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PURPOSE AND OBJECTIVES

This document has the purpose of providing a comprehensive overview of the potential impacts that hydrogen aircraft could have on airports' infrastructure and operations. Bringing awareness about the implications of alternative energy aircraft on airports will help airports, governments, and other stakeholders from the industry to understand the challenges and possibilities behind this approach, which if materialised, could contribute towards reducing the environmental impact of aviation. This study builds on the material presented in the ACI's *Sustainable Energy Sources for Aviation: An Airport Perspective* white paper.

The objectives of this document are:

- To increase the awareness and understanding amongst airports regarding implications and challenges of hydrogen powered aircraft with respect to infrastructure, operations, and safety.
- To highlight some of the knowledge gaps in order to focus resources into closing such gaps.
- To provide useful references to airports and other aviation stakeholders where additional information can be found.
- To highlight some of the stakeholders involved in present and historic initiatives for hydrogen-powered aviation.
- To share key learnings and common questions across the community of hydrogen aviation stakeholders.

INTRODUCTION

Background

Recent announcements made by aircraft manufacturers have suggested that the first generation of hydrogen aircraft might be taking to the skies in the next 10-15 years^{1, 2, 3}. For the global economy and indeed for aviation to reach net zero, the use of fossil fuels will need to be reduced, and many countries have identified low or zero-carbon hydrogen as a promising means to transport, store and use renewable electricity. Japan, for example, aims to become a hydrogen society and has put in place some of the most ambitious plans to migrate their energy infrastructure to hydrogen⁴. The European Union published a hydrogen strategy which includes producing 1 million tonnes (mT) of renewable hydrogen by 2024, growing to 10 mT by 2030⁵. According to the International Energy Agency (IEA), the United States is also a key player by currently having the largest hydrogen fuel cell road vehicle fleet in the world⁶. It is foreseen that increased demand driven by these and similar actions will incentivise supply leading to the reduction of the cost of renewably sourced hydrogen.

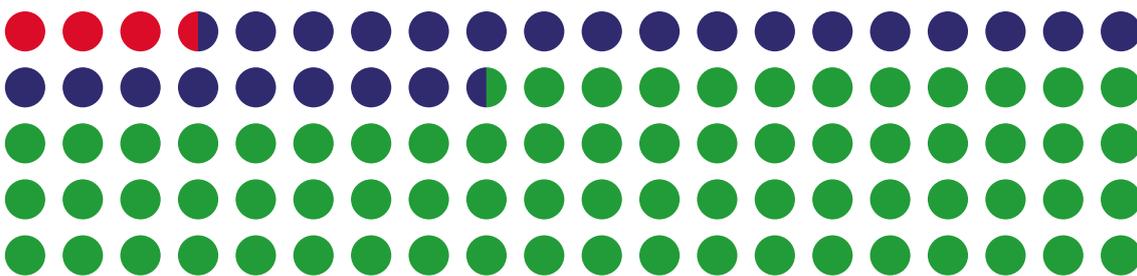


Figure 1: ATAG schematic indication of potential aviation energy use in 2050. Red: batteries, blue: hydrogen, green: SAF⁷

The aviation industry, through the Air Transport Action Group (ATAG), has set a global goal to reduce its carbon dioxide emissions by 50% by 2050 compared to those of 2005. Efficiency projections indicate that even a combination of measures, which include the increased use of sustainable aviation fuels (SAF) along with the introduction of technologies that improve the energy efficiency of aircraft and improved operations, will not be enough to meet this target. To be able to reach this, or any other more ambitious goal, the industry will likely have to rely on all the above plus introduce aircraft that use new alternative energy sources, such as hydrogen. Figure 1 from ATAG⁷ illustrates that all approaches, electrification via batteries (red), use of hydrogen (blue) and increased use of SAF (green) will be required to drastically reduce the emissions from civil aircraft. The circles represent how conventional aviation fuel could be replaced by alternatives. SAF occupies the largest share since most aviation fuel is burned on long-range missions for which electric aircraft using existing and projected battery technologies are not yet technically suitable and, for now, neither are hydrogen-powered aircraft due

to the large volume required to store the fuel and the storage space limitations in conventional tube and wing aircraft. Figure 1 assumes that hydrogen aircraft by 2050 could power aircraft of 150 seats or fewer on flights shorter than 120 minutes with some regional and commuter flights being powered by electric batteries. If the range was expanded, as suggested by the Zero-e concept of Airbus (120-200 seats, up to 2000 NM), these aircraft could eventually eliminate more than half of global aviation CO₂ emissions^{4,8}. The European Destination 2050 report shows a route to Net Zero European Aviation. The analysis shows that 20% of the reductions in European aviation CO₂ emissions by 2050 could come from intra-European hydrogen aircraft, using 3.7 mT of hydrogen⁹.

Uses and applications of hydrogen for aircraft

Hydrogen has many potential applications which support the decarbonisation of aviation. It is already used as a feedstock for drop-in sustainable aviation fuels, and for hydrogen fuel cells in experimental aircraft. If hydrogen fuel cells were to be adopted for use in aircraft, these would be refuelled with hydrogen at the airport; the hydrogen fuel cell would then produce electric energy from the electro-chemical reaction of hydrogen with oxygen from air, to power electrically driven propellers, leaving only water vapour as a by-product. Such aircraft, using compressed hydrogen gas, might offer double the range of battery powered aircraft, but gas storage systems are heavy so for longer ranges liquid hydrogen would be needed. Direct liquid hydrogen combustion through a gas turbine, for example, would require the liquefaction of hydrogen, the subsequent fuelling of liquid hydrogen into the aircraft, and the combustion of hydrogen in a gas generator, which can be used on a turbofan or turboprop of hybrid-electric engine configuration.

Hydrogen will need to be delivered to the aircraft in its gaseous or liquid form. This is a fairly significant change in operating conditions for airports with potential implications on the infrastructure, capital investment, operational practices and safety procedures. These will vary depending on how the fuel is utilised, the amount of fuel required and the type of hydrogen supply chain that will need to be established to serve the airport. The possibility of fuelling aircraft with hydrogen has been studied for nearly 50 years¹⁰. Some aspects of the early studies are still relevant and in agreement with recent research with regards to the airport infrastructure, but there is data that may be outdated and where knowledge gaps exist. These are highlighted at the end of the document.

Scope

This report is focused on the implications of the introduction of alternative energy aircraft into the airport system. It does not evaluate individual technologies, nor does it advocate for or against any specific approach. This review is purely focused on increasing the understanding of airports for future evaluations and planning, should these technologies advance and come into service.

HYDROGEN SUPPLY CHAIN

Infrastructure to deliver hydrogen to the airport and to store it

The first substantial difference to point out between conventional aviation fuel and hydrogen is that its supply chain can be different depending on the route-to-tank, which in turn depends on the capabilities and infrastructure assets of each airport. Hydrogen can be transferred into the airport via pipelines, trucks, or trains in a similar and parallel way as conventional fuels (pathway 2, 3 as shown in Fig. 2), but it could also be made on or near site if water, renewable electricity, and the required land surfaces are all available (pathway 1 as shown in Fig.2). As shown in Fig. 2, hydrogen can also arrive at the airport in its liquid or gaseous form. If it arrives in its gaseous form, a liquefier is required to convert the hydrogen into liquid. A fourth option, not shown in the figure, is introducing the hydrogen into the airport via exchangeable H₂ pods. These are specialised tanks filled with hydrogen which could be loaded into the aircraft by servicing vehicles, replacing the empty tank in the aircraft. Each path will have different infrastructure, operations, safety, and costs implications for airports.

In the 1970s NASA investigated different ways of delivering hydrogen to airports for civil aviation use: truck, trailer and pipelines for gaseous and/or liquid hydrogen¹¹. The study showed cases where for short distances (less than 64 km), the most economic transport method would be to transport the hydrogen in its gaseous form via pipelines and to liquefy as close as possible to the airport (or even better, at the airport itself). In this case, airports would need to allow for gaseous hydrogen (gH₂) pipelines to be built and operated within their premises. For larger distances, the report identified the use of trains or trucks to be more economical than a pipeline. In this case, the hydrogen should be liquefied at its source and transported in liquid form to optimise the space in the storage tanks.

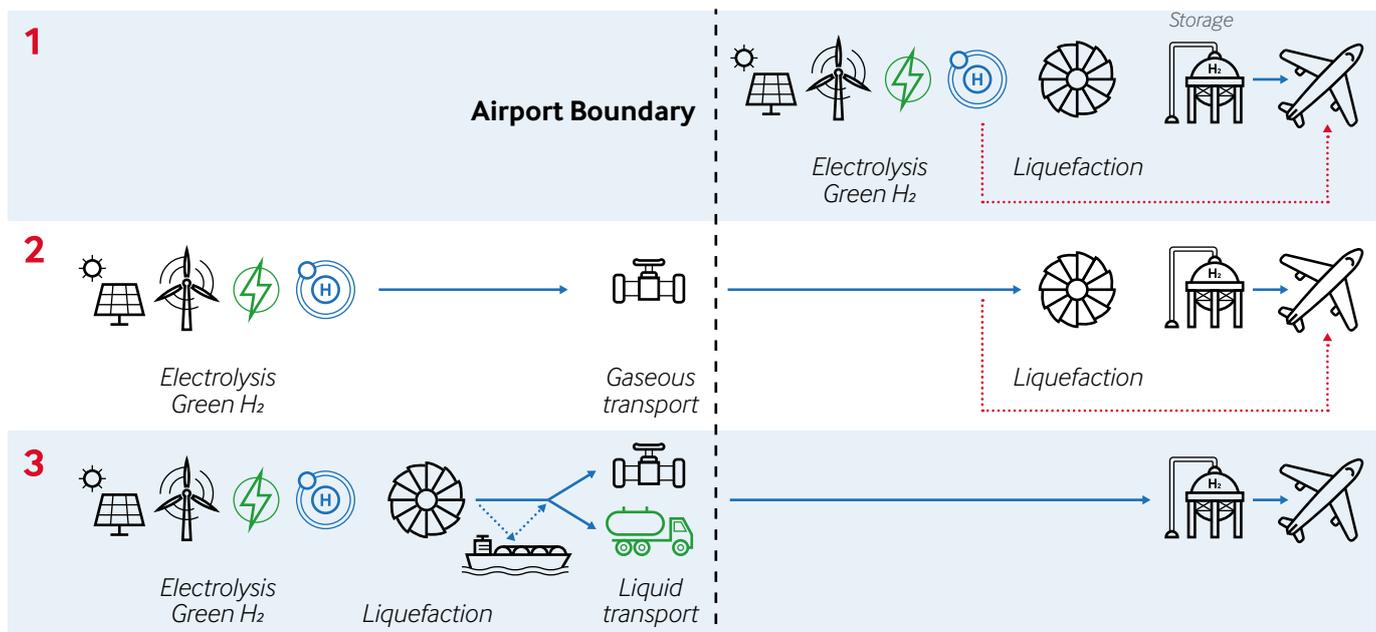


Figure 2: Three primary hydrogen supply chain/pathways into the airport

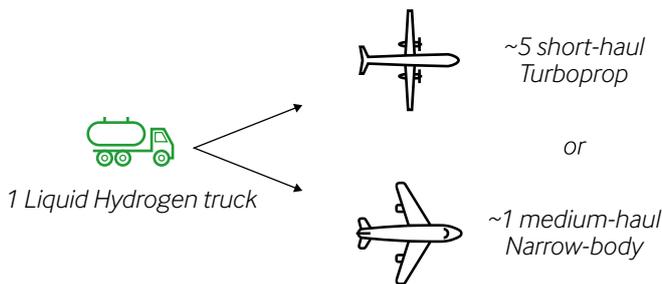
The International Renewable Energy Agency (IRENA) provides an up-to-date vision of the transportation of hydrogen¹². IRENA recognises that the availability of renewable electricity world wide is different in each region and thus envisions that some countries will manufacture hydrogen to satisfy their own supply as well as to export, while others might struggle to produce large amounts of green hydrogen (or any at all) and will require its import. The first such shipment occurred between Australia and Japan in 2019¹². The imported hydrogen is delivered and stored at the Kobe Port. Airports in the vicinity of this port already use hydrogen for their ground support equipment and could potentially benefit from this supply chain to serve aircraft at some point in the future. This is opening an international market for liquid hydrogen transportation which could benefit those airports that cannot manufacture the fuel on or near the site. The economy of scale derived from dedicated large-scale renewable energy generation facilities devoted to large-scale hydrogen production could significantly reduce manufacturing costs. This configuration would also reduce the infrastructure and energy required to produce the fuel at the airport, as it could arrive already in its liquid form and be stored and supplied to the aircraft. The increased cost derived from the transportation, balanced with the reduction in cost because of economies of scale, will have to be assessed on a case-by-case basis by the operator purchasing the fuel, in cooperation with the airport operator. Furthermore, the carbon footprint of each approach will need to be evaluated.

Other methods for large-scale transportation include converting the hydrogen with other substances and capitalising on well established supply chains and infrastructure, such as those existing for ammonia (NH₃) or natural gas (CH₄). Liquid organic hydrogen carriers (LOHC) are also showing promise in some regions around the world for transporting hydrogen in other molecules. According to IRENA, some countries expect to benefit from these methods to produce and export hydrogen. This, however, might not be suitable for aviation use since the hydrogen is required in its pure form and thereby infrastructure would be required on site to separate the hydrogen from the carrying elements and to subsequently liquefy it.

Most documents reviewed considered different implementation times: an early ramp up, in which hydrogen is mainly used for ground support equipment, general aviation or regional flights in selected airports, and a scale-up time frame in which hydrogen becomes more common in a larger number of airports. These findings are summarised below.

Early ramp-up period

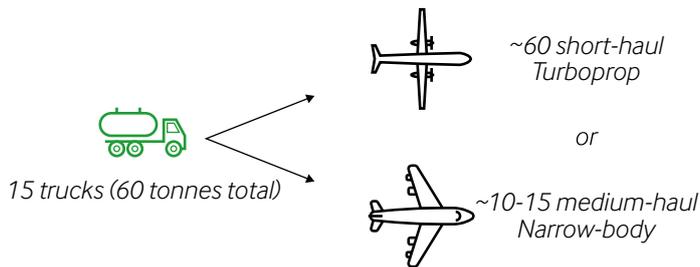
Hydrogen supply from one truck



For the first period, hydrogen could arrive at the airport in its liquid form via trucks. One single truck can carry up to 5t of hydrogen which would be enough to cater for about five hydrogen-powered turbo-prop aircraft (short haul) or one narrow body aircraft on a medium-haul mission.

It is not uncommon today to see fuel dispatched entirely by road transport using either trucks or trains. If green hydrogen is imported via trucks, Clean Sky 2 estimates that up to 60 t (15 trucks) of hydrogen per day could be easily managed in this way in a medium airport¹³ (catering for about 60 turboprop aircraft, or 10-15 narrow body aircraft). This agrees with the Cryoplane study¹⁴, which considered how to replace Sweden's domestic aviation with hydrogen aircraft¹⁵. This study analysed the implications of generating the hydrogen on site and trucking it to nearby airports to cater for diverted aircraft. Receiving all fuel via trains is also common practice. A medium-sized airport in Europe, for example, reported receiving the average daily required amount of fuel entirely by train (~4,000 t). For airports that have this current supply chain, therefore, the infrastructure required at the airport for the early ramp up, could be minimal. One single hydrogen storage tank (purpose built) would be enough to supply considerable amount of aircraft, and in some cases, this might not be required, and aircraft could be directly refuelled by the cistern truck. The emissions associated with transporting any fuel from its production facility to the aircraft tank are usually accounted for in the life cycle emissions (LCE) assessments of existing drop-in fuels (SAF or Jet A-1) and would need to be accounted for hydrogen as well. These emissions, however, normally form a very small share of the LCE of a fuel when compared to its direct combustion¹⁶.

Medium-sized airport requirements per day

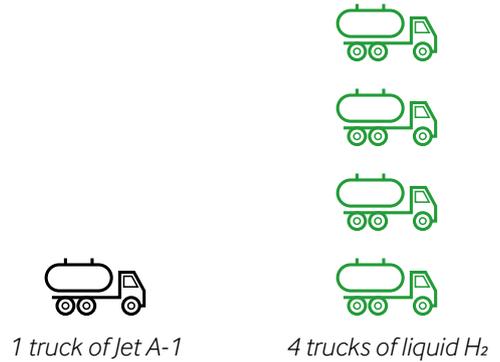


Small quantities of hydrogen could also be produced onsite at the airport, if an airport has available land and using electrical power from the grid or ideally from on site renewable electricity sources.

Scale-up period

A scale-up phase would require one order of magnitude more hydrogen than that considered on the early ramp up. Early^{10,11}, as well as more recent reports^{13,14}, have looked at the challenges associated with delivering large quantities of hydrogen to airports. As mentioned previously this will depend on the route-to-tank but some of the main challenges are outlined below. If trucks are used, this would increase traffic at and around the airport. Some medium airports today receive Jet A-1 fuel entirely by truck proving this might be feasible but will require consideration on a case-by-case basis. Moreover, the larger volume of hydrogen compared to Jet A-1 means that four times more trucks are required to transport the same amount of energy.

Same amount of energy



Space requirements for the production, liquefaction and storage of hydrogen at a given airport

Production

Producing, liquefying and/or storing hydrogen at the airport could be an option in addition or in substitution to bringing the hydrogen into the airport via trucks, trains, or in gaseous form via pipelines. Where these options are considered, space availability is a key requirement. Various studies have been conducted which estimate the land footprint of hydrogen infrastructure elements at airports. Studies done for Arlanda airport (2000s)¹⁵, a generic medium-sized airport by Schmidtchen et. al (1990s)¹⁸, Clean Sky and McKinsey (2020s)¹³, NASA (1970s)^{10,11}, and Zurich airport (1980s)²⁰ provide estimates for space requirements for liquid hydrogen production via electrolyzers, liquefaction and storage.

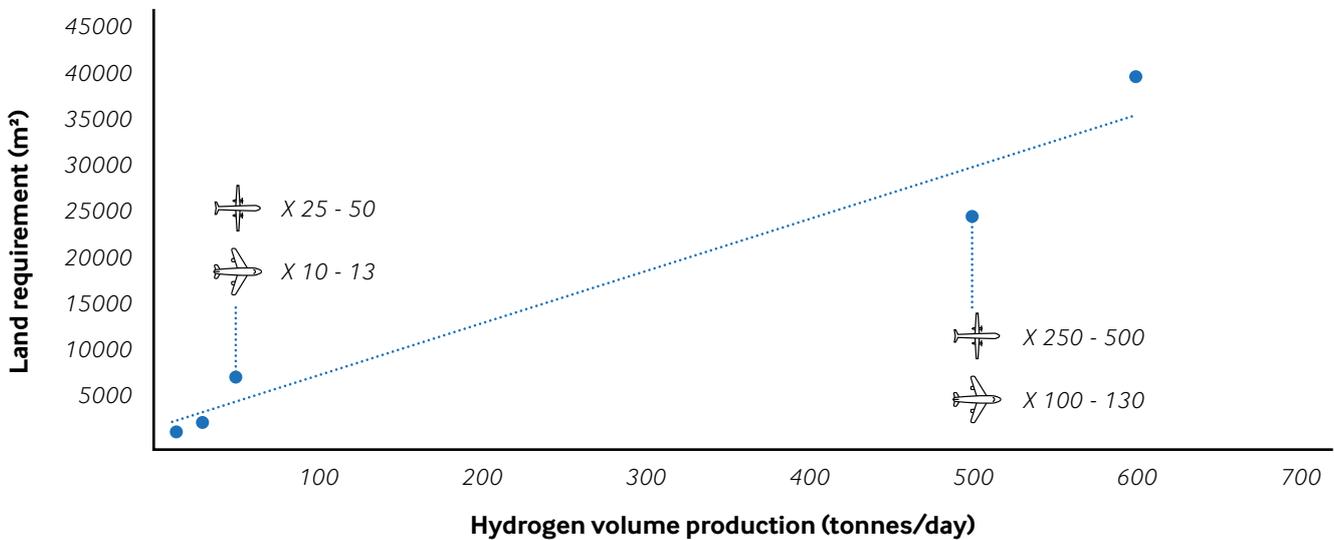


Figure 3: Space requirement at airports for hydrogen production via electrolysis, each point represents a different study^{13,15,18,20}

The requirements vary from the need to produce and/or liquefy between 15 t/day to more than 600 t/day of hydrogen via electrolysis. Most of the early studies focused on supplying hydrogen to wide-body aircraft which could travel up to 10,000 km and carry 400 passengers. The broad range of the hydrogen requirements depend on the expected traffic of such large aircraft which vary from 1 to over 100 take-offs per day. Figure 3 shows space requirements for electrolyzers to produce the hydrogen with indicative levels of traffic but adjusted for a turboprop aircraft and a narrow-body turbofan, as indicated previously.

Liquefaction

While there is some consistency on the land footprint for the generation of hydrogen via electrolysis (on a per-unit area basis), data provided varies greatly for the liquefaction process, as this depends on the layout of the different infrastructure elements required to complete the process (liquefier, cooling towers, air separator, control rooms etc.) Combined data for full requirements which include the production via electrolysis, liquefaction and storage plants is sparse and differs from 25,000 m² for a 500 t/day¹³ to 250,000 m² for a 700 t/day^{10,11}.

Storage

The International Energy Agency estimates that modern liquefied hydrogen storage tanks can have an efficiency of 99% and is an appropriate method for relatively small-scale applications and short periods of time where the fuel needs to be readily available (like in airports). Stored as a gas, even if compressed at 700 bar, hydrogen would occupy nearly seven times more space than a hydrocarbon fuel and thus storage in large quantities might not be appropriate for some airports due to space availability. Very large quantities of hydrogen can be efficiently and safely stored for large periods of time in salt caverns with efficiencies above 98%²⁴. This is the most economical way of storing it, but it requires large underground spaces which might reduce the feasibility for airports which are looking to move away from this practice.



Figure 4: 20 m diameter LH₂ storage tank in NASA Kennedy Space Centre, Courtesy of NASA

Liquid hydrogen occupies nearly four times more volume than an equivalent energy amount of Jet A-1. This means the storage facilities would have to be larger. The studies mentioned previously also varied in storage requirements considering anything between 15 t to 1,800 t of liquid hydrogen. Existing tanks used by NASA's space programme (Figure 4) have a capacity of 3,200 m³ each (220 t). Using the same indicative quantities as before, one of these tanks could potentially supply over 200 short-range turbo-prop aircraft or 40-50 narrow-body medium-haul aircraft. NASA (1970s) predicted three to five of these spherical storage vessels of 21.6 m in diameter would be needed to supply ~50 long-range (10,000 km) aircraft per day (400 pax capacity)^{10,11}. The amount of traffic supported by one single tank varies depending on the level of traffic, mission range and hydrogen management strategy.

New large tanks are being developed, capable of holding 4,700 m³ of liquid hydrogen¹⁹. These tanks, called integrated refrigeration and storage or IRAS, contain a heat exchanger that continuously reduces the temperature of the tank, eliminating boil-off and losses.

Comparison to current airport infrastructure footprint

As part of this study, some airports were surveyed to compare the above requirements with the space devoted to Jet A-1 fuel farms. Three airports provided inputs specifying areas between 30,000 m² (medium airport) and 80,000 (large airport) m². A graphic representation is offered in Figure 5, comparing existing infrastructure elements to the space required for hydrogen processing or storage. This figure expresses the areas of the electrolyzers in terms of their mass capacity to relate them to aircraft use. However, electrolyzers are usually sized based on the energy they consume. The electrolyzers considered here had footprints of 22 (600t/day) – 80 (50t/day) m²/MW. IRENA gives a range of 24-63 m²/MW based on the capacity and technology used⁵⁰. Liquefiers rarely stand on their own and have other infrastructure elements that support them. Their footprints can vary depending on the lay out and can be as broad as 25- 300 m²/t.

These requirements are specifically for those cases where hydrogen would be manufactured or liquefied on site. If the fuel arrives at the airport in its liquid form, only the storage tanks would be required. All of these infrastructure elements would have to exist in addition to the infrastructure required for drop-in aviation fuel (Jet A-1 or SAF). The space requirements reported are influenced by the technology of the liquefier, electrolyser, and storage tanks. For example, the IEA estimates that an Alkaline electrolyser requires twice the land footprint of a proton exchange membrane (PEM)²². Furthermore, PEMs deliver hydrogen at a higher pressure, thereby reducing

the liquefier needs. This latter technology is being scaled up and although today has higher CAPEX and OPEX than the traditional alkaline electrolyser method, this is expected to change soon. Solid oxide electrolysis cells (SOEC) have even higher efficiencies and lower land footprint but are still in the development stage^{22,23}.

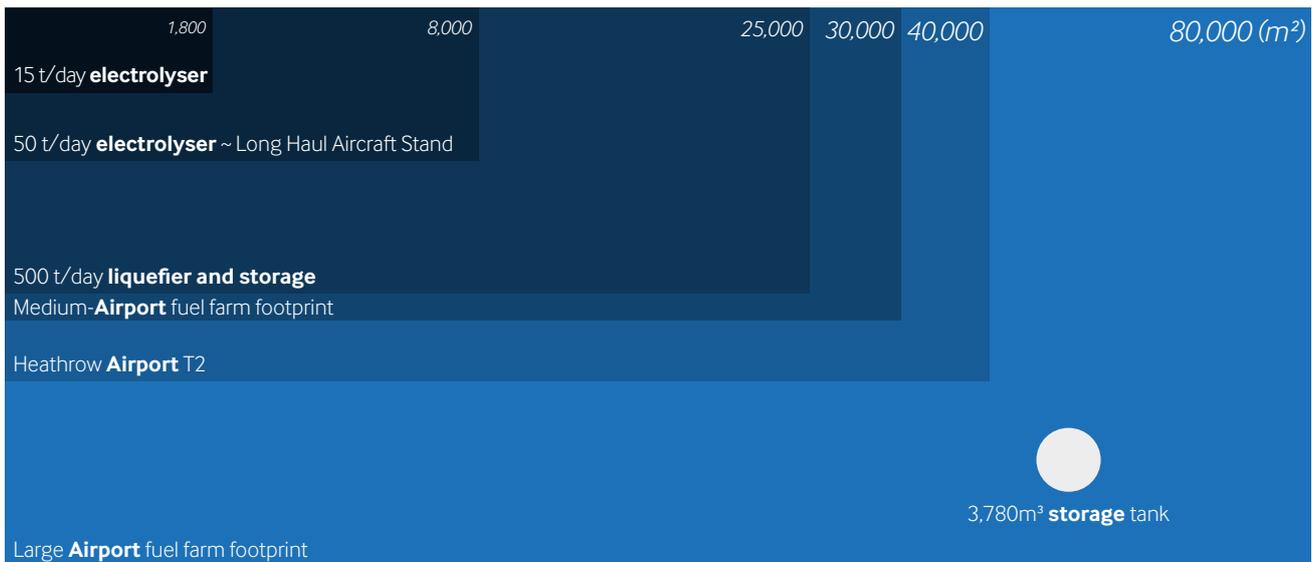


Figure 5: Visual comparison of land requirements for some hydrogen infrastructure elements, referenced to the footprint of existing infrastructure^{15,17,18}

In terms of transportation, Kawasaki Industries has recently launched a transatlantic hydrogen transport ship. The company envisions a 160,000 m³ capacity liquefied hydrogen carrier. Such a ship could house enough hydrogen to supply several airports based on the requirements mentioned previously²¹.

Energy requirements for liquefying and/or manufacturing hydrogen

Manufacturing and liquefying large amounts of hydrogen is a highly energy intensive process, comparable to the energy used by a small city. A few examples of this are provided below.

- Arlanda airport estimated the energy to produce and liquefy 50 tonnes of hydrogen per day, seven times the energy consumption of the airport when the report was published¹⁵.
- The 350 MW for liquefying 700 t/day from NASA were estimated for 50-100 wide-body aircraft operations per day completing missions of up to 10,000 km^{10,11}. Figure 6 translates these numbers to representative narrow-body aircraft and turboprops for the same amount of hydrogen.
- The Zurich airport study reports energy consumption for a 15 and a 30 t/day electrolyser plant along with a 15 t/day liquefier, estimated to support 15-30 turboprop operations per day.
- Clean Sky 2 predicts that worldwide 500-1,500 GW of energy would be required to supply aviation with hydrogen beyond 2050 (electrolysing) representing 20-60% of today’s global full renewable capacity.

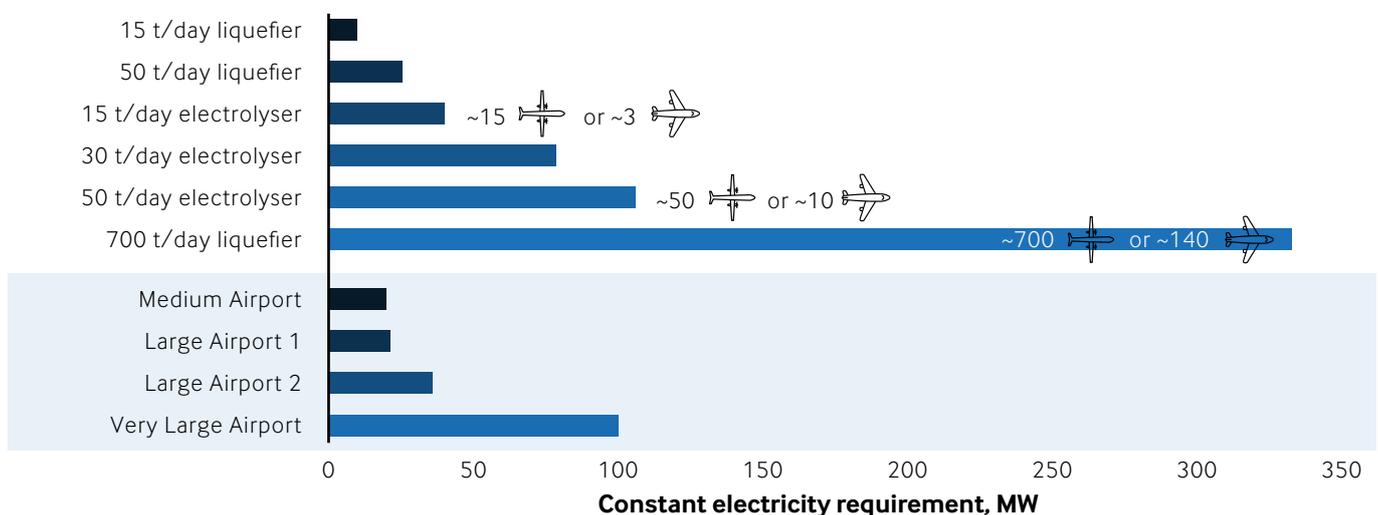


Figure 6: Energy requirements for some hydrogen processes compared to energy consumption of three airports of varying size and capacity

A survey on energy consumption was conducted for airport normal operations for the years 2018 and 2019, with the aim of contextualising the hydrogen electricity requirements outlined above. The replies from the four responding airports were received in absolute energy consumptions for a given year expressed in GWh. If a constant energy consumption (24h per day, 365 days) is assumed for comparison purposes, then the results showed 18, 20, 35 and 90 MW of averaged constant energy consumption per airport. This shows that the requirements to either liquify or produce hydrogen can be at least as large as, and in many instances much larger than, the current energy consumption of the entire airport for all other purposes (Figure 6). This would be relevant to airports where hydrogen is produced or liquefied on site. In those cases, peak load considerations will have to be accounted for along with energy utility resilience in coordination with the energy providers to ensure large grid outages or events do not impact airports.

The figures shown are influenced by the assumptions on liquefier and electrolysing technologies. As efficiencies rise, less energy will be required, although general aviation requirements could still be in the order of hundreds of megawatts if the use of this fuel becomes more widespread. The data from the studies quoted previously was aggregated and compared to modern energy intensities of both liquefiers and electrolyzers, as well as to projections into 2025 and 2030. The comparative tables are given below. The values can serve to start assessing the energy requirements to liquefy or manufacture a certain amount of hydrogen onsite (considering that 1 kg of hydrogen contains roughly three times more energy than 1 kg of Jet A-1). The values are indicative and could change depending on the specifications of the equipment used.

Table 1: Liquefier energy intensities according to several sources

Liquefier		
Specifications	Source	Energy intensity (kWh/kg)
700 t/day (100 a/c) liquefier	NASA ¹⁰	11.4
50 t/day liquefier	Haglund <i>et al</i> ¹⁵	12
15 t/day liquefier	Schmidtchen <i>et al</i> ¹⁸	14.4
20-40% of final energy requirements	IRENA ²³	11 to 23
Liquefier 2020	Hydrogen Europe ²⁵	11
Liquefier 2030	Hydrogen Europe ²⁵	7
Liquefier NREL study	NREL ²⁶	11
Liquefier current (possible)	Idealhy ²⁷	12 (6.4)

Table 2: Electrolyser energy intensities according to several sources

Electrolyser		
Specifications	Source	Energy intensity (kWh/kg)
50 t/day electrolyser	Haglund <i>et al</i> ¹⁵	50.4
15 t/day electrolyser	Schmidtchen <i>et al</i> ¹⁸	62.4
30 t/day electrolyser	Schmidtchen <i>et al</i> ¹⁸	62.4
Electrolyser alkaline today (2030)	Hydrogen Europe ²⁵	50 (48)
Electrolyser PEM today (2030)	Hydrogen Europe ²⁵	55 (48)
Electrolyser alkaline today (2025)	IRENA ²³	51 (49)
Electrolyser PEM today (2025)	IRENA ²³	58 (52)

At the time of writing, the largest operating electrolysers in Europe had capacities below 10 MW (9 MW in Rjukan, Norway and 6 MW in Linz, Austria)²⁸. The more efficient PEM electrolysers currently only exist in the 1 to 10 MW scale, but plans exist to scale this up to several 10s or 100s of megawatts (alkaline electrolysers have been built in the past capable of 160 MW or more)²². France plans to build five 100 MW green hydrogen units (each) in the next five years¹². The Hydrogen 2030 vision for Europe according to the European Hydrogen Strategy is to install up to 40 GW capacity of electrolysis in Europe by 2030.

The Clean Sky 2 study estimated that despite the fact that aviation could use large volumes of hydrogen (10-40 million tonnes by 2040 and 40-130 million tonnes by 2050) this would only represent 5-10% and 10-25% of the global projected hydrogen demand in 2040 and 2050 respectively, and thus termed the requirements feasible from a technical perspective¹³.

It will be a challenge for the global economy to produce such massive amounts of green hydrogen for aviation. The space limitations to store, produce, or liquefy hydrogen might be a challenge for some airports, and will have to be addressed on a case-by-case basis. For these reasons, strong policy support with government incentives will be required to scale up renewables and green hydrogen for the aviation sector.

In summary, depending on the route-to-tank, the supply chain infrastructure to receive and store hydrogen at airports could include: pipelines, trucks, distribution and safety valves, storage tanks, liquefier and potentially electrolyzers if the hydrogen is made onsite. Most of the energy consumption in the value chain is used for the electrolysis process, with about 20-30% of the energy dedicated to the liquefaction process.

Infrastructure to transport hydrogen within the airport

This section assumes that hydrogen has already arrived at the airport and is available for its final gaseous or liquid use. To distribute hydrogen around the airport and into the aircraft two pathways are considered: trucks and pipelines. NASA studied both possibilities, also including variations like having separate stands for hydrogen and Jet A-1 aircraft or having hydrogen refuelling stations away from the terminal¹¹. The study concluded that the most efficient way of speeding up turnaround times and minimising costs, would be to have dual fuel stands. This method was deemed feasible and would not compromise safety, as long as adequate procedures were put in place. Hydrogen aircraft could be refuelled at the stand in a similar way to conventional aircraft. The NASA study, along with others¹⁵, favour pipeline refuelling as opposed to truck from a safety, economic and environmental perspective. However, it is recognized that for early implementation, trucks might be used as is anticipated for other liquid alternative fuels, like SAF. Another alternative, not considered in detail here, is distributing the hydrogen in gaseous pipelines into the gates and having micro-liquefaction facilities at the gate.

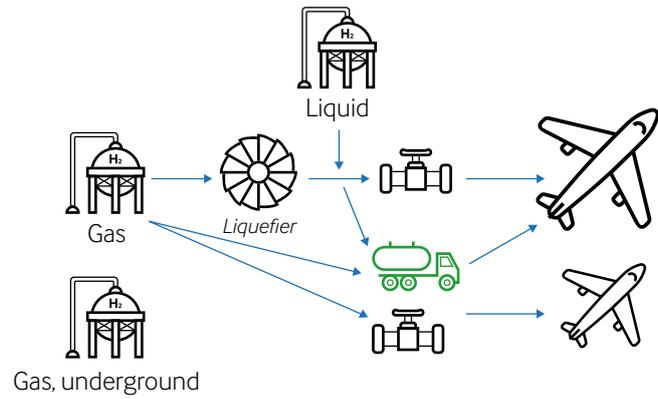


Figure 7: Hydrogen supply chain inside the airport

The NASA study, along with others¹⁵, favour pipeline refuelling as opposed to truck from a safety, economic and environmental perspective. However, it is recognized that for early implementation, trucks might be used as is anticipated for other liquid alternative fuels, like SAF. Another alternative, not considered in detail here, is distributing the hydrogen in gaseous pipelines into the gates and having micro-liquefaction facilities at the gate.

Table 3: Challenges and advantages of truck and pipeline hydrogen distribution inside the airport

Challenges		Advantages	
			
Ramp traffic and vehicle congestion	Infrastructure Costs	Less infrastructure	Boil-off recovery (up to 96%)
Truck emissions (GHG, AQ)	Maintenance Costs	Lower capital cost	Lower operating cost
Potential losses during transfer ⁴	Leak detection	Commercially available	Potentially safer
Heat source if truck has IC engine (ignition source)	Development timelines & permitting	Minimal permitting	Faster delivery

While today’s use of hydrogen is practically nonexistent in passenger aircraft and in commercial airports (with very few exceptions for vehicle fuelling and power generation by fuel cells for lighting applications), ample experience has been gained as a result of hydrogen handling in other industries. According to IRENA “hydrogen pipeline systems spanning hundreds of kilometres are in place in various countries and regions and have operated without incident for decades”¹². Similarly, there is a long track record of transporting hydrogen in dedicated trucks. Recent efforts in countries like Germany and the UK are investigating leveraging this knowledge to transport hydrogen in pure or mixed form into people’s homes for heating and cooking via existing natural gas pipelines^{29,30}. This experience could be used by airports when considering scaling up hydrogen to a point where pipelines are required. From a technical perspective it is feasible to do this, however the cost implications should be considered, as well as the appropriate safety procedures. Some challenges and advantages of both approaches are shown in Table 3.

NASA evaluated the infrastructure required inside the airport to supply hydrogen via pipelines, and summarised each into a few key cost centres¹¹ (Fig. 8):

- Liquefaction plant (if hydrogen arrives in its gaseous form or produced onsite)
- Distribution pipes and valves
- Trenching for pipelines
- Refuelling trucks

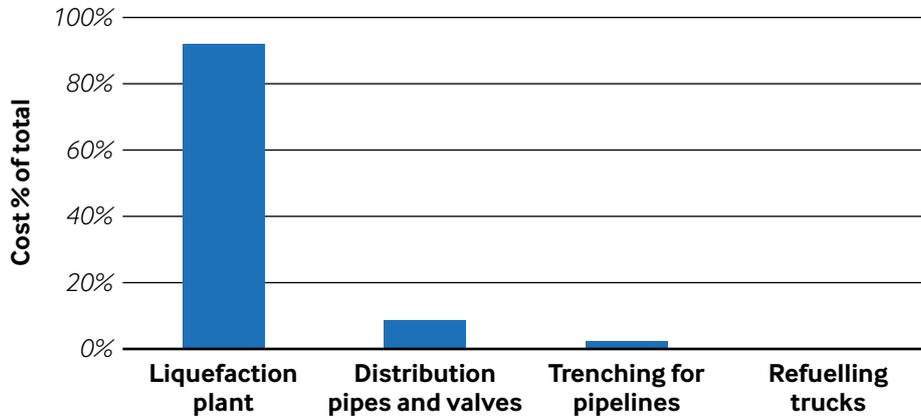


Figure 8: Infrastructure cost share at airports, assuming hydrogen arrives at the airport in its gaseous form (excludes electrolysis)

The NASA study estimated that 90% of the infrastructure costs related to the development of the liquefaction plant, while a minor percentage would correspond to the distribution infrastructure (Fig. 7).

Two distinct concepts for refuelling were identified in two separate studies. One involved a modification to the passenger boarding bridge, having a hydrogen pipeline connected directly to it with an operator sitting in a cabin where a refuelling boom would be operated (Figure 9-left). This would imply a more intrusive modification to the stand infrastructure and the refuelling point on the aircraft would have to be near the nose. The other approach envisioned refuelling the aircraft from the tail, with the pipelines configured accordingly. A connecting servicing truck would then join the refuelling port with the aircraft as shown on the right-hand side of Fig. 9^{10, 11}.

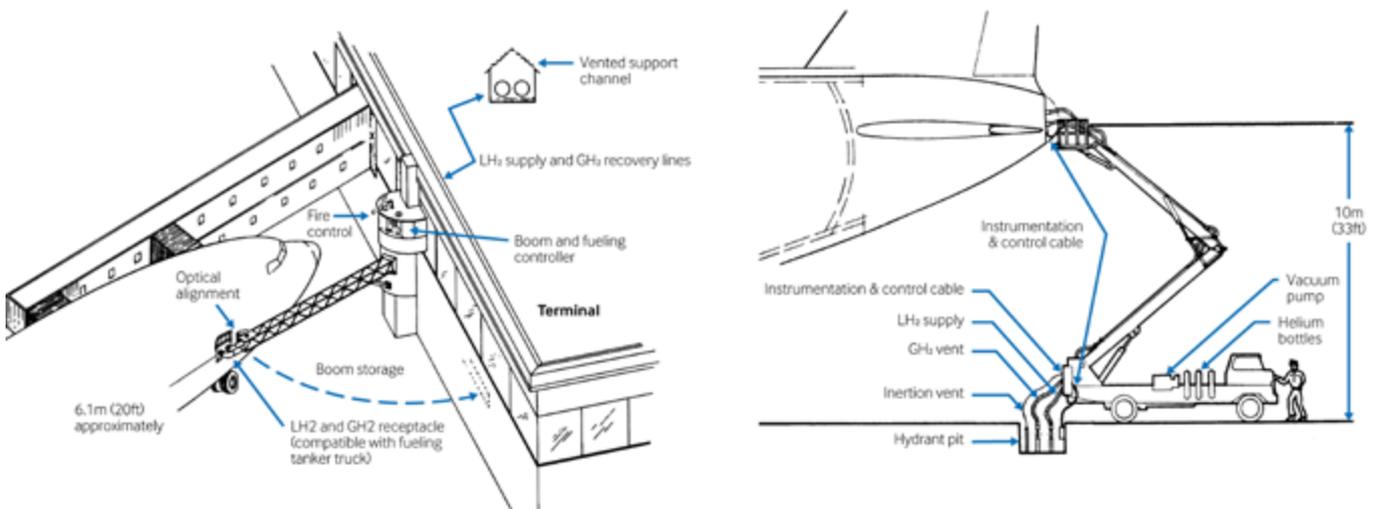


Figure 9: Options for hydrogen aircraft refuelling at the gate ^{10, 11}

These two concepts are shown for illustration only and are taken from studies which date back to the 1970s. Both of these approaches were deemed feasible from a technical and safety standpoint by the authors of the reports. It is recognised that modern operational procedures and technologies might offer more optimum solutions, with fewer consequences on the aircraft stand design, than those considered in the quoted studies. In the case of pipeline distribution, these would require a new hydrant system which would have to run in parallel to the Jet A-1 delivery system.

HAZARDS AND SAFETY CONSIDERATIONS

Passenger perception

Even though hydrogen has been used for decades in several applications, many people still perceive it to be unsafe. A lot of this fear arises due to the infamous Hindenburg disaster in 1937 in which the fabric skin of an airship caught fire and 36 out of the 97 people on board lost their lives. The aviation industry was in its infancy in 1937 and current aircraft are no longer made of flammable fabric but of resistant metallic and composite materials. The Hindenburg accident, however, can be taken as an example of hydrogen hazards and consequences. One of the NASA reports on the use of hydrogen and aviation¹¹ notes that the airship contained 125,000 m³ of gaseous hydrogen, the skin caught fire 50 metres above the ground, the airship crash landed, and 61 people survived. There was no explosion, most of the hydrogen escaped the airship and the rest quickly burned. Most of the damage to the airship was caused because of the flammable materials with which its structure was made as well as the impact on landing.

Passenger perception about the safety of hydrogen remains a clear challenge, and airports and other aviation stakeholders will need to engage with them to ensure positive public perception of hydrogen powered aircraft. Similar efforts were made, for example, in the United States, to introduce hydrogen for public transport and private cars. The 'Permitting Hydrogen Fuelling Stations' initiative showcases the required level of cooperation between the public, the local fire and building departments, and the code and regulation makers to advance the design, installation and operation of hydrogen fuelling stations for road transport³².

Physical properties of LH₂ vs Jet A-1 and hazards

Hydrogen fires exhibit a very different behaviour compared to Jet A-1 fires and as such present different hazards³¹. Table 4 lists some physical properties of hydrogen compared to Jet A-1 and their safety-related implications.

Table 4: Selected properties of Jet A-1 fuel compared to liquefied hydrogen^{13, 33-41}

	Jet A-1	Cryogenic hydrogen, LH ₂	Implications
Boiling point (°C)	167-266	-252	Frostbite, hydrogen boil-off, material embrittlement
Flammability Limits (%)	0.6 to 4.7	4 to 75	High likelihood of hydrogen fire, but higher concentration required to start it
Min. ignition energy (mJ)	0.25	0.02	High likelihood of hydrogen fire with weak sparks
Burning velocity (cm/s)	18	265-325	A hydrogen fire would finish faster than a kerosene one
Buoyancy		14x lighter than air, rise at 20 m/s	Gaseous hydrogen disperses quickly
Self ignition Temp (°C)	210	585	Harder to ignite hydrogen with pure heat
Fire heat radiative fraction	30-40%	10-20%	Hydrogen fires could be less destructive, as they radiate less heat, but present challenges due to invisible flame

Low temperatures

Jet A-1 fuel can be kept in its liquid (more manageable, and safer) form at high temperatures above 160°C. Hydrogen, however, needs to be cooled to an extremely low temperature of -252°C. This generates a new hazard, compared to Jet A-1: frostbite. Any pipes, tanks or valves which are in contact with the liquid and are not well insulated will be frozen at this temperature, posing risks for the personnel working in proximity to such infrastructure. Materials which do not suffer from embrittlement at that temperature will have to be selected for this purpose (as is currently the case in the hydrogen industry).

A rise in temperature inside the storage (or transport) container could cause hydrogen to boil and evaporate¹⁴. This will increase the pressure inside the vessel and will make leakages more likely. The hydrogen industry has established procedures to deal with this through pressure relief valves, hydrogen leakage sensors and changing colour paint or tape which detects and helps identify leakages. Such practices and systems might need to be adapted to comply with aviation safety standards¹⁰.

Flammability limits

The flammability limit is the required concentration of a flammable gas in air, in order for the mixture to be ignited. While Jet A-1 has a narrow flammability range of 0.6-4.7%, hydrogen's is much wider, (4-75%). If the Jet A-1 vapour concentration in air is higher than 4.7%, a fire will be unlikely to occur. However, a hydrogen fire is possible in concentrations going from 4-75%. For this reason, unventilated indoor hydrogen storage should not happen so that hydrogen gas is never allowed to accumulate in closed spaces to concentrations higher than 4%. The lower flammability limit, however, is higher for hydrogen (4%) than it is for Jet A-1 (0.6%), making hydrogen safer at low concentrations^{10, 11, 18}.

Ignition energy

The energy required to start a fire is ten times lower for hydrogen than for Jet A-1, so a considerably weaker spark is required to ignite hydrogen than to ignite other flammable hydrocarbon gases. The likelihood of a fire if the concentration of hydrogen is within the flammability limits, is therefore extremely high. For this reason, unprotected flames and sparks should be kept away from any hydrogen handling infrastructure, vessel or vehicle, and special attention needs to go into avoiding any leakages especially in places where the hydrogen can be constrained and not allowed to evaporate and diffuse quickly. This challenge has been successfully tackled by the hydrogen industry so far, so the aviation industry needs to learn from existing standards, procedures and regulations and apply them to an airport environment¹⁰. A comprehensive review of over 300 standards and codes can be found in the references⁴², these include infrastructure elements (pipelines, storage tanks, valves), fuel cells and refuelling stations.

Buoyancy and diffusivity

Gaseous hydrogen is extremely light and buoyant (14 times lighter than air). Leakages or spills in an open space will evaporate and diffuse quickly, reducing the hazard of flammable gas accumulation or spills, and the risk of fire will be reduced (this is related as well to its low boiling temperature)¹⁸. This is less true, however, for liquid cryogenic hydrogen which at temperatures of -252°C is denser than air. In case of a catastrophic tank rupture, hydrogen could behave as a dense flammable gas which could travel for several meters before it gets dispersed⁴³. In ENABLEH2, Holborn et al.⁴³ studied the dispersion behaviour of large liquid hydrogen releases considering different ground properties, release rates and atmospheric conditions, and compared it to experimental NASA data. Research is ongoing on this area to identify the hazardous zones of such occurrences.

Vaporisation and burning rate

Liquid hydrogen vaporises and burns at a much faster rate than Jet A-1, consequently, a pool fire for a liquid hydrogen spill will be of much shorter duration. NASA, in a dedicated study comparing Jet A-1 and liquid hydrogen pool fires, crashes, and fire balls for aviation, estimated that a full fuel release of an aircraft containing 150 m^3 (~10t) of fuel would burn in 10 seconds in the case of hydrogen and 2 minutes in the case of Jet A-1. The results were of similar magnitude regardless of whether the mass or energetic contents of the fuels were compared³⁵. Similar studies conducted by the ENABLEH2 initiative in 2020, compared liquid hydrogen spill hazards for a narrow-body passenger Cryoplane type aircraft design using high-fidelity computational fluid dynamics (CFD) methods⁴⁴. The results also suggest that liquid hydrogen pool fires would be of much shorter duration⁴⁵ compared to conventional aviation fuels potentially leading to a less destructive fire¹⁰, see Figure 10.

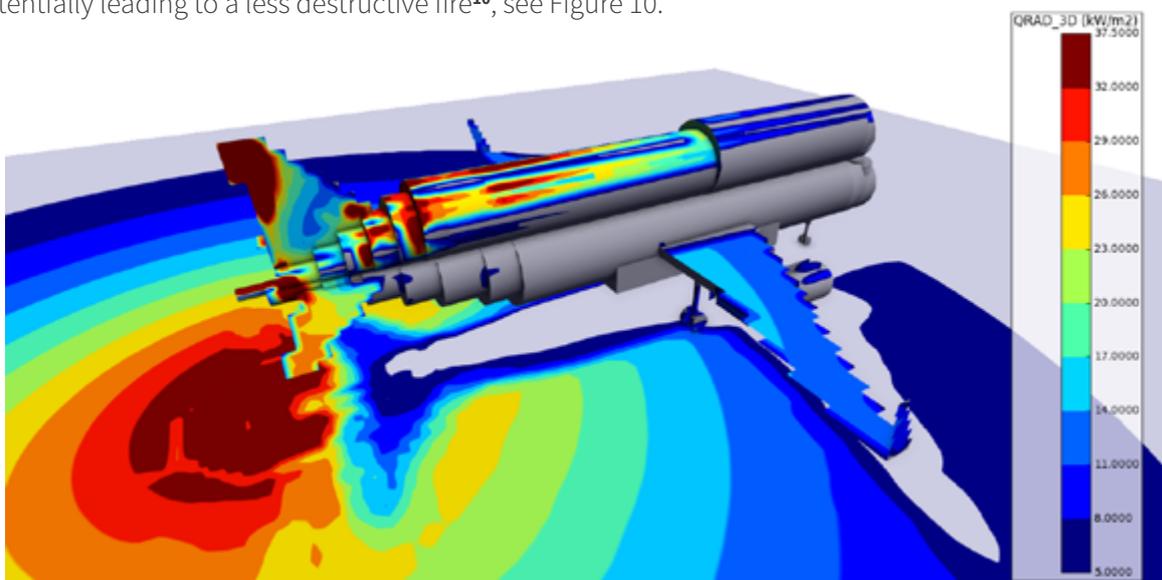


Figure 10: Modern simulation of the heat release of a fire caused by a large scale release of hydrogen from the back of a narrow body aircraft. Courtesy of P.Holborn (LSBU, ENABLEH2)

Fire radiative heat flux

A hydrogen fire would release about 10% of its heat as thermal radiation compared to 30-40% for an equivalent fire of Jet A-1^{35, 10, 18}. Although hydrogen has a higher heat release rate and flame temperature than liquid natural gas (LNG) or Jet A-1, a hydrogen fire releases a smaller fraction of its heat as thermal radiation and more of this radiation is blocked by the water vapour in the surrounding atmosphere. This is a consequence of the radiation produced by a hydrogen flame being emitted by excited water vapour rather than the carbon-based species – especially soot particles – that are produced by hydrocarbon flames, which are more efficient thermal radiators⁴⁵.

Because hydrogen fires have a relatively short duration and produce a lower thermal radiation dose than comparable Jet A-1 fires, they may produce less hazardous consequences than Jet A-1 in this respect^{45, 35}. Early studies on hydrogen aircraft accidents, concluded that the danger to by-standers of hydrogen fires could be less than a hydrocarbon fuel since, for example, a fire ball would be of lower height, lower diameter, shorter duration and would emit less heat. For a stationary aircraft which was engulfed in a fire, the characteristics quoted before could mean that “the result is a significantly lower heat dose for LH₂ than the other fuels, due mainly to the shorter fire duration”³⁵.

These results were done on ideal conditions for limited amounts of released fuel, and more research is required to assess a wider variety of scenarios which could change those conclusions. The studies also do not consider cases that might occur during refuelling operations, where there could be a spill of LH₂ which is not immediately ignited – resulting in dispersion of a flammable hydrogen gas cloud which could subsequently become ignited, resulting in an explosion or flash fire. These additional hazards posed by using LH₂ for fuelling aircraft also need to be taken in to account and are currently being addressed by the ENABLEH2 initiative, amongst others.

Other hazards related to hydrogen fuel at airports

Although transportation and storage of LH₂ is seen to be no more hazardous than similar use of Jet A-1 fuel, the risks are unique and so procedures for specific hazards must be put in place⁴².

In terms of clearance distances for storage, for example, NASA notes that many times the surroundings cause more hazard to the storage facilities, than the hydrogen tanks to the surroundings. Some of the early standards written in 1975 in the USA were to protect the tanks from the buildings in case the building caught fire and not the other way around¹¹. The clearance distance suggested was 30m (natural gas is 90m in comparison). The shorter clearance distances compared to other hydrocarbon fuels were consistent with a study done in the context of the Cryoplane initiative on ground operations of hydrogen aircraft⁴⁶.

Some studies suggest that while storage and operation hazards need “be no greater than equivalent Jet A-1 fuelling and may be lower”, the main point of attention will have to be in the interface between the airport infrastructure and the aircraft during refuelling, maintenance, testing and defuelling. Some general recommendations from the studied sources are:

- The area of unsecured spark ignition vehicles around the aircraft might be large - a radius of 27m from the point of refuelling was suggested in one study. The refuelling point which will be the reference for this distance will also change (tail or nose refuelling, instead of under-wing¹¹).
- Avoid hydrogen fumes accumulating in closed spaces like the aircraft cargo compartments or under the aircraft wings and ensure adequate ventilation.
- Appropriate separation of LH₂ facilities from roads, buildings, and runways.
- Automate sensing and shutdown systems.
- Reduce ignition sources within the identified safety area.
- Consider provisions to confine or control large LH₂ spills in critical areas (aircraft stands, fuel facilities, etc.).

Existing standards, codes and regulations for gaseous and liquid hydrogen like the United States NFPA2⁴⁷ already include provisions for the safe design, operation and installation of hydrogen infrastructure. Many other countries or regions have equivalent national standards⁴⁸. The International Standards Organization (ISO) also has specific material on hydrogen equipment and infrastructure (for generation, detection, storage, or transmission of hydrogen, e.g., ISO 19880). Their suitability to the aviation sector will need to be assessed in detail.

AIRCRAFT/AIRPORT COMPATIBILITY AND GROUND OPERATIONS

The ICAO Aerodrome Design Manual (Doc 9157), and the ICAO Airport Planning Manual (Doc 9187) highlight some physical characteristics of airport infrastructure elements such as runways, taxiways, parking aprons and aircraft stands. The documents provide ways to classify airports and aerodromes based on specific metrics of these infrastructure elements to ensure their harmonisation across the world as well as to ease compatibility with aircraft. For example, some airports handle aircraft with passenger capacities going from 20 to 500 people, take-off masses from 600 to 500,000 kg, wing spans and lengths from 20 to 80 m. The infrastructure and operations at airports are tailored to accommodate this wide range of physical aircraft characteristics. The aircraft mass, for example, helps determining the thickness of the materials used in the construction of runways, taxiways, and aprons, as well as the runway lengths. A significant increase in aircraft mass, would require changes to the pavements. A longer wingspan, for example might mean that the clearance between the runway and taxiways is no longer met or the aircraft will not fit in a given parking stand (which in turn could mean a redesign of the terminal building).

In reviewing these documents, a non-exhaustive list of 12 aircraft characteristics was extracted, which ensure compatibility with existing infrastructure. A qualitative assessment of these characteristics has been done by ACI and Airbus based on Airbus’ Zero-e programme. The purpose of this assessment is to start identifying which aircraft characteristics might affect which airport infrastructure elements, and in this way, start focusing the evaluation and implications of such changes to airports (Table 5). This assessment was done on very preliminary designs of hydrogen aircraft, and so the results could rapidly change.

Table 5: Zero-e airport compatibility parameters

	Likely to change		Unknown if it will change	Unlikely to change
	Will need special infrastructure considerations	Won't need special infrastructure considerations		
Wingspan				x
Maximum take-off weight		x^a		
Maximum landing weight		x		
Main gear wheel span			x^b	
Fuselage length	x^c			
Nose wheel angle				x^b
Electric power demand				x
Turnaround time				x^d
Required runway distance			x	
Engine blast production				x
Turning radius			x^b	
Servicing design (position of cargo, passenger doors, position of refuelling port etc.)			x	

- a. It is still unclear whether a hydrogen aircraft will be heavier or lighter than the Jet A-1 aircraft it might replace. The MTOW could be lower because the fuel weight will be considerably less, but the cryogenic tanks to host the hydrogen below -252°C will be heavier than current Jet A-1 tanks. These aircraft, however, are not expected to be heavier than the heaviest aircraft operating in commercial airports, and thus no special infrastructure considerations are predicted.
- b. These parameters will depend on future aircraft design choices rather than on the source of power (hydrogen or other).
- c. Aircraft might be longer, to accommodate the larger fuel volume. Gate compatibility will have to be addressed. Clean Sky 2 predicts 5-10 metres more for a narrow body aircraft¹³.
- d. A turnaround time (TAT) duration similar to today's Jet A-1 TATs is a design objective for Airbus, however the refuelling process will require new types of equipment and operations. TAT could be longer than for Jet A-1 aircraft in specific cases where the refuelling time exceeds the duration of other processes. The possibility of parallel refuelling with catering and passengers boarding and deplaning will have to be reassessed. If refuelling operations cannot be done in parallel with the rest of the standard handling activities, the turnaround times would increase.

The previously outlined characteristics of hydrogen, the possibilities for supply chain and the expected aircraft/airport compatibility could have other operational challenges, which the reviewed reports deem as important but feasible to overcome. Some of those are outlined below:

Operations on aircraft stands

To avoid hydrogen gas concentrations, leakage management will have to become a top priority while refuelling. Some extra procedures could be implemented to avoid potential accumulation of hydrogen gas in aircraft compartments or under the wings. This might further change turnaround procedures.

If aircraft are refuelled by trucks, and larger or more trucks are required, the traffic at the ramp might be an issue (it already is for some airport operators). Autonomous vehicles for refuelling (robotic handling of refuelling pipes) could speed up fuel transfer for larger aircraft and reduce ramp traffic and associated hazards. For both, pipeline and truck refuelling, a novel type of coupling and refuelling equipment will need to be developed along with the safety guidelines for their use.

Flexibility of refuelling the aircraft on any stand will be required.

Hydrogen network availability

Hydrogen would have to be available at the port of departure and the port of arrival of the aircraft. Early assessments of the introduction into service of hydrogen envision tight regional or domestic networks expanding with time to international or inter-regional flights. The availability of hydrogen at many airports will be a challenge.

Those airports which are equipped to supply hydrogen to aircraft would need to be backed up by the alternative airports in the vicinity in case flights are diverted. The feasibility study done on Zurich Airport²⁰, envisioned that the airport could manufacture hydrogen on or near site and supply its alternative airports with smaller quantities of hydrogen via trucks.

Rescue and fire fighting

The rescue and fire fighting procedures will need to be reviewed and adapted to accommodate potential hydrogen fires. Due to the short duration of a H₂ fire, all the fuel might be consumed by the time the fire fighters arrive at the zone of the incident, so their role in responding to an incident or accident might change. The risks of explosion of high concentrations of hydrogen in confined spaces will also have to be addressed by the fire fighting crews, all of which will result in new training and potentially specialized equipment. The Hyresponder project, for example, is an initiative that looks to train first responders for hydrogen safety throughout Europe⁴⁹.

COST CONSIDERATIONS

According to the International Energy Agency, over 95% of the hydrogen produced worldwide comes from natural gas²². The major cost component of this type of hydrogen is the natural gas itself (on average 50% of the cost) with the CAPEX cost representing the second largest component, about 30%²². The production costs change depending on where the hydrogen is made and whether the released carbon is captured and stored or not (Figure 11). The cost of renewable hydrogen, however, is significantly different and composed mostly of CAPEX and electricity energy costs²³. As renewable electricity costs continue to fall, and as electrolyzers scale up and become more efficient, the cost of renewable hydrogen could drop by up to 40% by 2030 becoming lower than that of blue hydrogen (from methane with carbon capture and storage)⁵⁰. In some regions which benefit from low renewables costs this might be a reality in the next three to five years¹². A recent report from IRENA predicts that a combination of cost reductions in electricity and CAPEX for electrolyzers, combined with increased efficiency and operating lifetime could deliver up to 85% reduction in hydrogen costs, making green hydrogen cheaper than fossil fuels (<1 USD/kg) before 2040⁵⁰.

This might impact the hydrogen supply into airports as the final users will give preference to those supply chains which have the lowest environmental and economic cost. Furthermore, it might encourage airports to produce hydrogen on site for their own use as well as to supply it to other sectors.

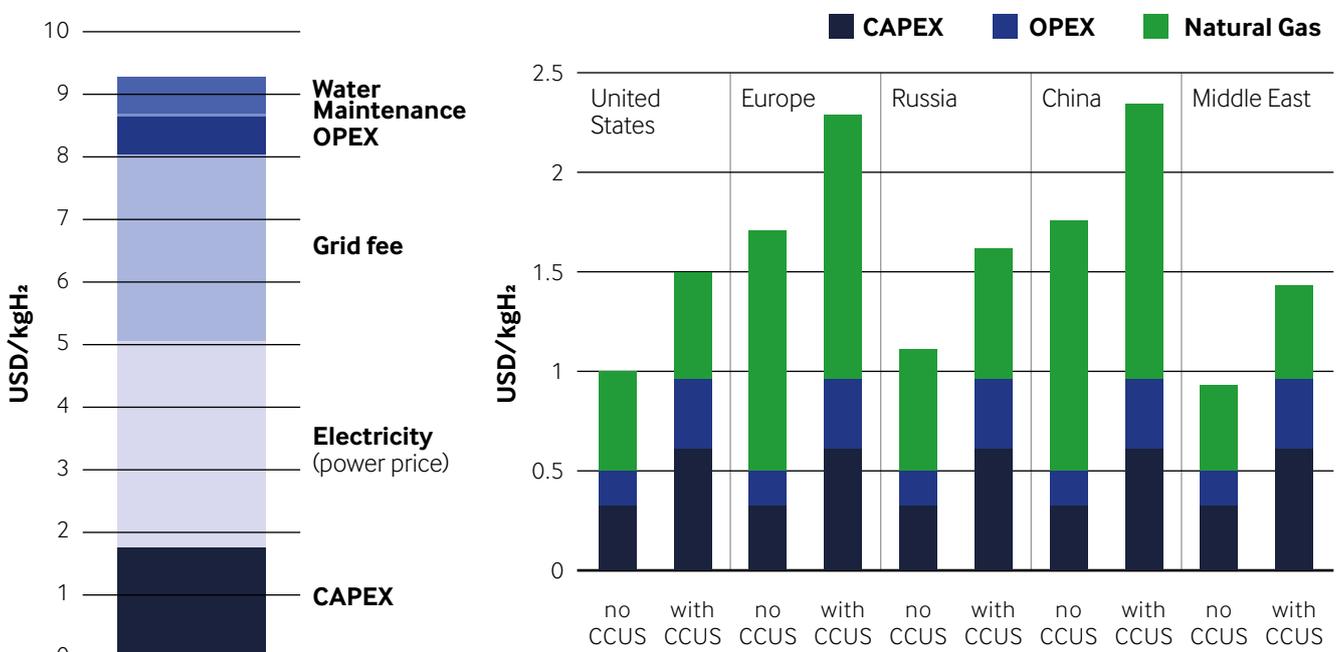


Figure 11: Left: production costs of renewable hydrogen²³, Right: production costs of blue hydrogen²². Carbon capture, utilisation and storage (CCUS)

Today, most fuel infrastructure at airports is owned and operated by consortia of airlines and sometimes energy companies. Very few airports own or operate the fuelling infrastructure. It is still thus to be defined what role airports will play in developing this infrastructure. There are cases where some airports (which have space availability) see opportunities to invest in producing hydrogen or renewable electricity for their own use, (if the regulatory structure allows for this) and for selling to third parties outside the airport, but others where the role of the airport will be to provide the hydrogen suppliers with space to run their operations.

GAPS IDENTIFIED

The review of documents highlighted further areas where more information needs to be gathered to further inform analysis and/or future pursuit of hydrogen refuelling infrastructure, including but not limited to:

Resources

- Up-to-date case studies where the energy requirements, space and water availability are assessed.
- Up-to-date studies highlighting the challenge of up-scaling hydrogen for its use in aviation, as well as the energy requirements mapped at a regional level.
- Considerations on ramp up phasing based upon airport size, scale, service and geography.

Operations on stands

- Safety perimeter from refuelling point / facilities, depending on aircraft design, and refuelling location, which will probably not be at the wings as with current aircraft.
- Evaluation of refuelling while other ground service operations are taking place, for example during boarding or deplaning, as well as any extra procedures during the turnaround process.
- Evaluation of refuelling a hydrogen aircraft at a stand while a conventional Jet A-1 aircraft is also being refuelled nearby.
- Emergency procedures and equipment in case of H₂ flexible hose pullout and H₂ leakage mix with hazardous materials, and whether the experience in the hydrogen road (or rail) transport sector can help to inform any of the above.

Operations

- Specifications to account for winter operations or other specific weather conditions. Evaluation of how these will affect airport operations related to hydrogen aircraft.
- Leak management procedures in the industry and how these can be adapted to an airport environment.
- Evaluation of safe maintenance procedures, for example if the aircraft tanks need to be completely emptied, boil-off management, or indoor maintenance procedures.

Infrastructure

- Case studies highlighting best internal distribution of hydrogen depending on the airport and aircraft pair, and infrastructure implications of this.
- An up-to-date estimation on the costs of infrastructure and ownership format is required.

Staff

- Qualification and training for rescue and fire fighting services, ground handling service providers and fuel service providers.

OPPORTUNITIES FOR AIRPORTS AND CASE STUDIES

While hydrogen is mainly addressed in this report as a fuel to reduce aircraft emissions (scope 3), it can also be used by airports to reduce their own emissions. Hydrogen is a versatile fuel which can be used to power ground support equipment via combustion or fuel cells, as well as to warm the terminal, heat up water, or for cooking in the terminal restaurants. If the hydrogen is produced on site, airports could become providers of this energy source to other sectors, contributing to decarbonise the city that hosts them. A recent initiative launched in Paris, for example, looks into transforming airports in the region into hydrogen hubs⁵¹.

In Japan, Kansai Airports has three hydrogen stations; one in Osaka International Airport (Itami) and two in Kansai International Airport (KIX). The Kansai Airports case is of special interest as it combines many of the aspects addressed in this report:

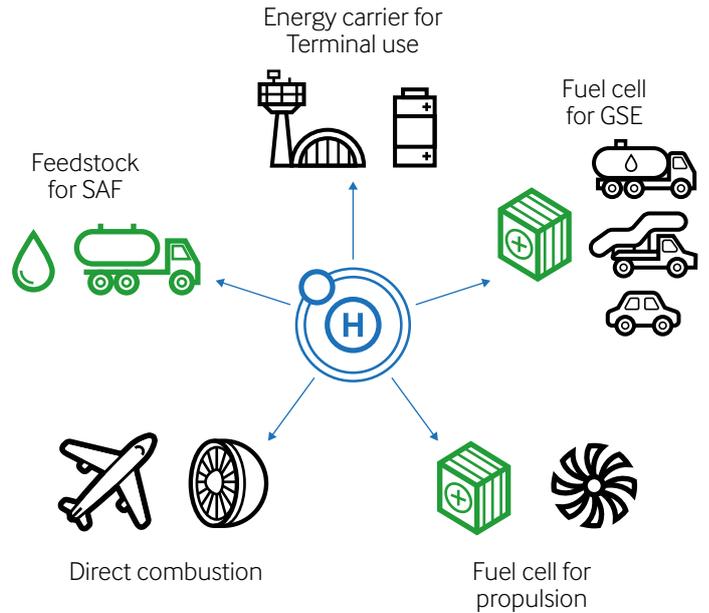
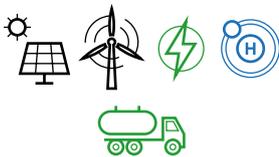


Figure 12: Opportunities to use Hydrogen at airports



Decarbonising ground support equipment (GSE): The main uses of hydrogen now at KIX are refuelling hydrogen fuel cell passenger vehicles (HFCV) and forklifts (HFCFL). The airport currently has 22 operating HFCFL, 4 HFCV, and has plans to expand the capabilities to passenger buses and other GSE.



Combined supply chain of hydrogen: The airport currently generates renewable electricity on site with wind and solar PV. This could be used in the future to generate hydrogen but today it is brought to the airport by trucks.



International hydrogen supply chain: Although today the hydrogen the airport uses is locally sourced, an opportunity might present itself to capitalise on the vicinity of the airport to Kobe port, which has infrastructure to store imported liquid hydrogen.



Collaborative working: The project is supported by the Japanese government which has ambitious plans to decarbonise and to incorporate hydrogen as an energy vector to achieve this. The airport collaborates with the local government, the ground service equipment operators, vehicle manufacturer and the hydrogen provider.

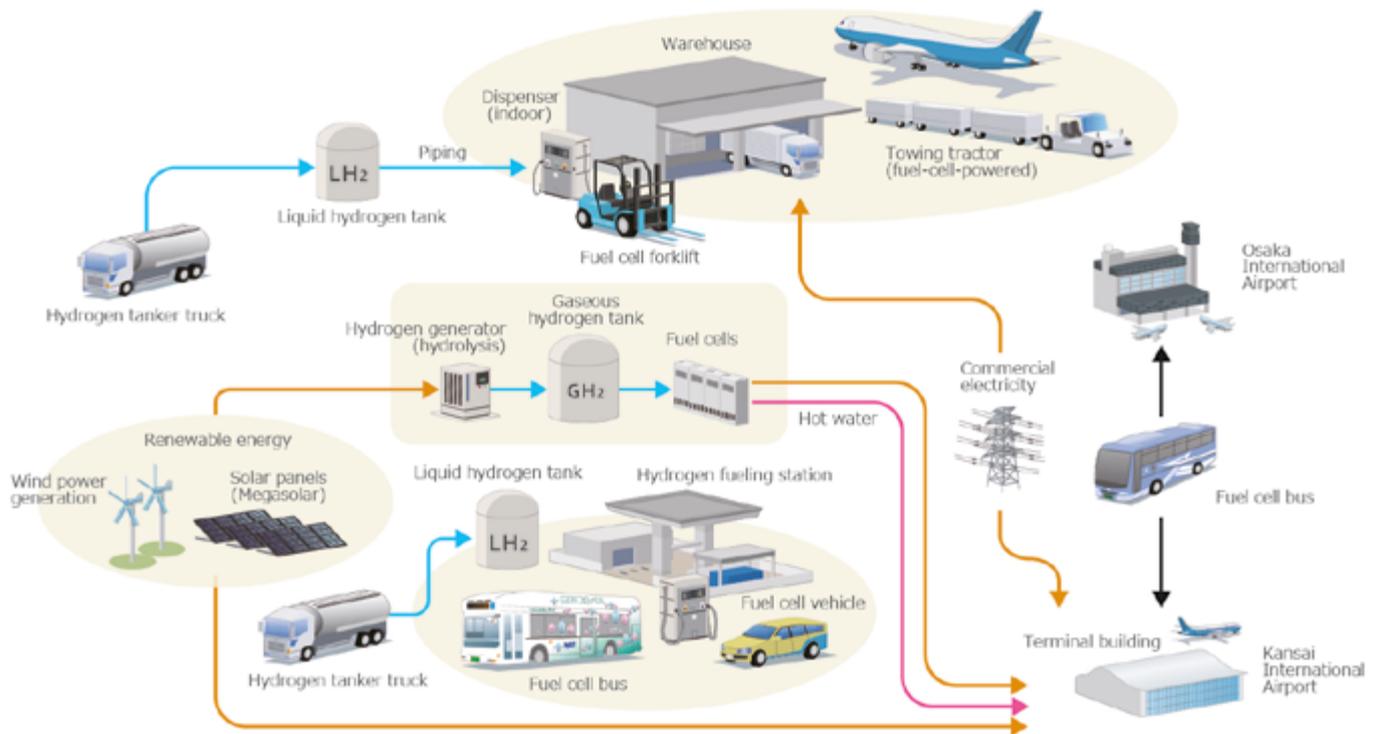


Figure 13: Kansai Airport Hydrogen Grid Project, Courtesy of KIX Airport⁵²

In 2019, ITM Power opened a hydrogen refuelling station at Gatwick airport, the second busiest airport in the United Kingdom. The unit uses grid electricity (which in the UK is almost 50% from renewable sources) and water to generate hydrogen on site. This charging station is for cars and so can enable zero-emission road transport for passengers as well as help decarbonising airport car fleets. Gatwick is also working with Metrobus on refuelling its forthcoming hydrogen bus fleet. Future plans might include incorporating airport buses to the system. With the United Kingdom committed to reaching net zero emissions, Gatwick sees the introduction of hydrogen for ground applications as a way to start familiarising airport employees and passengers with the fuel for future acceptance into other, longer-term potential uses like aircraft.

CONCLUSIONS

The review of documents and stakeholder engagement provided a first insight into some of the implications that hydrogen-powered aircraft could have on airport infrastructure, operations and safety procedures. This document is a summary of the collected sources and so far no internal analysis has been done to back up or contradict the reviewed sources.

With regards to the supply chain of hydrogen into the airport, different routes were explored such as:

- Manufacturing hydrogen on site.
- Importing hydrogen in its gaseous form and liquefying on site.
- Importing hydrogen in liquid form.
- Importing hydrogen in exchangeable pods to be loaded into the aircraft by catering equipment.

The best route-to-tank will be dependent on the demand of hydrogen at the airport, on the airport's location, on the distance from where the hydrogen comes from, the space available at the airport and the accessibility to the feedstock of hydrogen. This difference in routes and manufacturing procedures will determine the infrastructure required at the airport. For low traffic levels at an initial ramp-up period, the infrastructure requirements could be minimal if hydrogen arrives via trucks already in its liquid form.

It was seen that while it is more favourable to transport hydrogen within the airport via pipelines, directly to the gate (from an economical, safety and efficiency standpoint), this might only happen once the economies of scale justify the required investment in infrastructure.

With regards to safety, it is recognised that hydrogen is a hazardous substance, which is flammable and in certain conditions prone to explosions. However, its physical properties make it at least as safe as, and sometimes safer than, Jet A-1 fuel. The most important takeaway is that hydrogen is different, it has different safety risks and challenges, and specialised procedures will be required to handle this fuel safely.

A large supply of hydrogen into the airport (or manufacture of hydrogen at the airport) can also help airports to reduce their own emissions by decarbonising GSE, boilers, heaters or providing hydrogen charging stations for private vehicles or passenger buses, in the same way as actively pursuing electrification of these end uses.

Collaboration between the ACI and ATI, and engagement with other stakeholders will continue to further understand the implications of hydrogen aircraft into airports. Next steps involve a more in-depth understanding of the infrastructure costs of such approaches considering the specific capabilities of each airport, as well as continuous monitoring on the development of the topics highlighted in this document.

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Appendix: Conversion parameters for Liquid Hydrogen compared to Jet A-1

Basic properties:

	Jet-A1	Cryogenic Hydrogen (L-H ₂)
Specific energy - LHV (MJ/kg)	43	120
Density (kg/m³)	775–840	70.8

Comparison for the same mass:

	Weight: metric tonne	Energy content (MJ)	Volume: m ³	Volume: L	Volume: US gallons
LH₂	1	120,000	14.1	14,124	3,731
Jet A-1	1	43,000	1.19	1,190	314

Comparison for the same energy content:

	Weight: metric tonne	Energy content (MJ)	Volume: m ³	Volume: L	Volume: US gallons
LH₂	1	120,000	14.1	14,124	3,731
Jet A-1	2.8	120,000	3.32	3,322	878

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