public the stringent safety procedures and designs for all the hydrogen and aircraft systems in accordance with the aviation standards, codes and regulations. The focus is on the intersection and guidance of existing industrial hydrogen practices with requirements towards fueling at an airport.	Industry should have robust, but practical safety standards and procedures to address design of hydrogen systems and fueling to maintain aviation safety with the appropriate levels of mitigation with identified risks, as with all fuels. For aerospace, there will likely ask for a high level of safety criteria (approximately 10 ⁻⁹) level of risk criteria which may involve redundancies and/or additional safety measures.
Operational training	Identify what is different about existing hydrogen handling and usage from current aviation fuels such as kerosene and SAF. Simultaneous H ₂ fueling will also need to be managed. There is a need to understand how multi-fuels (charging, liquid and gaseous hydrogen, and liquid/fossil fuels) will work safely together in an airport.	Utilize the extensive industry training and upgrade it as needed.

An important starting point in understanding the safety aspects of hydrogen use in aviation is to understand the differences between hydrogen fuel and conventional fuels. The table below highlights the difference in properties between liquid kerosene which is the most used aviation fuel, and hydrogen in the most common utilized phases, gas and liquid.



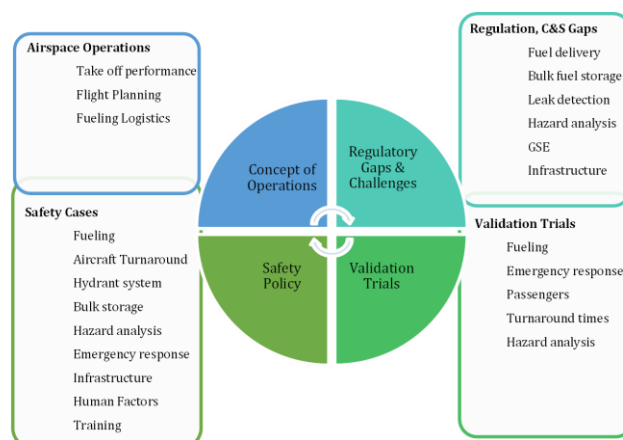
Multimodal H₂-Airport Hub

Table 7: Properties of hydrogen and kerosene.

	Parameter	Units	Hydrogen		Kerosene
Normal Storage Conditions	State		Liquid LH2	Gas GH2	Liquid
	Temperature	K (°C)	20 (-253)	298 (25)	298 (25)
	Pressure	bar	1.5	700	1
	Density	kg/m ³	71	39	804
	Flammable Range in Air	vol%	4 to 75	4 to 75	0.6 to 4.7
	Minimum Ignition Energy	mJ	0.02	0.02	0.25
Specific Energy	Gravimetric Efficiency	%	60	10	98
Autoignition (hot surface)	Temperature	K (°C)	858 (585)	858 (585)	498 (225)
Buoyancy		m/s	See Note ⁷	Gaseous: 14X faster in air	Heavier than air
Diffusivity	@ 20°C	cm ² /se c	n/a	0.756	

There are extensive emergency response documents and references for fuel cell vehicles (see Reference 7 for more information). Properly trained operators, technicians and emergency responders are critical to the successful introduction of hydrogen (see Reference 8). However, the first responder materials and training for hydrogen storage, transport and delivery should be updated for airports. Fuel cells do not contain very large amounts of energy when turned off. The amount of energy in a fuel cell turned off is significantly smaller than the energy contained in a high voltage battery providing a similar level of power for propulsion. Overall, the safe introduction and integration of hydrogen at an airport top level points are shown in Figure 6 below.

Figure 6: Key factors for a safe introduction and integration of hydrogen to an airport.



⁷ Note: LH2 is heavier than air, however the extreme cold of the cryogenic gas compared to ambient temperatures causes it to quickly vaporize and become high buoyancy gas upon leaving its containment. Standards are under development for plumes of cold hydrogen. Vent stack height and plume characteristics should be reviewed with aircraft during fueling.



6. H₂-Aero Fuel Matrix

H₂-Aero has worked between the aircraft OEM and hydrogen industries to develop a H₂ fuel guideline meant to be used as a basis for Airport demonstration and a starting point for standards. The goal of this section is to define fuel storage per each aircraft categories: eCTOL (electric conventional take-off and landing), eVTOL (electric vertical take-off and landing), eRotor (electric rotorcraft), LTA (lighter than air or dirigible).

6A. Use Case Class vs. H₂ Storage Type

Below is an overview of FAA CFR 14 aircraft use cases vs. H₂ storage type. It is expected that the following aircraft table will represent the type of hydrogen storage used — GH₂ and LH₂ — per aircraft type and use case. In this respect, there is a time element represented with the green X. This X represents a limited period of time for demonstration or interim early phase only before there is LH₂ available.

Table 8: Use case class vs. H₂ storage type.

CFR 14 Class	Use Case vs. H ₂ Aircraft Type	GH ₂ Gaseous Hydrogen	LH ₂ Cryogenic Hydrogen
Part 21.17(b) Special Category	H ₂ -Airships	X	X
Part 21.17(b) Special Category	H ₂ -eVTOL aircraft (≤19 passenger)	X	X
Part 23	Small aircraft: H ₂ -eCTOL and H ₂ -eSTOL aircraft (≤19 passenger)	X	X
Part 27 or 29	H ₂ -eRotor	X	X
Part 25	H ₂ -Regional Aircraft (100), H ₂ -Narrowbody (100), H ₂ -Widebody (200+)		X

6B. Hydrogen Fuel Capacity vs. Size of Aircraft

Below is an overview of hydrogen aircraft related to size vs. fuel capacity which may be found at the same airport (except LTA-airfields). The colors represent potential fueling categories between the aircraft classes. The hydrogen capacity ranges from less than 100 kg to over 10,000 kg of hydrogen storage capacity. The aircraft shown are examples of categories which may evolve over time.



Multimodal H₂-Airport Hub

Figure 7: Hydrogen fuel capacity vs. size of aircraft (courtesy of Novadev, ZEV Station and LTA Technologies).

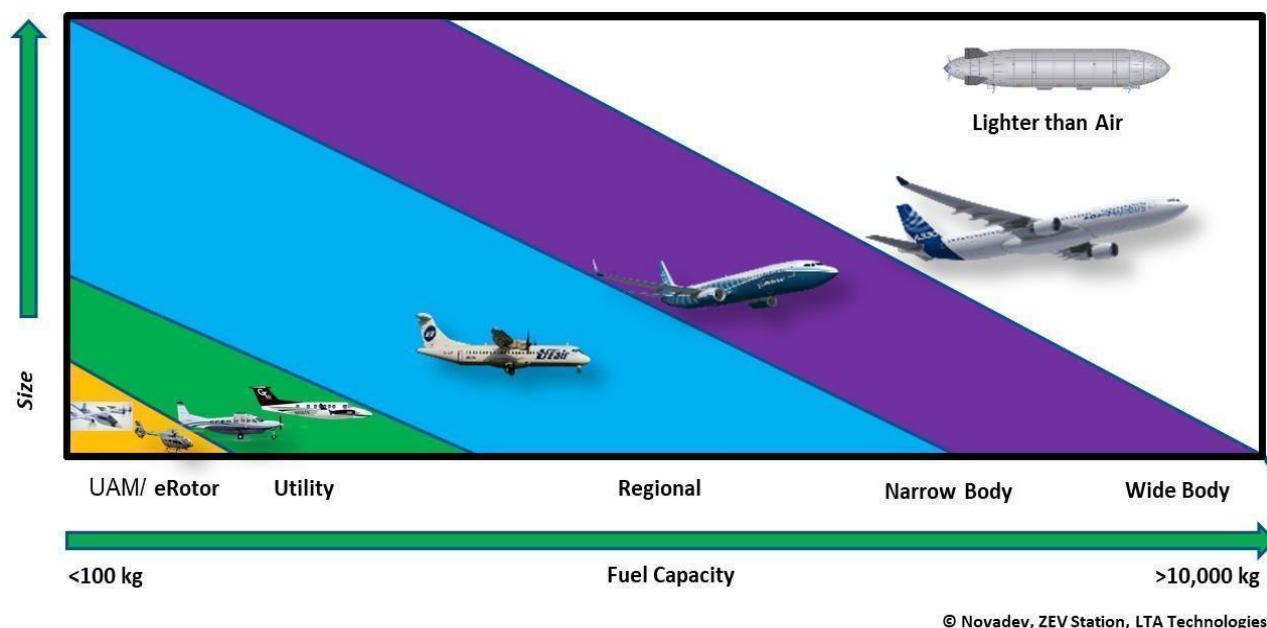


Table 9 describes the H2-Aero Team’s hydrogen use case per aircraft type. Each type of aircraft has an approximate range shown (without reserve). The table shows the hydrogen storage amounts for each of these aircrafts which is necessary to be able to calculate hydrogen fueling as well as understanding the scaling towards the airport hub. The H2-Aero Team developed consensus upon the acceptable aircraft fueling time which is based on conventional vehicle limits. Note, the larger jet fueled aircraft (regional, narrowbody and widebody) are harmonized on Aerospace Technology Institute’s FlyZero Report. There are also multiple use cases representing the location where the hydrogen fueling would occur such as the airport tarmac, rooftop, airfield and so on).



Multimodal H₂-Airport Hub

Table 9: H₂-Aero Team hydrogen amounts for aircraft type.

Use Case vs. H ₂ Aircraft Type	Typical vs. Maximum Range (no reserve) in nm	Onboard H ₂ (kg) GH ₂ /LH ₂	Customer Fueling Time	Use Case Location	Fuel Use Case Location
→ Small Aircraft: H ₂ -eCTOL/eSTOL	250-500 nm	GH ₂ - 100kg	25-30 minutes	Airport	Airport tarmac
→ UAM (short range)	57 nm (UAM)	<100 kg	15 minutes	Rooftop/ Vertiport/ Airport etc.	Heliport*/Vertiport ⁸ Airport/Autonomous refueling
→ H₂-eVTOL – AAM (Long Range)	~150 nm (AAM)	>100 kg			
→ H₂-eRotor (5pa/7000 lb.) H ₂ - eRotor (13pa/9000 lb.)	350 nm 512 nm	G-LH ₂ 60-90kg LH ₂ 210-360kg	15 minutes 30 minutes	Rooftop/H-Pad, etc.	Heliport*/Vertiport/ Airport/Autonomous refueling
Large Aircraft eCTOL				Airport	Airport tarmac
→ Regional	800 nm (LH ₂)	1300 kg	20 Minutes		ATI Two Scenarios
→ Narrowbody	2400 nm (LH ₂)	2600 kg	25-30 Min		<u>Small-Medium</u> LH ₂ Fueling Trucks
→ Widebody	5750 nm (LH ₂)	11700 kg	1 hour		Airport tarmac
					<u>Large:</u> (2040) LH ₂ Hydrant Pipeline
→ H₂-Airships	540 nm 5000 nm	GH ₂ -100kg LH ₂ -5000-10000kg ⁹	30min-1h	Airfields	Airfield, Hangar

⁸ Helipad encompasses heliport — ground and rooftop (vertiport), helideck — all maritime applications including oil rig and ship, all austere take-off and landing conditions.

⁹ Hydrogen used for Airships is solely for propulsion (not for buoyancy)



Multimodal H₂-Airport Hub

7. H₂-Airport Demo: Public-Private Partnership and Sandbox

This airport demonstration chapter contains an outline for fueling trials accompanying flight tests for the industry. The intention is for a public-private partnership to use the content to advance technology and standardization especially for hydrogen fueling and fueling interfaces. Though OEM technologies and data may be proprietary, there is a great benefit to share data to help further standardization for safety, fueling interface, protocols and procedures. There is an additional summary for a “sandbox” testing environment which is meant to be potentially a separate test between regulators and industry and used in some cases to create regulations (CAA example).

7A. H₂-Airport Public-Private Partnership

The goal of this public-private partnership is to test multiple types of aircraft, with respective fueling types on the airport tarmac. Both gaseous and liquid hydrogen fueling respectively would benefit from data sharing. Mobile fuelers in the form of gaseous tube trailers (e.g., around 700 kg at 50 MPa) and liquid hydrogen trailers (e.g., 4000 kg at 253°C, 1 MPa) on the tarmac are depicted in the illustration below. The trials could take place at multiple airports and potentially on runway independent locations (heliports) for urban air mobility (UAM), eVTOL, eRotor, and lighter than air, among others.

Figure 8: Gaseous hydrogen trailer — fuel cell aircraft demonstration (courtesy of ZEV Station).



The H₂-Aero Team has proposed that a testing demonstration should gather onboard storage data from both sides of the coupling at the mobile airport hydrogen refueler and the aircraft tanks. The recommended data set should include hydrogen temperature, pressure and flow rates, along with aircraft and fueler safety monitoring, leak detection, alarms, etc. Gathering local requirements such as fueling safety distances would also be beneficial.

Ambient conditions should be monitored. The documentation of extreme temperature conditions on the tarmac would greatly benefit the data integrity. For example, fueling on the tarmac in hot ambient environments (e.g., Palm Springs, Palm Springs International Airport (PSP), etc.) could give an extreme case data set to help validate fueling protocols and powertrains. Any lessons learned or concerns from this demonstration and potential safety upgrades should also be brought forward in a final evaluation.



Multimodal H₂-Airport Hub

Within the bounds of this proposed public-private partnership there are many areas of potential collaborative partnerships for development and demonstration. For instance, a number of aircraft OEMs could share the same mobile fueler and the data set may be easy to compare. A substantial benefit to the aerospace and transportation industries would be the harmonization of standards, and to avoid parallel development of incompatible standards that could impede the use of hydrogen as an aviation fuel.

It is suggested that multiple hydrogen demonstrations be developed in multiple locations to perhaps be able to fly between the locations and/or compare data in real time.

Figure 9: Liquid hydrogen trailer — fuel cell aircraft demonstration (courtesy of ZEV Station).



7B. Key Outcomes to an H2-Aero Public-Private Partnership

Suggested outcomes through collaboration in a hydrogen aerospace and fuel public-private partnership:

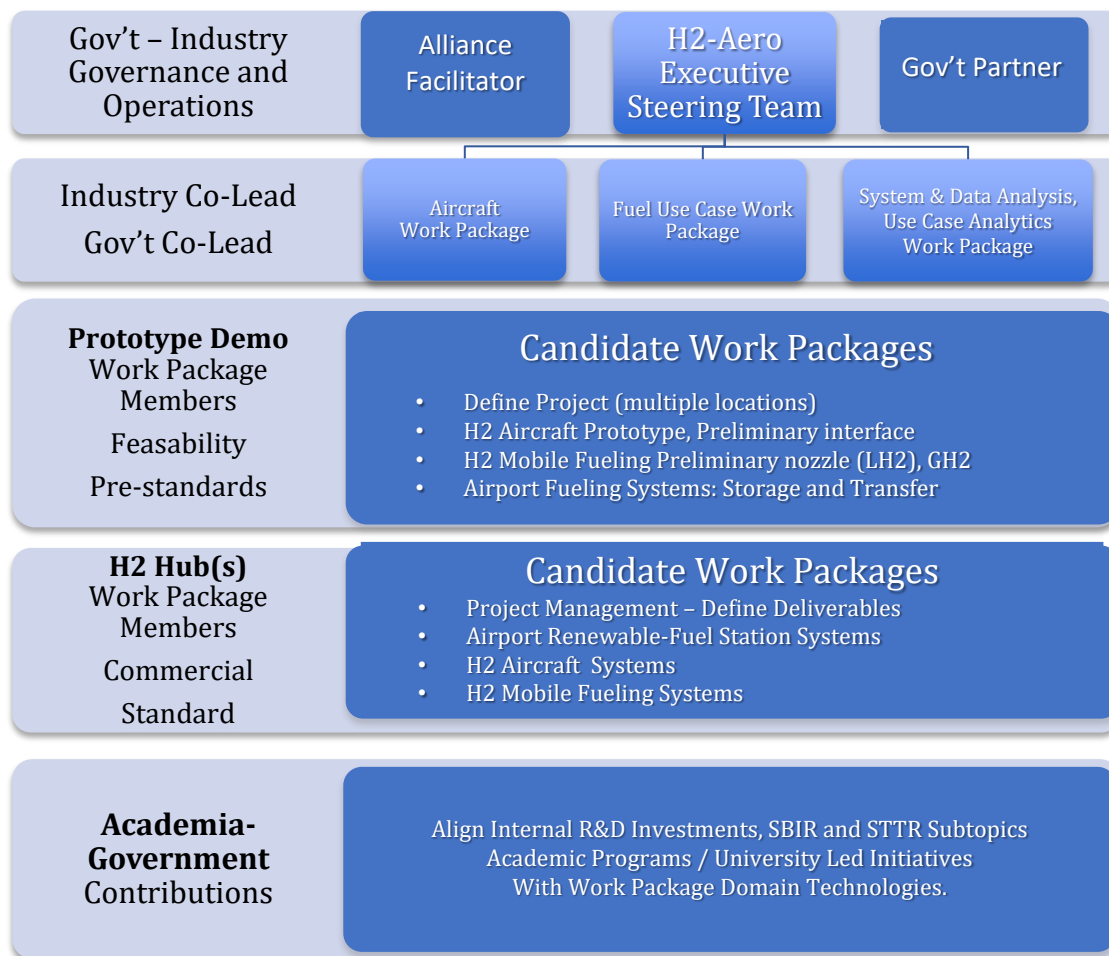
- Safety and performance of gaseous and liquid hydrogen fueling per aircraft class.
- Validation of coupling technology (nozzle/receptacle).
- Validation of fueling protocol and aircraft communications (e.g., SAE AIR8466)
- Definition of minimum safety distances.
- Demonstration for robustness of fueling under extreme conditions.
- Information for harmonizing and streamlining permitting.
- Information to create data-based standards and regulations related to hydrogen storage and fueling.
- Information for best practices for fueling operations and safety protocols.

The purpose of an H2-Aero Public-Private Partnership (PPP) is the sharing of data, financing and resources aimed at promoting the accelerated development of standards, aircraft and hydrogen hubs at airports. The following PPP structure example includes multiple levels of coordination; industry and government co-lead working packages; prototype demonstration of aircraft and mobile fueling systems; hydrogen hub working packages for airports, aircraft manufacturers, ground vehicle manufacturers, and hydrogen production and distribution; and academia and government contributions. Below is an example overview of such a public-private partnership structure.



Multimodal H2-Airport Hub

Figure 10: Outline of the H2-Aero proposed public-private partnership demonstration.



7C. “Sandbox” Testing Environment

A sandbox environment is an isolated testing environment between industry and regulators to help organizations demonstrate new technologies while addressing safety and risk mitigation. This can assist in firsthand data gathering regarding the status of the technology. Similar to a public-private partnership, the goal in this case is to demonstrate the safe hydrogen aircraft operation and fueling in a controlled environment. Ideally, the public-private partnership and sandbox testing could be combined. However, this depends on whether it makes sense to individual aircraft OEM and regulators.

Within this sandbox, issues can be identified including gaps between the design or intended operations and acceptability under existing regulations. This is carried out by identifying hazards, proposing mitigations, and investigation through testing and simulation in safe environments to gather data to support a safety case. The sandbox is comprised of a targeted iterative process for planning, testing and data including redesigns and documenting lessons learned.



Multimodal H₂-Airport Hub

The reference section contains a link for sandbox guidance for future flight developments as an example of the learning process (e.g., used with regulations) for new technologies.

Within the sandbox testing environment, the following information can be identified:

- Operating procedures
- Operating environment
- Technology, or operational solutions
- Timescales to technology maturity

Suggested areas for a sandbox include gathering information from the industry and government:

Performance Data

- Flight demonstration and power usage.
- Safety and performance of gaseous and liquid hydrogen fueling protocols per aircraft class.
- Validation of coupling technology (nozzle/receptacle).
- Validation of fueller and aircraft communications.
- Demonstration for robustness of fueling under extreme conditions.

Information

- Powertrain information.
- System and aircraft hydrogen storage and receptacle.
- Information for harmonizing and streamlining minimum permitting including safety distances.
- Best practices for fueling operations and safety protocols and standards for fuel transfer and communications.
- Key safety protocols and mitigations.



8. Multimodal H₂-Airport Hub (Ecosystem)

Due to the large volume of ground vehicle traffic outside the airport as well as aircraft and ground support equipment within an airport, there is great potential to combine this demand and create a large hydrogen airport hub. Thus, the concept of a multimodal hydrogen hub has evolved to supply hydrogen, at scale, for both ground vehicle and aerospace applications at the airport. Since ground transportation is further advanced in commercializing, the H₂-Aero Team is advising to first start with a station servicing mainly the vehicles outside the airport (cars, trucks, buses) and then expand to an entire airport hub. The goal is to develop a scalable “cookbook” to assist airports and hydrogen hub developers to size their future hydrogen activities and ecosystem by helping estimate the amount of transportation fuel needed for an entire Airport ecosystem.

In order for a Multimodal H₂-Airport Hub to be successful, there will be collaboration needed between aircraft manufacturers, technology companies and hydrogen infrastructure providers, along with government officials. Further, a hydrogen airport could act as a hydrogen hub enabling sector coupling for instance between ground vehicles off the highway and emerging hydrogen aerospace. This can be done by creating a centralized hydrogen hub near the airport to reduce cost and ensure the fuel supply for both industries.

To understand the size of a multimodal hydrogen hub, the first task is to understand the expected order of magnitude of hydrogen demand that is required at that airport and in the near vicinity. The anticipated hydrogen demand should be aligned with the near- and medium-term feasibility of the amount of green hydrogen production and supply within that locale. For this reason, the H₂-Aero Team chose a small regional airport as an attainable example for a hydrogen hub and to complement the work done with ATI’s FlyZero effort at a large airport, namely London’s Heathrow Airport.

The scope of airport activities that could be served via hydrogen include:

1. Ground vehicles: highway traffic — cars and trucks — as well as airport traffic such as buses and rental cars.
2. Ground service equipment (GSE): tugs, baggage equipment, fueling trucks and forklifts.
3. Aviation and aircraft: eCTOL, eVTOL, UAM and eRotor.

The H₂-Aero Team determined that the first step in selecting an airport for a pilot demonstration is calculating the level of hydrogen usage — excluding additional reserves, etc. — determined by an airport’s policy. A first implementation of an airport hub would be valuable for demonstration of hydrogen-powered flight as well as GSE. The airport chosen by the team as an example was a small regional airport, Long Beach Airport (LGB), due to its proximity to existing hydrogen demand from heavy-duty trucks and hydrogen being created in the Port of Long Beach.

In order to calculate the amount of hydrogen needed, a number of factors had to be understood: The number of flights and duration, aircraft size and constraints in energy supplies, both electrical needs, and fuel transfer across the airport (externally and internally).

The daily hydrogen demand for Long Beach Airport was calculated from publicly available information: The number of flights per day, aircraft type and route duration using fuel cells for the propulsion system and the estimated efficiencies for the respective flight power levels. The results were validated with recommendations of the fuel matrix in chapter 6, H₂-Aero Fuel Matrix, developed with input from the industry representatives on the H₂-Aero Team. Below are the steps taken for the calculation as well as an illustration of the elements needed to estimate for a hydrogen airport for aircraft and ground vehicles:

Roadmap to match hydrogen supply and demand, with the expected growth:

- A. Target airport description — small hub, towered regional airport.
- B. Hydrogen demand within the airport: aircraft and ground service equipment.
- C. Hydrogen demand outside the airport: cars and MD and HD vehicles.



Multimodal H₂-Airport Hub

- D. Determine how the hydrogen will be produced and delivered for the pilot phase and up to full commercial operation.
- Aircraft hydrogen storage quantity and type per use case and location. Is this using hydrogen storage tanks on aircraft or on ground?
 - Ground vehicle storage quantity and type per use case.

Figure 11: The H₂-Aero vision for a Multimodal H₂-Airport Hub for both ground vehicles and aircraft (courtesy of ZEV Station).



8A. H₂ Airport Ecosystem Overview

In addition to demand, the hydrogen hub should also consider the type of hydrogen that is required for each application. For example, the anticipated uses of ground support equipment and rental cars may be satisfied with hydrogen supplied in gaseous form at 350 bar or 700 bar. For example, short-haul aircraft are expected to utilize gaseous hydrogen. For regional- and medium-haul flights, liquid hydrogen is required to attain equal range to jet fuel. Due to the potential variety of hydrogen types required at the airport, considerations should be given to the appropriate amount of onsite storage, compression, and potentially liquefaction or production. All these demands will directly factor into the amount of renewable electricity required and should be balanced against the expected hydrogen and the electricity supply reality. The ability of the local electric grid to support this approach will be a key enabler or restriction.

This hydrogen hub establishes a ground vehicle station as an “anchor” which later expands to a hydrogen hub to fulfill the growing need of hydrogen aircraft.

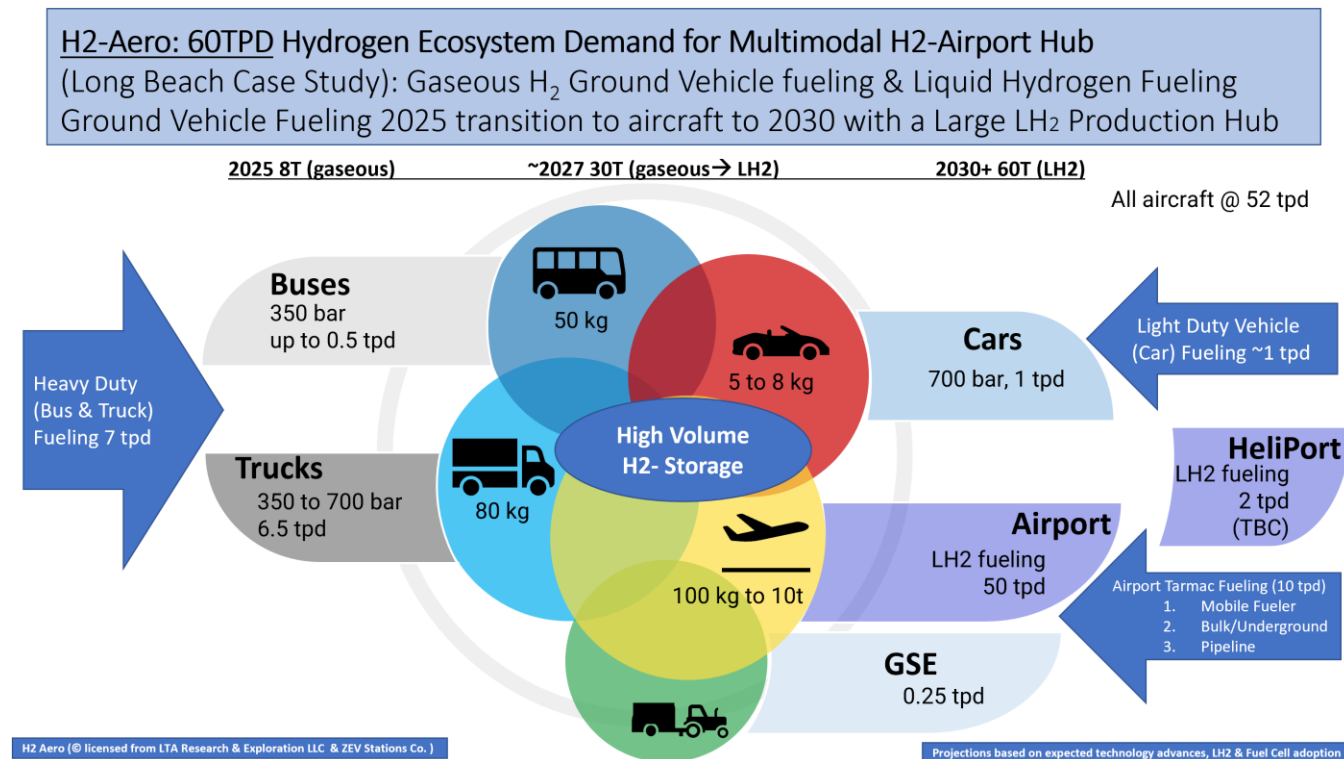
Delivering the hydrogen to the required end use location and vehicle also should be considered in the development of a hydrogen hub. For example, for rental cars and buses, a relatively “standard” Hydrogen Refueling Station (HRS) located onsite would likely be sufficient. However, in the short term, for aircraft and rotorcraft operations, gaseous or liquid mobile refuelers will be required. These mobile refuelers will have to be supplied by a hydrogen depot on site or very near offsite. At the depots, adequate compression, chilling and capacity (flow rates) will be required to support the speed and frequency of aircraft operations at the selected hydrogen hub. In the longer term, hydrogen pipelines



Multimodal H₂-Airport Hub

may be required to deliver fuel for aircraft if the number of vehicle operations gets unmanageable. Below is the resulting calculation for the 60 T/D Hydrogen Airport Hub using the Long Beach Airport example including ground vehicle hydrogen, aircraft and GSE.

Figure 12: Hydrogen ecosystem for Multimodal Airport Hydrogen Hub (courtesy of LTA Technologies, ZEV Station)



A roadmap for a small airport hub, using the Long Beach Airport as an example H₂-Airport Hub ecosystem, is given below:

The timeline for the H₂-Airport Hub starts in 2025 with mainly a ground vehicle station servicing 8T/day (Cars, Trucks, Busses) with a minor amount of development aircraft (~0.5T/day). Thereafter, the Hub is scaled with the aircraft being converted in stages to reach 60T/day by 2030.

1. Project the speed and scale of transition to hydrogen fuel at airport and Infrastructure Development to match H₂ demand.
 - a. Timeline from 8 T/day ground vehicle hydrogen station: For ground vehicles (7.5 T)/GH₂ Interim Aircraft 2025 Demonstration (0.5 T).
 - b. Scaling of hydrogen hubs over time: For Aircraft 52 T/day by 2030.
2. Estimate number of ground vehicles stationary fueling.
 - a. Transport vehicles: 7 T/Day trucks.
 - b. Ground Support Equipment vehicles (tugs, baggage handlers, etc.): 0.25 T/day.
 - c. Cars: public, private and rentals: 1 T/Day cars.
3. Determine delivery method, number of mobile trailers to support aircraft.
 - a. H₂ gaseous trailer (50 MPa): GH₂ approximately 1 T GH₂, usable (2025–)
 - b. H₂ liquid trailer: LH₂ approximately 4.5 T LH₂, usable (2027–).



Multimodal H₂-Airport Hub

8B. Airport Hydrogen Supply Scenarios

How hydrogen is delivered to the airport will likely depend on the size of the airport H₂ demand, the location and geography of the airport relative to H₂ supply sources, renewable energy sources and the nature of the electricity grid and the scale of hydrogen demand. It is expected that airports will transition between different supply options as demand increases. The potential hydrogen delivery methods can be summarized by the three scenarios below: In Scenario 1, hydrogen is generated and liquefied off-site and supplied by road tankers to the airport.

Figure 13: Scenario 1 — Hydrogen generated and liquefied off-site, supplied by road tankers to the airport (courtesy of ATI).

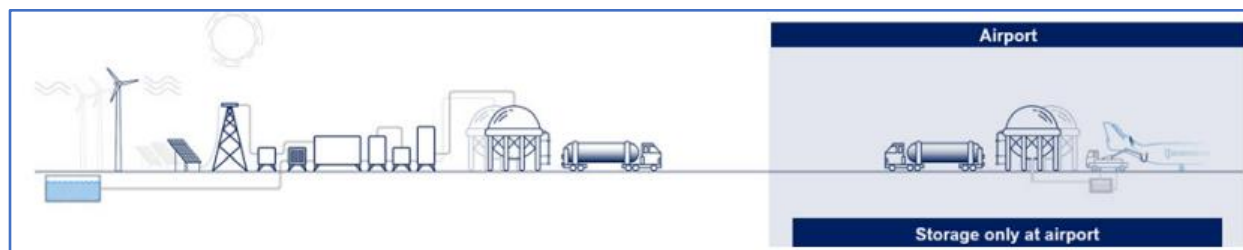
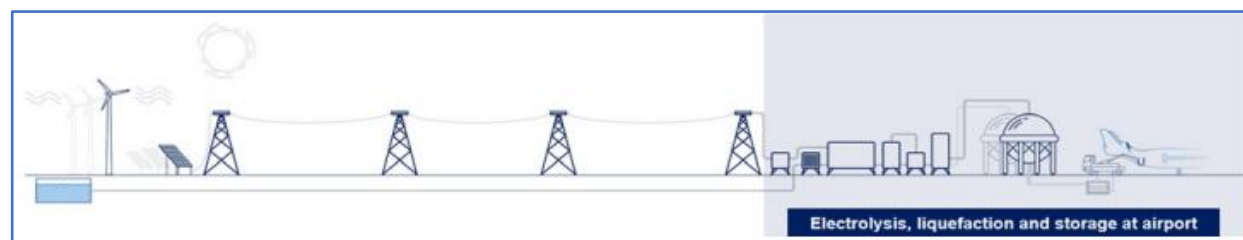


Figure 14: Scenario 2 — Hydrogen generated off-site, supplied in a gas pipeline to the airport and liquefied at the airport (courtesy of ATI).



Figure 15: Scenario 3 — Hydrogen produced and liquefied locally at the airport (courtesy of ATI). Note: Renewable methods of onsite hydrogen production could be electrolysis, pyrolysis, etc., which require a grid and renewable power source.



To offer a perspective for the different hydrogen delivery scenarios, in the case of smaller multimodal hydrogen airport hubs, there may be a requirement of 60 T/day for both aircraft and ground transportation. If hydrogen is produced onsite, it would be approximately 175 MW needed for electrolysis, compression as well as liquefaction (see the example of Long Beach Airport). If delivered onsite, this small H₂-Airport Hub would need 14 LH₂ Trucks delivered per day (without reserve). For example, at larger airports, there will be exponentially more hydrogen required, up to approximately 450 LH₂ truck deliveries a day could be required (London Heathrow example).



Multimodal H₂-Airport Hub

Scenario 1, delivery onsite, may be the preference for most airports in the initial years of ground vehicles and aircraft operation due to its lower capital cost compared to Scenarios 2 and 3. However, when the frequency of tanker deliveries increases to a level that may cause congestion on local roads or the off-load point, then either Scenario 2 or 3 may be the preferred solution. The National Renewable Energy Laboratory (NREL) has done analyses ¹⁰which have found that the frequency of liquid truck deliveries becomes far too frequent very quickly for ground vehicle heavy-duty vehicle stations (more than 8 T/day). This would only be compounded by the large amount of liquid hydrogen truck deliveries needed for airport hydrogen hubs.

The choice between Scenario 2 or 3 may be based on the most economically advantageous approach in the context of a particular airport and to a large degree relies on the availability and economics of the electricity supply available. For the larger example, by the year 2050 a typical large hub airport could require between 3.5 and 4.5 GW for electrolysis and liquefaction with a significant need also for fresh water. This is in the order of magnitude for a nuclear power or significant renewable installation.

In these examples, once tanker delivery is no longer viable, there may be a requirement to produce onsite and for larger applications for a gaseous hydrogen pipeline supply feeding on-airport liquefaction. A pipeline would also be able to supply gaseous hydrogen for alternative use cases at airports and to expand the support of ground vehicle fueling. There should be a reserve planned for hydrogen storage onsite as per needs.

It should be noted that another renewable hydrogen production, for example from biomass, pyrolysis, requires significantly less energy than electrolysis. There are significant differences in hydrogen production energy usage: Pyrolysis is considerably more efficient than other processes, with a specific energy demand of 37.8 kJ/mol H₂ compared with 63.3 kJ/mol H₂ for steam reforming or 285.9 kJ/mol H₂ for hydrogen production by electrolysis.

Below are three examples of hydrogen hubs with estimates of hydrogen per day needed, as well as potential delivery scenarios. Note: airports may require more than two to three days of storage (to be determined by each airport), not shown in the table.

Table 10: Airport hydrogen delivery scenarios and approximate sizes of hydrogen hubs.

Airport Size	Approximate H ₂ Hub Size	2025	2030	2035	2040
Small Hub (regional) e.g. Long Beach* (LGB) Palm Springs (PSP)	~ 60*-100 T/Day	Scenario 1 or 3	Scenario 1,2 or 3	Scenario 1,2 or 3	Scenario 1,2 or 3
Medium Hub (intermediate) e.g. Oakland (OAK), Sacramento (SMF) Manchester (MAN)	~ 100-1000 T/Day	Scenario 1 or 3	Scenario 1,2 or 3	Scenario 1,2 or 3	Scenario 1,2 or 3
Large Hub (major international) e.g. Los Angeles (LAX) London Heathrow** (LHR)	~ 1000-1800** T/Day	Scenario 1 or 3	Scenario 1,2	Scenario 1,2	Scenario 1,2

¹⁰ <https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf>



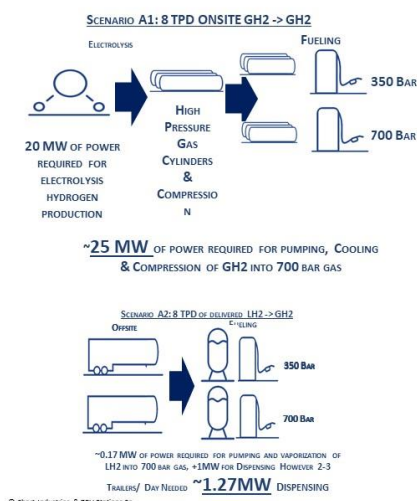
Multimodal H₂-Airport Hub

The figure below describes a comparative example of two scenarios for the small airport hub. The scenarios are number 1 (LH₂ transport) and number 3 (onsite production of hydrogen with liquefaction) showing energy usage for onsite production compared to LH₂ transport. The assumption is that the energy sourced is “green” based on zero-carbon electricity such as direct renewables and/or grid based nuclear, hydropower and renewable, etc.

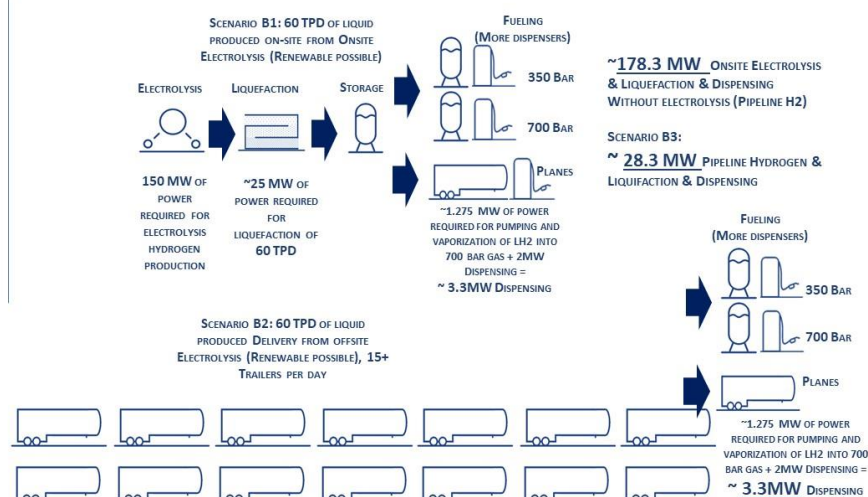
Figure 16: Delivery and production scenarios in a 2025–2030 small airport (courtesy of Chart Industries and ZEV Station). The below scenarios show the amount of hydrogen delivery and energy required to supply A) 8TPD Multimodal Ground/ Small Aircraft Transport (LH₂ → GH₂) Station and B) 60 TBD Multimodal H₂-Airport Hub.

Scenario A1) is the Multimodal 8TPD Station with onsite hydrogen production vs. A2) 2x 4T Trailer Delivered H₂ for the Multimodal Station. Scenario B1) is a small airport 60T/day H₂-Hub including onsite production, liquefaction and dispensing vs. B2) 15x 4T trailers deliveries per day vs. B3) Pipeline Hydrogen with onsite liquefaction and dispensing.

8 TPD Ground Transportation/ Trailer

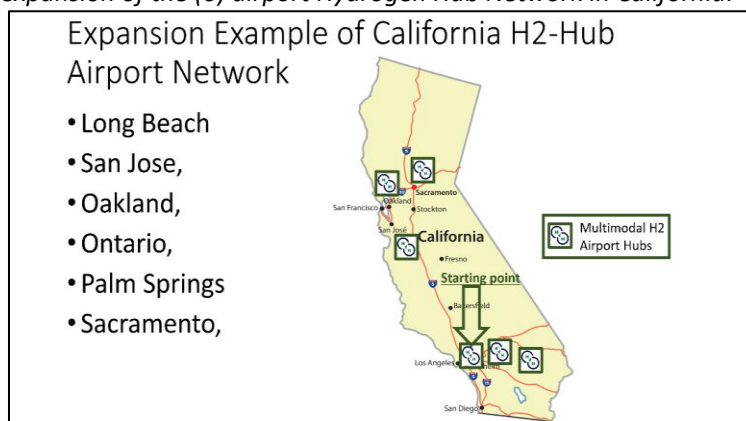


60 TPD Multimodal H₂-Airport Hub



In addition to the example of a small hydrogen hub, it is important that a network of hydrogen airports be planned for the technology to be successful. It is suggested that this network be made of small and medium sized airport hubs, exemplified by from the California map below of six airports such as: Long Beach (LGB), Palm Springs (PSP), Ontario (ONT), Oakland (OAK), Sacramento (SMF) and San Jose (SJO). The H₂-Aero Team suggested this list based on potential small and medium sized H₂-airport hubs, but feasibility would need to be investigated by industry & local governments.

Figure 17: Example of an expansion of the (6) airport Hydrogen Hub Network in California.





9. Conclusion

To accelerate the transition to hydrogen in aviation, there are many advantages to creating a multimodal ecosystem at the airport. This whitepaper proposes using a ground vehicle station as an “anchor,” or starting point that would later grow into a Hydrogen Hub to serve the entire airport. The objective is to achieve economies of scale using the initial demand from fueling light-duty to heavy-duty — exterior to the airport and later expanding to aircraft fueling. This will require substantial industry and government cooperation and funding but holds great potential to reduce emissions in both transportation sectors.

Though SAF has taken the forefront as the primary means to reduce aircraft carbon emissions, hydrogen offers numerous benefits and greatly advances the replacement of fossil fuels. To establish hydrogen as a primary fuel at the airport through a hub, there are policy and funding mechanisms needed for the scaling of this technology. To do this, a focused hydrogen strategy should be established together with trade groups, industry and academia, among others, to accelerate hydrogen as an airport fuel. One key goal is to support the FAA and other federal and local government organizations to develop hydrogen aviation policy and regulations for hydrogen at the airport (such as with the five-year plan).

There are key gaps in codes and standards needed to commercialize hydrogen aviation. The H2-Aero team indicated the highest priority is to create hydrogen fueling and station standards at SAE AE-5CH. The specific need is for hydrogen fueling with significantly higher flow rates for aircraft. In addition, it is recommended that the hydrogen safety code, NFPA 407 should be updated with experience gained in NFPA 2 and with the decades of work done with hydrogen ground vehicle fueling.

H2-Aero recommends a follow-on public-private partnership to coordinate parallel airport hydrogen demonstrations with different types of aircraft (eCTOL, eRotor, etc.) developed within a state. At a later stage, the goal is to expand to other regions to enable a network of hydrogen airports where airlines can book travel locations. This demonstration project may be used to help validate standards and to test demonstration hydrogen aircraft and fueling technology.

Airports need to prepare and plan for a significant expansion related to onsite power availability, hydrogen storage and new fuel transport in order to implement a Hydrogen Hub. This whitepaper establishes a baseline for small, medium and large hubs, knowing the aircraft makeup and range required. The H2-Aero Team chose a small regional airport as a starting point due to the challenges to scale hydrogen hubs. The goal of this whitepaper is to create a “cookbook” to assist entities to appropriately size hydrogen infrastructure for commercial hydrogen aircraft as well as ground vehicles to create a Multimodal H₂-Airport Hub.

The H2-Aero Team proposes a collaborative effort to decarbonize aviation with zero-carbon sourced hydrogen hubs to accelerate commercialization for both zero emission vehicles (ZEVs) and hydrogen aircraft.



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Abbreviations

C&S	Codes and Standards
CAA	Civil Aviation Authority (UK)
CFR	Code of Federal Regulations (US)
DOE	Department of Energy (US)
eCTOL	Electric Conventional Take-Off and Landing
EPA	Environmental Protection Agency (US)
eCTOL	Electric Conventional Take-Off and Landing
eRotor	Electric Rotorcraft
eSTOL	Electric Short Take-Off and Landing
EUROCAE	European Organization for Civil Aviation Equipment
eVTOL	Electric Vertical Take-Off and Landing
FAA	Federal Aviation Administration (US)
FAR	Federal Aviation Regulations (US)
FC	Fuel Cell
g/s	Grams per second
GH ₂	Gaseous Hydrogen
GSE	Ground Service Equipment
H ₂	Hydrogen
HD	Heavy-Duty
HDV	Heavy-Duty Vehicles
ICAO	International Civil Aviation Organization
kg	Kilogram
kJ	Kilojoules
LDV	Light Duty Vehicles
LH ₂	Cryogenic Hydrogen
Lwater	Liters of Water
MD	Medium-Duty
MJ	Megajoule
mol H ₂	Moles of hydrogen
MPa	MegaPascal
NASA	National Aeronautics and Space Administration (US)
NFPA	National Fire Protection Association (US)
NO _x	Nitrogen Oxide
OEM	Original Equipment Manufacturer
PPP	Public-Private Partnership
PRV	Pressure Release Valve
SAF	Sustainable Aviation Fuels
SO _x	Sulfur Dioxide
T-PRD	Temperature Pressure Relief Device
UAM	Urban Air Mobility
VTOL	Vertical Take-Off and Landing



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VFS thanks all the members and contributors of the H₂-Aero Team for producing this whitepaper.

More information on VFS and its hydrogen-related activities can be found at www.vtol.org/hydrogen.