Infrastructure and supply pathways for liquid hydrogen at airports: A technical framework for feasibility and airport master planning

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Abstract

Hydrogen-powered aviation is increasingly considered a promising option for reducing aviation emissions, particularly on regional and short-haul routes. The use of liquid hydrogen (LH_2) as an aviation fuel offers significant environmental benefits, but its adoption and integration require the development of new infrastructure at airports, including hydrogen liquefaction facilities. This paper lays the groundwork for assessing the feasibility of onsite hydrogen liquefaction by examining the technical principles, supply chain configurations and spatial requirements of such facilities. The study starts with a comprehensive overview of hydrogen as an aviation fuel, outlines current aircraft developments and compares three LH_2 supply pathways: centralised offsite liquefaction, onsite liquefaction from offsite hydrogen, and full onsite production and liquefaction. Drawing on real-world examples from operational liquefaction facilities in South Korea, the US and Canada, the study presents a generalised layout for airport-based liquefaction facilities, detailing core liquefaction process zones and supporting systems. These zones serve as a planning tool for early-stage spatial assessments, safety zoning and integration of hydrogen liquefaction facilities with existing airport infrastructure. The layout presented in this study is modular and scalable, allowing airports to adapt infrastructure to varying hydrogen demand and spatial constraints. While current liquefaction plants demonstrate technical feasibility and viability at scales up to 90 tons per day (tpd), this study explores the practical challenges of implementing such infrastructure at airports. These include gaining access to gaseous hydrogen via backbone networks, energy demands, constrained land availability, safety zoning requirements and regulatory complexity. Rather than resolving these issues, the paper provides a descriptive framework to understand and assess them, supporting airport master planning and future airport feasibility studies. This article is also included in ***The Business & Management Collection*** *which can be accessed at https://hstalks.com/business/.*

Keywords

sustainable aviation, hydrogen, liquid hydrogen, LH2, airports, hydrogen liquefaction

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INTRODUCTION

Aviation faces increasing pressure to decarbonise. The European Union (EU) has established legally binding targets to achieve net zero greenhouse gas (GHG) emissions by 2050, covering all sectors, including aviation.[1] Additionally, the International Air Transport Association (IATA) has committed its member airlines to achieving net zero carbon emissions by 2050.[2] Given aviation's growing contribution to global GHG emissions, a systematic and ambitious decarbonisation strategy is essential. These ambitions require not only technological innovation but also a rethinking of airport infrastructure and energy systems.

The Destination 2050 roadmap, developed by a coalition of European aviation stakeholders, outlines four key measures to achieve net zero emissions in the sector by 2050:[3] advancements in aircraft and engine technology, improved air traffic management (eg implementation of the Single European Sky), market-based economic measures, and the adoption of alternative fuels and sustainable energy sources. Among these, sustainable aviation fuels (SAF) are projected to deliver the largest share of emission reductions due to their compatibility with existing aircraft and fuelling infrastructure. Other emerging technologies, such as battery-electric and hydrogen-powered aviation, offer potential for zero-emission flight on short and medium-haul routes, but require significant infrastructural adaptations at airports.

Policy frameworks set the direction, but the realisation of hydrogen-powered aviation depends on the readiness of airport infrastructure. LH_2 in particular presents unique opportunities due to being a carbon-free fuel (if electrolysis and renewable energy sources are used), but also challenges due to its cryogenic nature, volumetric characteristics and safety requirements. The adoption of this new fuel will require a coordinated approach across aviation, energy, engineering and regulatory domains.

This paper focuses on one of the critical enablers of hydrogen-powered aviation: onsite hydrogen liquefaction at airports. It provides a technical and spatial framework by examining the components of a hydrogen liquefaction facility, its integration within airport environments and the trade-offs between centralised and decentralised LH_2 supply models. By establishing this foundation, the paper supports future feasibility assessments and strategic planning efforts, enabling airport operators to prepare for the infrastructural transition required to facilitate future hydrogen-powered aviation.

HYDROGEN AS AN AVIATION FUEL

The absence of carbon in hydrogen makes it an environmentally friendly fuel, considering it is produced green without carbon emissions. Multiple methods, which vary in their environmental impact, can be used to propel an aircraft with hydrogen. The most environmentally friendly method makes use of a fuel cell in combination with an electric motor. An electrochemical reaction of hydrogen in the fuel cell generates the electric power needed for the electric motor and propellor. This method eliminates CO_2, soot and virtually all NO_x.[4] Water vapour, however, is still produced and could form contrails under given conditions. These contrails prevent thermal radiation emitted by the earth to make it outside the atmosphere, thereby resulting in a warming effect.[5] Another method is the direct combustion of hydrogen, which, while still cleaner than kerosene, generates NO_x due to high-temperature processes, although new engine designs can mitigate this.[6]

At ambient conditions (20°C, 1 atm), hydrogen is a gas (GH_2). Hydrogen's high gravimetric energy density (≈120 MJ/kg, when using the lower heating value, versus ≈ 46 MJ/kg for kerosene, subject to the exact mixture of the jet fuel[7]) makes it attractive for aviation. The low volumetric energy density of hydrogen, however, poses a challenge when considering hydrogen as an energy carrier for transport.

The volumetric energy density of hydrogen at 700 bar is ≈ 4.8 MJ/L,[8] while LH_2, the state of hydrogen when cooled to −253 °C (20K), achieves ≈ 8.5 MJ/L. As a comparison, the volumetric energy density of kerosene is ≈ 34 MJ/L at ambient pressure and temperature.[9] This means that, given a fixed flight distance, less LH_2 is needed in terms of weight compared to kerosene, but more LH_2 is required in terms of volume. Because of this, and due to the need for cryogenic storage in the fuselage — unlike kerosene, which is typically stored in the wings — LH_2 is mostly considered applicable for regional (<500km), short (between 500 and 1500km) and parts of medium-haul flight operations (between 1500 and 4000km).[10] As an indication, intra-European traffic recorded 22,588 daily flights in 2024 with an average flight distance of ≈ 1.150km.[11] Notably, regional routes are the most carbon-intensive per seat-kilometre, making them ideal candidates for LH_2 adoption.[12]

HYDROGEN AIRCRAFT DEVELOPMENT

Retrofit and clean sheet hydrogen-powered aircraft projects have been announced by several manufacturers. ZeroAvia is developing a hydrogen fuel cell propulsion system intended to be used as a retrofit system for existing turboprop aircraft such as the DHC Dash 8 Series and the ATR 42/72, types widely used on regional routes by airlines such as Aer Lingus Regional, SATA, Widerøe, Finnair, Westjet, Air Canada, QantasLink and Air New Zealand. German company H2FLY has tested its HY4 aircraft and is further integrating its fuel cell system into a Dornier 328 demonstrator.[13]

Airbus has announced its ZEROe programme back in 2020. Four concept aircraft, of which the turboprop version with the fuel cell propulsion system is the most likely to be developed first, have been introduced by the company and demonstrator projects have been launched.[14] The company's fuel cell prototype and powertrain testing supported the viability of fuel cell technology as propulsion method for its ZEROe aircraft. Market introduction is expected to be after 2035.[15] Other developments by manufacturers such as Fokker Next Gen,[16] Conscious Aerospace[17] and Embraer Energia[18] are still in their conceptual phase. Although technology is still at various stages of development, current initiatives indicate a growing interest in hydrogen propulsion for regional aviation.

LIQUID HYDROGEN SUPPLY TO AIRPORTS

Currently, airlines predominantly utilise kerosene as aviation fuel. Airports facilitate the infrastructure required to receive, store and distribute fuel, typically via hydrant systems or mobile fuel bowsers (tankers), while fuel operations are carried out by specialised service providers. The associated supply chain, including production, transport, storage and distribution of kerosene on the airport, have proven to be both feasible and viable for many decades. In contrast, hydrogen supply chains for airports, particularly those for LH$_2$, are nearly non-existent at present.

To understand the future landscape of hydrogen supply at airports, Figure 1 outlines potential LH$_2$ supply chain configurations. All future supply chains commence with the production of hydrogen, which can be produced through various methods. Currently, steam methane reforming (SMR), which uses methane as a feedstock, often referred to as 'grey' hydrogen, dominates global hydrogen production.[19] The carbon intensity of this hydrogen can be reduced by capturing and storing CO$_2$. This hydrogen is considered 'blue' but can still differ in carbon intensity. The Porthos project in Rotterdam, the Netherlands, which integrates grey hydrogen facilities with a CO$_2$ transport and storage system, is an example of such a carbon capture and storage system. To achieve net zero emissions by 2050, however, airports will eventually need LH$_2$ derived from renewable or 'green' hydrogen, produced through electrolysis and with use of renewable energy sources such as wind, solar and hydro.

Hydrogen can be produced domestically or in countries with abundant renewable energy sources. If produced abroad, the hydrogen needs to be transported to the country where it will be used. Long-distance hydrogen transport can be achieved via pipelines, utilising for instance retrofitted or new pipelines between North Africa and Europe,[20] or via ships. In the latter case, hydrogen can be shipped in liquified form as LH$_2$, ammonia or liquid organic hydrogen carriers (LOHC).

Ammonia and LOHC, however, require a hydrogenation step, adding hydrogen to a compound before transportation, and a dehydrogenation step, removing hydrogen from a compound, locally if imported. These processes come

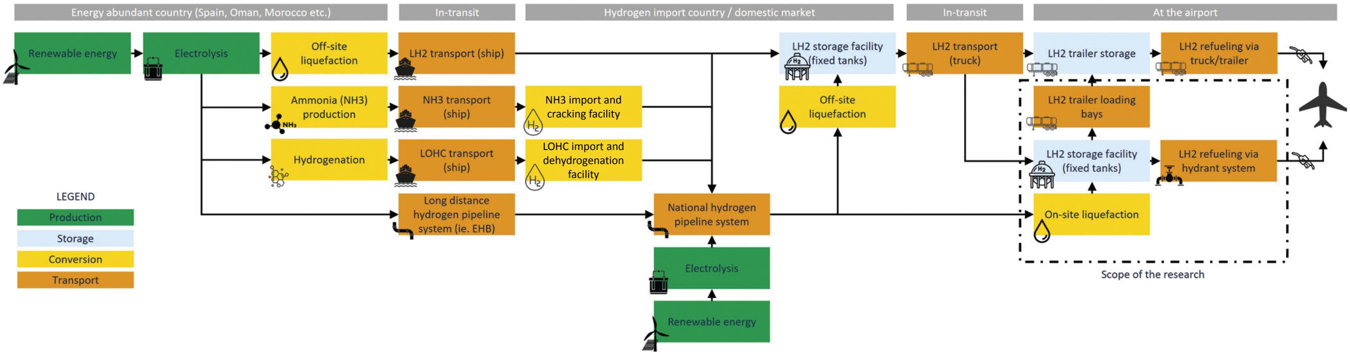

Figure 1 Simplified LH$_2$ for airports supply chain overview

with additional energy costs in the range of 20–40 per cent,[21,22] depending on the energy carrier and the process efficiency, and can be associated with additional carbon emissions if the energy used for conversion is not fully renewable. On top of that, these specific carriers have the disadvantage of not solely consisting of hydrogen.[23] When hydrogen is required in its liquid form, such as for hydrogen-powered aviation, the direct import of LH_2 eliminates an additional conversion step. This approach reduces energy losses and operational complexity,[24] but introduces new supply chain challenges such as cryogenic transportation and storage infrastructure. Nevertheless, scaled transportation of LH_2 remains in its infancy compared to ammonia, which benefits from an established global trade infrastructure. Ultimately, the choice between domestic production and importation of hydrogen will depend on the levellised cost of hydrogen (LCOH), which includes conversion losses throughout the chain and infrastructure readiness.

The final segment of the supply chain, the delivery of LH_2 to the airport, can be broadly categorised into three main types,[25] which differ primarily in the extent and complexity of the required onsite infrastructure.

Offsite hydrogen production and liquefaction

In this scenario, hydrogen is produced and subsequently liquefied at a centralised offsite facility, which may be located either domestically or internationally. The resulting LH_2 is intended to supply multiple customers, including but not limited to users at the airport, thereby enabling potential economies of scale and reduced supply costs.[26,27] The LH_2 is then transported to the local airport using insulated tank trailers via road, rail, or barge (inland waterways). These transport vessels typically make use of vacuum multilayer insulation (MLI) technology to prevent high boil-off rates and have a storage capacity ranging from 2–4 tons of LH_2.[28] Previous studies have demonstrated the technological feasibility of this delivery method and highlighted potential synergies with centralised liquefaction infrastructure, particularly when integrating the tank trailer with onsite refuelling systems for direct LH_2 dispensing at the airport.[29,30]

This approach is subject to logistical constraints, however, particularly the high frequency of deliveries required to meet increasing airport hydrogen demand at scale. This may lead to increased traffic and operational complexity at and around the airport, especially for large hub airports.

This particular supply chain method is considered feasible for the delivery of LH_2 during the introduction years of hydrogen-powered aviation and for airports with lower overall demand. Moreover, this pathway may serve as a transitional stage, allowing airports to evolve toward more integrated solutions as infrastructure and demand mature.

Offsite hydrogen production and onsite liquefaction

In this scenario, hydrogen is produced at an offsite production facility, which may be located either domestically or internationally. The hydrogen is transported in gaseous form via pipeline to the airport, where it undergoes onsite liquefaction. This supply pathway is dependent upon the development and availability of dedicated hydrogen pipeline infrastructure, such as the European Hydrogen Backbone (EHB). Local branch pipelines are required to connect the airport to the main hydrogen network, with length and complexity depending on the airport's proximity to the nearest feasible main pipeline connection point. At the airport, the necessary infrastructure includes a hydrogen gas receiving station, a liquefaction plant, buffer storage and a loading area. For reference, Air Liquide's 30 tons per day (tpd) liquefaction facility in Nevada, USA, occupies ≈ 57,600m^2 (of which ≈ 30,000m^2 is dedicated to the installations themselves), while the 90 tpd facility in Incheon, South Korea, spans ≈ 50,000m^2 (largely allocated to plant-specific installations). These examples illustrate the spatial impact of onsite liquefaction facilities. An in-depth analysis of both facilities is provided later in this paper, along with a forecast of daily LH_2 demand for airports of varying sizes.

This supply approach reduces the need for transportation but introduces significant capital and energy requirements. The liquefaction process itself is energy-intensive and places additional pressure on airport electrical infrastructure.

This pathway offers assurance and scalability and may be suitable for airports with medium to high demand, or airports that are not connected to centralised liquefaction facilities. Successful implementation requires coordination between airport operators, energy providers, infrastructure developers and local authorities. Current literature on this specific supply method for airports is limited. Therefore, this LH_2 supply route will be examined in greater detail in this study.

Onsite hydrogen production and liquefaction

In this scenario, hydrogen is both produced and liquefied directly at the airport. This configuration entails the highest level of onsite infrastructure development, including renewable energy installations, electrolysis units and a liquefaction plant — installations that can range from several thousand to tens of thousands of square meters, depending on daily hydrogen demand and system configuration.

This pathway has been identified as a potentially cost-effective solution for airports with relatively low LH_2 demand, particularly for annual requirements up to approximately 1,000 tons per annum (tpa) or less than approximately 3 tpd.[31] For higher demand volumes, offsite liquefaction becomes more economical due to economies of scale and reduced onsite infrastructure requirements. This is even more applicable when such infrastructure can be shared among multiple users outside the airport.

The feasibility of this pathway is highly dependent on geographic location and correspondingly the particular yield for onsite renewables, such as solar and wind. Airports in southern Europe, for example, may benefit from high solar irradiance; however, these solar installations must be carefully placed to avoid reflection that could interfere with pilot visibility.

Alternatively, airports may source green electricity via Power Purchase Agreements (PPA), reducing spatial and operational impact. Given that many airports operate within highly constrained land environments, sourcing green electricity from the grid may offer a more practical option.

This pathway also involves complex permitting, zoning and safety requirements due to the presence of multiple high-risk installations. It requires close coordination among stakeholders and careful integration with existing airport operations.

In summary, the three LH_2 supply pathways present a range of trade-offs between centralised and decentralised facilities (see Table 1). The optimal pathway for airports will depend on specific factors such as hydrogen demand, proximity to hydrogen import and production clusters, access to hydrogen backbones and availability of land and energy.

Each pathway presents not only technical and spatial trade-offs, but carries implications for safety, regulatory compliance and stakeholder coordination. Airports may adopt a phased approach, beginning with offsite delivery and gradually transitioning to more integrated onsite solutions as hydrogen demand increases and offsite delivery is no longer operational feasible. Ultimately,

Table 1 LH_2 supply to airports: trade-off between centralised and decentralised facilities

	1. Offsite hydrogen production and liquefaction	***Offsite hydrogen production and onsite liquefaction***	***Onsite hydrogen production and liquefaction***
Airport installations	LH_2 storage unit LH_2 dispensing (truck or hydrant)	GH_2 receiving station Onsite GH_2 pipeline GH_2 purification unit GH_2 pre-cooling unit GH_2 liquefaction unit LH_2 storage unit LH_2 dispensing (truck or hydrant)	Renewable energy installations (eg solar) Electrolyser Onsite GH_2 pipeline GH_2 purification unit GH_2 pre-cooling unit GH_2 liquefaction unit LH_2 storage unit LH_2 dispensing (truck or hydrant)
Hydrogen source	LH_2 via transport modalities (ie road transport)	GH_2 via hydrogen backbone	GH_2 sourced via local production
Spatial impact	Low	Medium	High
Energy requirements	Low, mostly for storage and dispensing	High, mostly for liquefaction	Very high, mostly for electrolysis and liquefaction
Operational impact	Limited onsite operations. Operational experience can be leveraged from existing LH_2 delivery and storage practices	Moderate onsite operations that might conflict with critical airport assets. Requires coordination with pipeline operators and management of liquefaction processes	Extensive onsite operations that might conflict with critical airport assets. Requires integration of renewable energy systems, hydrogen production units and management of liquefaction processes
Regulatory requirements	Less complex, as production and liquefaction installations are located off airport premises. Permits are required for LH_2 storage and dispensing only	Moderate complexity. Requires permits for pipeline integration, hydrogen liquefaction, and LH_2 storage and dispensing	High complexity due to multiple installations (eg electrolysers, liquefiers) located on airport grounds and unique corresponding regulations
Commercial impact	Lower CAPEX for airport, but higher OPEX due to recurring transport costs	Higher CAPEX for the development of the liquefaction plant, with potential for lower OPEX depending on plant capacity and efficiency. Will also require a GH_2 offtake agreement to ensure consistent supply via the hydrogen backbone	Highest CAPEX due to extensive infrastructure requirements. Cost-effectiveness depends heavily on renewable energy availability and system optimisation
Scalability	Scalable via increased deliveries but limited by logistics	Scalable with modular liquefaction trains and dependent on pipeline capacity	Scalable with modular electrolysers and liquefiers; constrained by land and energy availability
Supply security	Vulnerable to transport disruptions and external supply chain risks	More resilient due to pipeline supply and dedicated liquefaction onsite	Highest resilience due to self-sufficiency if renewable energy (onsite or via a PPA) is secured

the choice of supply pathway will depend on a combination of strategic priorities, available land, energy access, and the broader local or national hydrogen ecosystem in which the airport operates.

AIRPORTS AND THEIR LH$_2$ DEMANDS

Understanding the variations of projected LH$_2$ demand across different airport categories can bring perspective for the further evaluation of future needed hydrogen infrastructure, ranging from scale to design. LH$_2$ demand at airports significantly influences the configuration of the LH$_2$ supply chain and the associated infrastructure requirements at airport sites. Research activity in this domain has been growing, with several recent studies incorporating LH$_2$ demand estimations using specific airports as case studies.[32,33,34,35]

A more comprehensive analysis by Hoelzen *et al.*,[36] presented in Table 2, included demand calculations for 104 airports, categorising them by size and estimating LH$_2$ requirements for the periods 2035/40 and 2050. The 2035/40 timeframe is characterised by low to modest demand levels, reflecting the initial introduction and deployment of hydrogen-powered aviation during this period. Although Airbus has announced a delay in the entry-into-service (EIS) date of its first ZEROe aircraft, introducing uncertainty into the original timeline, the demand calculations remain useful as relative indicators. The exact timeframes in Table 2 have therefore been modified to represent periods after EIS. The year 2035/40 is adjusted to years 0–5 after EIS and the year 2050 to year 15 after EIS.

These demand projections not only inform infrastructure sizing but also influence the feasibility of different LH$_2$ supply pathways. Airports with lower demand may initially rely on offsite delivery, while larger airports may require integrated onsite liquefaction or production systems. Actual demand,

Table 2 Classification of airport categories and projected LH$_2$ demand per year (tLH2/a) after EIS

Commercial airport category (# of airports)	*Total annual passenger (PAX), Mn*	*LH$_2$demand range in years 0–5 after EIS, tLH$_2$/a*	*LH$_2$ demand range in years 0–5 after EIS tLH$_2$/d**	*Amount of daily LH$_2$ trailer deliveries in years 0–5 after EIS**	*LH$_2$ demand range in year 15 after EIS, tLH$_2$/a*	*LH$_2$ demand range in year 15 after EIS, tLH$_2$/d**	*Amount of daily LH$_2$ trailer deliveries in year 15 after EIS**	*Exemplary airports*
Very large (25)	>10	5,000–10,000	14–27	5–9	100,000–300,000	274–822	92–274	London Heathrow, Frankfurt Airport
Large (21)	5–10	1,000–5,000	3–14	1–5	50,000–100,000	137–274	46–92	Hamburg Airport, Birmingham Airport
Medium (28)	2.5–5	1,000–5,000	3–14	1–5	20,000–50,000	55–137	19–46	Valencia Airport, Gothenburg Airport
Small (19)	1–2.5	1,000–5,000	3–14	1–5	10,000–20,000	27–55	9–19	Bremen Airport, Madeira Airport
Regional (11)	<1	1,000–5,000	3–14	1–5	5,000–10,000	14–27	5–9	Graz Airport, Mykonos Airport

Note: With additional columns indicating daily LH$_2$ demand (tLH$_2$/d) and the corresponding number of daily LH$_2$ trailer deliveries. These additional columns are marked with an asterisk (*) and provide a simplified indication. The calculations assume a constant annual demand distributed evenly over 365 days, without accounting for seasonal variability. Each LH$_2$ trailer is assumed to have a storage capacity of 3 tons, with delivery numbers rounded up to the nearest whole unit. The annual PAX size for a very large airport is relatively low compared to current hub airport figures but has to do with the fact that no further cost scaling effects can be achieved for demands over 100–200 k tLH$_2$/a.[37] Therefore, these airport categories have been taken into account.

Source: Hoelzen *et al.*[38]

however, will depend on the development of hydrogen-powered aviation.

State-of-the-art hydrogen liquefaction plants, encompassing small-scale (1–10 tpd), medium-scale (10–50 tpd) and large-scale (50–100 tpd), are generally sufficient to meet airport needs during ramp-up years of hydrogen-powered aviation. These capacities are also expected to serve the long-term needs of smaller airports, those handling up to 10 million passengers annually, during the first 15 years following EIS. If, however, hydrogen-powered aviation becomes commercially viable and demand grows significantly, particularly in the period 15 years after EIS, further development of larger-scale liquefaction facilities will be necessary to supply large and hub airports with over 10 million passengers annually.

To support infrastructure planning and supply pathway selection, it is important to first understand the hydrogen liquefaction process. The following sections introduce the fundamental principles that shape the design, energy requirements and operational characteristics of liquefaction systems that are suitable for airport environments.

BASIS FOR HYDROGEN LIQUEFACTION

Hydrogen consists of two atoms and occurs in two different isomeric forms which differ by the nuclear spin of the protons in each hydrogen atom. If the spin is in the same direction, the hydrogen is called orthohydrogen (o-H_2). If the spin is in the opposite direction, the hydrogen is called parahydrogen (p-H_2). The concentration of o-H_2 and p-H_2 is temperature dependent. Hydrogen near ambient conditions consists of 75 per cent o-H2 and 25 per cent p-H2, also known as 'normal hydrogen'. As hydrogen is cooled, the proportion of p-H_2 increases. This conversion releases heat, which if it occurs slowly in storage tanks can lead to evaporation losses (boil-off).[39] Actively increasing the concentration of p-H_2 throughout the cooling and liquefaction process helps reduce these losses and is important for efficient use of LH_2 in aviation.

Hydrogen holds another unique characteristic that needs to be taken into account when aiming to liquefy the molecule. Typically, gases cool when expanded from high to low pressure, a principle known as the Joule-Thomson effect. Hydrogen, however, together with helium and neon, exhibits a negative Joule-Thomson coefficient at ambient temperature, which means that the temperature of hydrogen gas will increase when being expanded.[40] A positive Joule-Thomson coefficient, meaning that the hydrogen gas will cool down upon expansion, will only take place once the hydrogen gas is below its inversion temperature (202K or −71°C)[41]. To reach this point, liquid nitrogen (LN_2) is commonly used as a refrigerant in hydrogen liquefaction systems. Once below the inversion temperature, hydrogen can be further cooled and eventually liquefied at its critical temperature of 33.2K (−239.95°C).[42] These unique properties of hydrogen influence the design and complexity of the installations required for liquefaction and therefore have direct implications for airport infrastructure.

Hydrogen liquefaction

The development of thermodynamic fundamentals in the late 19th century has led to advances in cryogenics, often defined as the science and technology dealing with temperatures less than about 120K (−153°C).[43] In 1898, Sir James Dewar was the first to achieve hydrogen liquefaction at a temperature of 20K (−253.15°C).[44] A dewar, a vacuum flask used for storing cryogenics, is still named after the inventor. Gas liquefaction technologies, including those for LH_2, have been further developed in the subsequent period from 1900 to 1950.[45] Large-scale production processes have been reviewed and developed in this period as well. Technology in the field of cryogenics has advanced significantly in the last decades, driven by growing demand in sectors such as liquefied natural gas (LNG) transport and storage.

The hydrogen liquefaction process can be divided into the four following main stages:[46]

1. Pre-liquefaction hydrogen conditioning.
2. Pre-cooling (to approximately 80K using a refrigerant).
3. Cryocooling (further cooling to approximately 30K).
4. Liquefaction (converting cooled GH_2 to LH_2 at temperatures lower than 30K).

Figure 2 provides a schematic overview of one of the most commonly used hydrogen liquefaction cycles. Each stage of the process is described in detail in the following sections.

Pre-liquefaction hydrogen conditioning

Before hydrogen can be liquefied, it must be purified. Hydrogen gas, typically delivered via pipeline, can originate from various hydrogen methods, such as SMR, chlor-alkali electrolysis or water electrolysis. Each method results in varying levels of purity. SMR, the currently predominant method, introduces trace impurities such as CO, CO_2 and CH_4, whereas electrolysis may result in traces of water vapour and O_2.[47] These impurities pose risks of freezing and condensation within the liquefaction process, potentially causing blockages and plant shutdown.[48] To mitigate these risks,

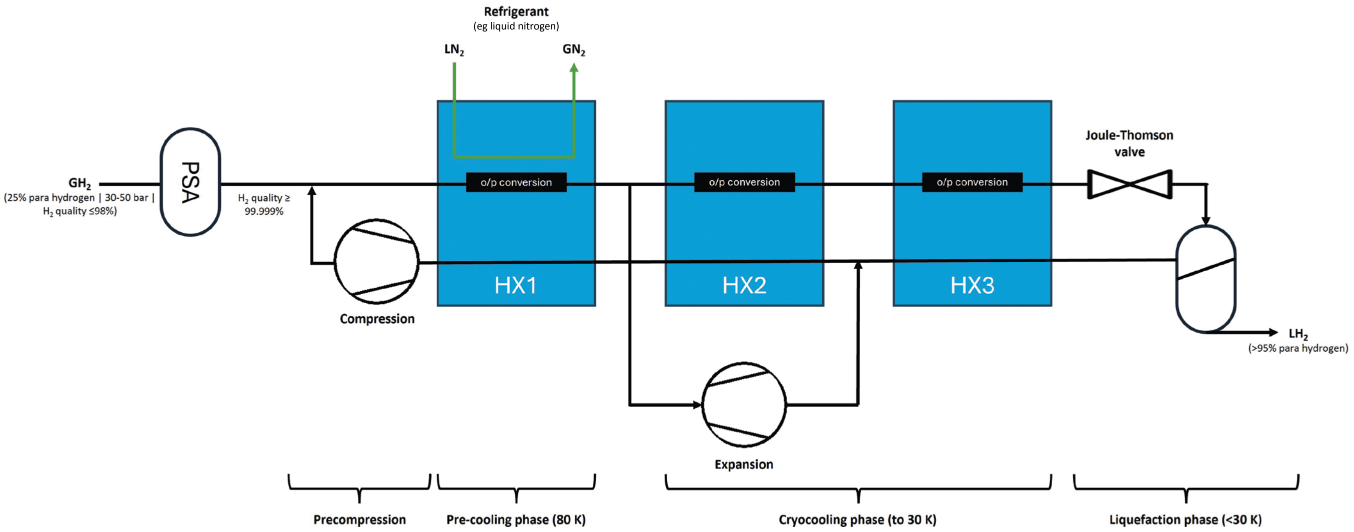

Figure 2 Schematic overview of a hydrogen liquefaction process based on the Claude cycle incorporating LN_2 in the pre-cooling cycle and utilising 98 per cent purity level hydrogen feed gas supplied via a pipeline system with an operating pressure of 30–50 bar

impurities are removed using a pressure swing absorber (PSA), reaching purities up to 99.999 per cent.[49] Additional cryogenic absorbers can adsorb residual impurities ensuring hydrogen purity levels below 1 ppm.[50] These purification steps and corresponding absorption infrastructure are essential when hydrogen is received via pipeline connections, a scenario anticipated for future airport applications. Current standards for repurposed pipelines (eg CEN TS17977) suggest a purity of 98 per cent,[51] which is insufficient for direct use in liquefaction processes.

After purification, feed gas hydrogen is directed to subsequent cooling and liquefaction phases. Hydrogen gas, including hydrogen gas that did not condense and is reused in the process, or 'cold return gas', is compressed to higher pressures using a hydrogen turbo compressor. This step is energy-intensive and along with intercooling, accounts for 39 per cent of total losses, significantly contributing to the operating expenses of hydrogen liquefaction.[52] Increasing the inlet pressure can reduce the work needed in the subsequent refrigeration process, but is constrained by equipment pressure limitations (such as those for heat exchangers) within the plant[53] and has been found to offer limited benefits in terms of economic optimisation.[54] Additionally, installing higher-efficiency compressors involves substantial upfront capital expenditure (CAPEX), which is a critical factor in the overall economic assessment of hydrogen liquefaction facilities.[55]

Pre-cooling

Pre-cooling is essential for achieving temperatures below the inversion temperature of hydrogen. This process involves lowering the temperature of hydrogen gas before commencing further cooling stages, and takes place in a cryogenic cold box, a vacuum-insulated enclosure housing various components essential for the liquefaction process, such as heat exchangers, turbines and piping.[56] In this setup, hydrogen gas passes through a heat exchanger, where it is indirectly cooled by a refrigerant, typically to around 80K (−193,15°C). To improve efficiency and reduce boil-off losses, materials such as iron oxides and ionic crystals are used to help convert o-H_2 to p-H_2.[57]

LN_2 is commonly used as a refrigerant in large-scale hydrogen liquefaction plants.[58] LN_2 is produced by separating air into its components, nitrogen, oxygen and argon, using an air separation unit (ASU). The ASU compresses and cools air and finally separates gases based on their boiling points. The separated LN_2 is then employed as a refrigerant in the pre-cooling stage of hydrogen gas. LN_2 can also be reused in a closed-loop system.

More energy-efficient and cost-efficient pre-cooling methods using mixed refrigerants are presented as concepts in current literature.[59] Mixed refrigerants, which are combinations of refrigerants, result in better temperature control and reduce exergy losses during pre-cooling. These systems, common in LNG plants, require additional equipment and investment (CAPEX) but offer better efficiency and lower operating costs (OPEX). To minimise environmental impact, mixed refrigerants are typically designed as closed loop cycles and selected to meet environmental standards.

Cryocooling

In the cryocooling stage, hydrogen gas is further cooled to near its liquefaction point within a cold box. Two major liquefaction types stand out: the Claude cycle and the Linde-Hampson cycle. The Claude cycle combines expansion through a turbine with Joule-Thomson cooling, while the Linde-Hampson cycle relies solely on Joule-Thomson cooling.

During this expansion, the gas performs work on the turbine, extracting energy and significantly cooling the hydrogen gas to its critical temperature necessary to reach its liquid state. The hydrogen gas is cooled through a series of heat exchangers and a part of the hydrogen gas is fed to the expansion engine and used for further cooling.[60] Although the Claude cycle requires higher upfront investments in equipment, it exhibits overall lower power consumption than the Linde-Hampson cycle.[61] This method is more efficient and suitable for large-scale plants producing over 2 tons per day.[62] Although it requires more complex equipment, it consumes less overall power and is widely used in modern hydrogen liquefaction facilities.

Liquefaction

Once hydrogen gas is cooled to around -253°C (20K), it is expanded through a valve, causing a further drop in temperature, facilitating the phased transition of hydrogen from gas to liquid. The resulting mixture of hydrogen gas and liquid is then directed to a phase separator. The LH_2 is subsequently collected and transferred to vacuum-insulated storage tanks, ensuring minimal heat ingress and maintaining low temperatures. Any remaining hydrogen gas is recycled back into the system to improve overall efficiency.

CURRENT HYDROGEN LIQUEFACTION PLANTS

Large-scale development of hydrogen liquefaction began around 1960, driven primarily by the Cold War space race and the aerospace initiatives in the US, especially the National Aeronautics and Space Administration (NASA).[63] One of the earliest operational plant, known as 'Baby Bear', was established in Painesville in 1957, with a capacity of 0.68 tpd, using by-product GH_2 from nearby industrial processes. Two larger plants, 'Mama Bear' (4.5 tpd) and 'Papa Bear' (27 tpd), followed soon after. By the 1980s commercial demand for LH_2 led to further development of liquefaction facilities.[64]

Today, LH_2 is used in aerospace and semiconductor manufacturing. It is also increasingly recognised as a key enabler for hydrogen-based mobility solutions, owing to its high energy density, economic viability, and technical suitability for storage and distribution.[65]

Current hydrogen liquefaction plants range in scale from small-scale producing less than 1 tpd to plants with capacities of up to 90 tpd. Many of these are integrated within industrial clusters, benefitting from access to GH_2 (for instance, as a by-product from an adjacent industrial plant) and supporting gases such as nitrogen. Global hydrogen liquefaction capacity is reported to be 350 tpd with the majority located in the US.[66] For comparison, the LNG capacity exceeds the hydrogen liquefaction capacity by more than 500,000 times,[67] and can be seen as a reference point for LH_2 and potential future developments.

Table 3 lists selected hydrogen liquefaction plants worldwide, including their capacity, land use and specific energy consumption (SEC) if available. Three liquefaction plants in Europe, operated

Table 3 Selection of hydrogen liquefaction plants throughout the world

Country	*Location*	*Operator*	*Construction year*	*Capacity (tpd)*	*Capacity (tpa)*	*Land use (m2)*	*Specific energy consumption (kWh/kgLH$_2$)*	*Additional information*	*Coordinates*	*Source*
Germany	Leuna	Linde	2008	10	≈ 2,000	Unknown	10.3	Expanded in 2021	51.323152, 12.001726	68
Germany	Ingolstadt	Linde	1992	4.4	≈ 1,460	Unknown	13.58	Decommissioned		69
Netherlands	Rotterdam	Air Products	1987	5.6	≈ 2,000	Unknown	Unknown	Expansion to 35 tpd	51.876270, 4.259658	
South Korea	Incheon	Incheon Green Energy Co	2022	90	≈ 32,850	≈ 50,000	Unknown		37.508643, 126.653395	70
France	Waziers	Air Liquide	1985	10	≈ 3,650	Unknown	Unknown		50.377998, 3.106921	
United States	North Las Vegas	Air Liquide	2018	30	≈ 10,950	≈ 57,600	Unknown		36.316269, –114.988511	71,72
United States	Woodbine	Plug Power	2022	15	≈ 5,475	Unknown	< 11		30.841808, –81.679585	73,74
Canada	Bécancour	Air Liquide	1987	8.2	≈ 3,000	≈ 38,000	Unknown		46.382693, –72.375904	

by Air Products (the Netherlands), Air Liquide (France) and Linde (Germany), collectively produce around 20–25 tpd.

To better understand the current state of hydrogen liquefaction, it is useful to examine real-world examples of modern plants that exemplify recent advancements in the field. The hydrogen liquefaction plants located in Incheon, North Las Vegas and Bécancour serve as representative cases of state-of-art infrastructure. The following section provides a detailed overview of these plants, focusing on their technological configurations and layout designs.

Liquefaction plant 1: Incheon, South Korea

The world's largest hydrogen liquefaction facility is located in Incheon, South Korea, operated by SK E&S, using the Claude cycle process (see Figure 3). Commissioned in 2024, the plant is designed with a daily production capacity of 90 tons and an annual output of approximately 10,950 tons. The total investment for the project amounted to approximately 700 billion KRW (≈ €442m). The facility is organised into several operational zones, each serving a specific function in the liquefaction process.

Hydrogen used in the plant is sourced as a by-product from the nearby SK Incheon Petrochem facility. Before liquefaction, the hydrogen is purified using a PSA system, labelled as the 'H_2 purifier' in Figure 3, which removes contaminants such as carbon monoxide, carbon dioxide and moisture. This precondition process upgrades the purity from 92 per cent to the 99.999 per cent required for liquefaction.

Central to the facility are three cold boxes (cold box 1, 2 and 3) or

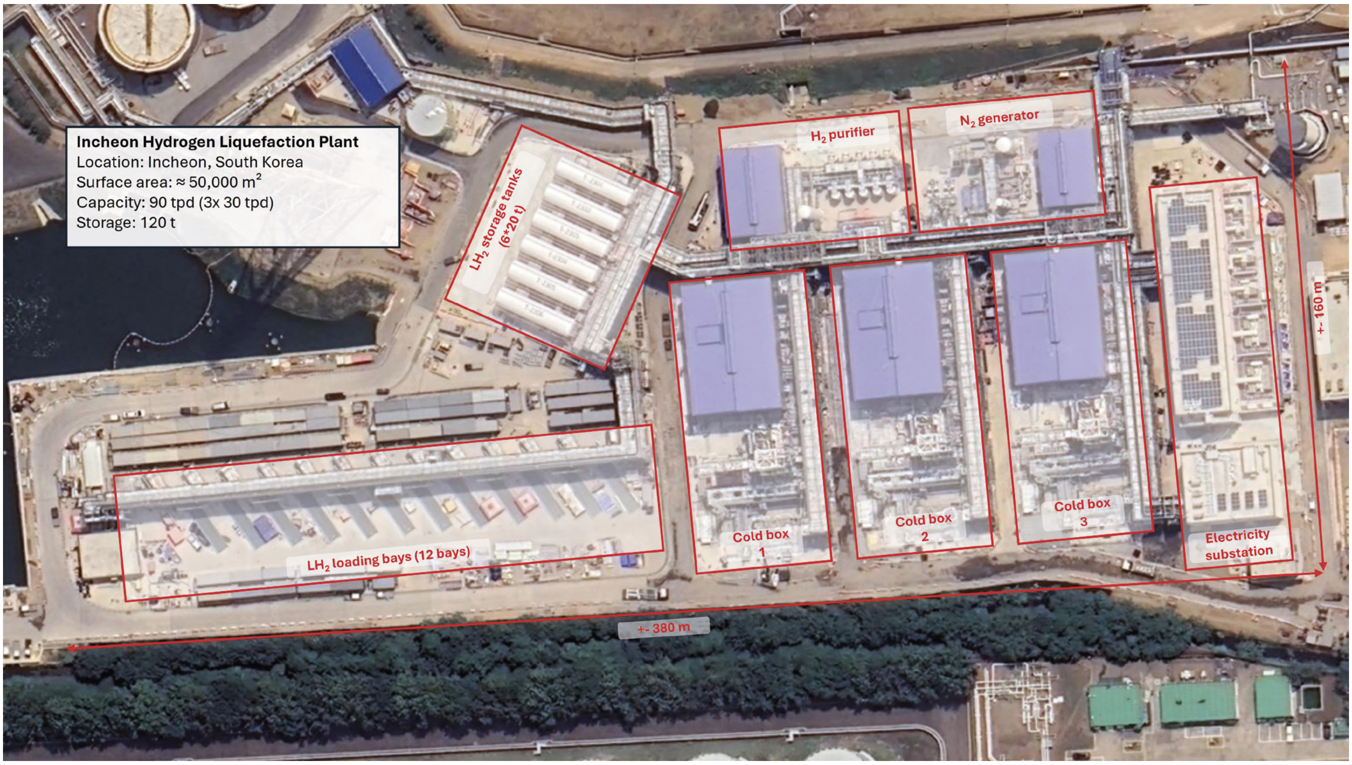

Figure 3 Hydrogen liquefaction plant in Incheon, South Korea

'trains', each capable of producing up to 30 tpd. This modular configuration provides operational flexibility given demand fluctuations. Pre-cooling is achieved using a nitrogen refrigeration system and an onsite ASU, labelled as the 'N_2 generator' in Figure 3. Electrical power is supplied through a dedicated electricity substation, ensuring stable and continuous operation.

For storage, the facility includes six horizontal cylindrical 20 ton cryogenic tanks, totalling 120 ton of LH_2 buffer storage. Twelve loading bays facilitate the transfer of LH_2 to cryogenic transport trailers. The transfer process relies on gravimetric flow and pressure differentials, eliminating the need for mechanical pumping.

The LH_2 produced at the facility primarily supports mobility applications, including the fuelling of up to 5,000 fuel cell buses annually. Its cryogenic form enables efficient distribution to hydrogen refuelling stations across South Korea, including one of the three stations located at Incheon Airport (ICN). These stations serve the airport's fleet of 35 fuel cell buses and other regional users.

Liquefaction plant 2: North Las Vegas, Nevada, USA

The North Las Vegas hydrogen liquefaction plant (see Figure 4), operated by Air Liquide, commissioned in 2022, has a daily production capacity of 30 tons and an annual output of approximately 30,000 tons. The total investment in the project was approximately US$250m (≈ €221m).

Hydrogen is primarily produced onsite via SMR. The facility operates under

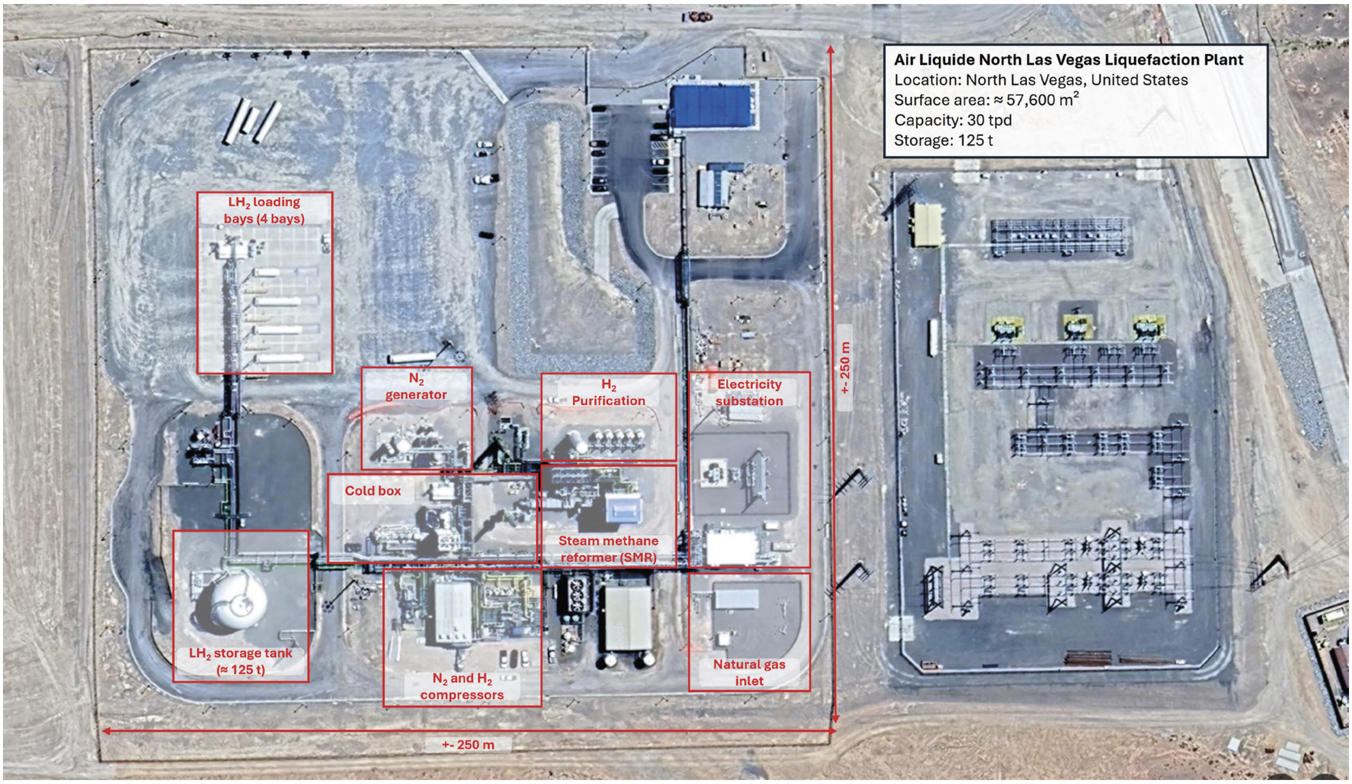

Figure 4 Hydrogen liquefaction plant in North Las Vegas, USA

renewable natural gas and renewable electricity contracts, ensuring that the hydrogen produced for California is certified renewable through verifiable and auditable pathways. Following production, hydrogen undergoes purification using a PSA to remove impurities. The purified hydrogen is then cooled to cryogenic temperatures using a cold box system, with pre-cooling provided by a nitrogen refrigeration loop supported by an onsite ASU. The facility is powered by a dedicated electrical substation and includes integrated compressors for both hydrogen and nitrogen, enabling precise pressure regulation and seamless coordination between gas handling, purification and liquefaction processes.

Once liquefied, LH_2 is stored in a spherical cryogenic tank with a buffer capacity of approximately 125 tons. Distribution of the LH_2 is managed through four cryogenic trailer loading bays, allowing transfer of LH_2 to transport vehicles. The facility supports both mobility and industrial markets.

Liquefaction plant 3: Bécancour, Québec, Canada

The Bécancour hydrogen liquefaction plant has been operated by Air Liquide since 1987 (see Figure 5). The plant has a daily liquefaction capacity of 8.2 tons and an annual output of approximately 3,000 tons.

Located next to a chlor-alkali plant, the site initially utilised by-product hydrogen. In 1987, the facility installed a 7MW alkaline electrolyser powered

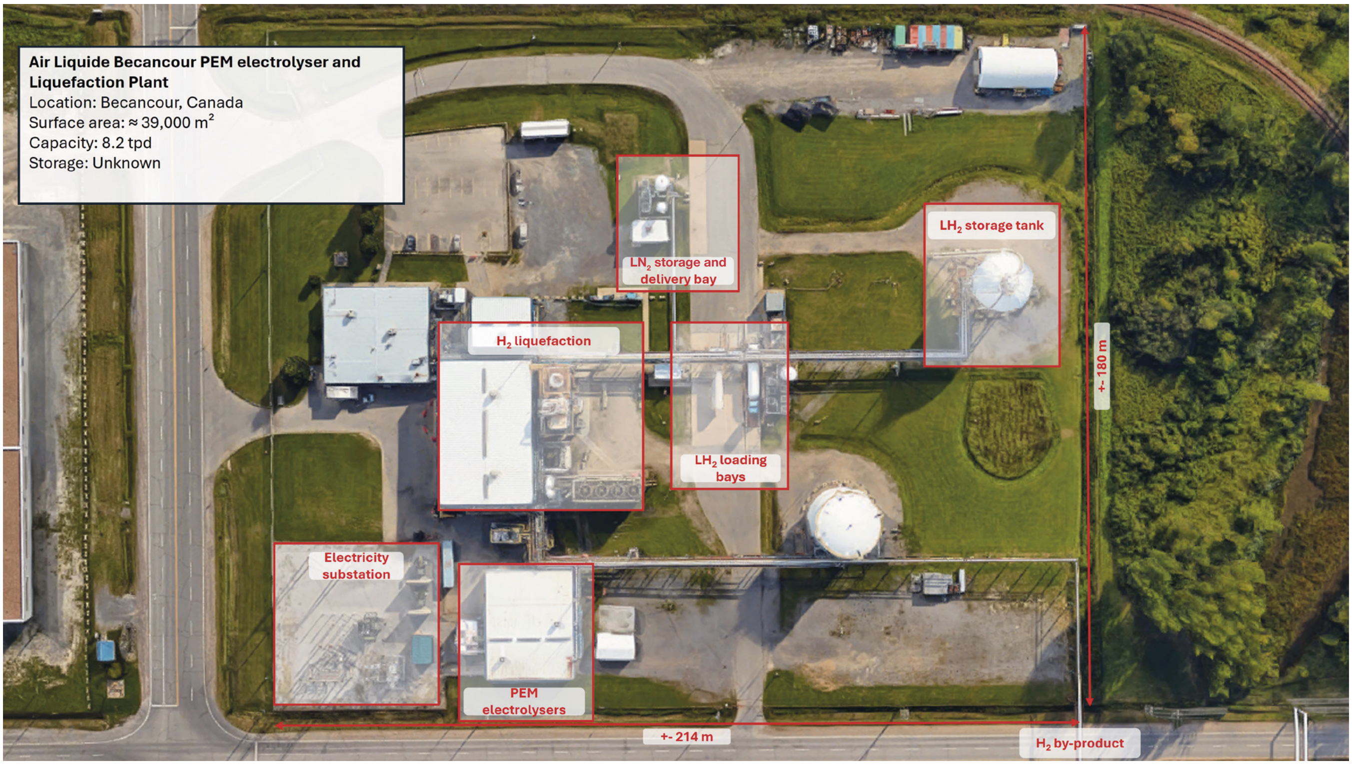

Figure 5 Hydrogen liquefaction plant in Bécancour, Canada

by renewable electricity derived from a nearby hydropower source.[75] In 2021, this system was replaced by four 5MW proton exchange membrane (PEM) electrolysers, increasing the electrolysis capacity to 20MW. This upgrade boosted hydrogen output by 50 per cent while maintaining the same physical footprint. Hydrogen is liquified onsite using LN_2 as refrigerant in the pre-cooling phase. Unlike other facilities, the LN_2 is not generated onsite but delivered externally.

Although the exact LH_2 storage capacity is not publicly specified, it can be assumed to be in the range of 50–100 tons.

AIRPORT LIQUEFACTION FACILITY LAYOUT

Building on the insights from the literature review and the examination of three large-scale hydrogen liquefaction facilities, this section introduces a generalised layout concept tailored for airport environments. The layout, visualised in Figure 6, serves as a foundational tool for airport master planning, enabling early-stage spatial assessments, safety zoning and integration with existing infrastructure. It is designed to be scalable and modular, allowing adaptation to varying hydrogen demand and land availability. Safety zoning is integral to the layout design to ensure separation between critical plant components and surrounding airport infrastructure. These zoning requirements are not fixed, but rather adaptable to the specific operational context of each airport, thereby taking into account proximity to ground and air operations, passenger areas and other critical assets on and around the airport.

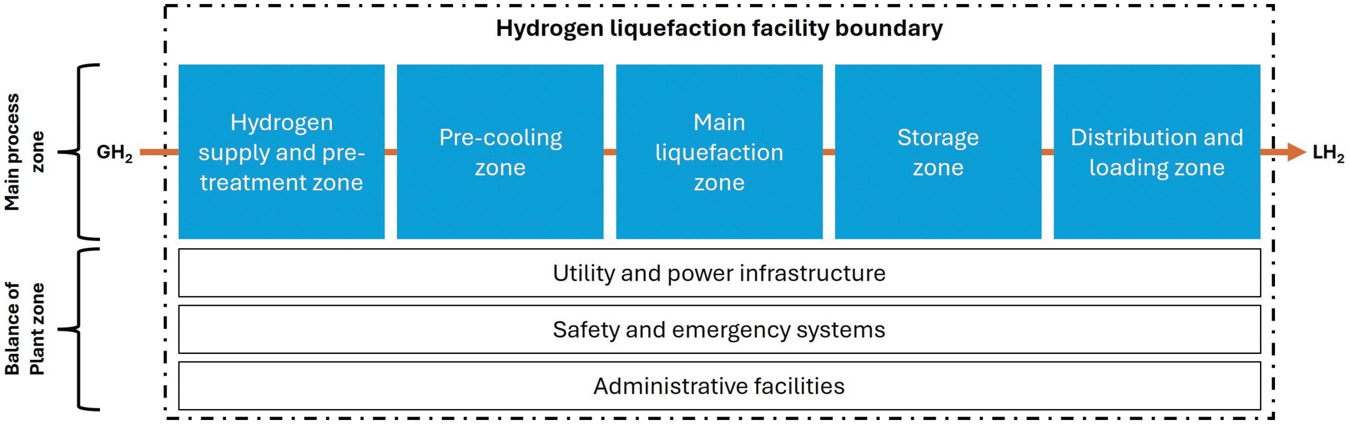

Figure 6 Generalised layout of a hydrogen liquefaction facility at an airport with GH_2 pipeline access

The hydrogen liquefaction facility can be conceptually divided into two main categories:

1. *Main process zone*: This zone includes all systems directly involved in the intake, purification, liquefaction, storage and distribution of hydrogen. These systems perform the core liquefaction process onsite.
2. *Balance of plant (BoP) zone*: This zone includes all supporting equipment necessary to ensure safe, efficient and continuous operation of the plant. These are indirectly linked to the main liquefaction process.

The following subsection will provide a more detailed overview of generalised onsite hydrogen liquefaction layout, detailing the infrastructure components and impact for airports.

Main process zone

Hydrogen supply and pre-treatment zone

This designated zone enables the reception of GH_2 from an adjacent hydrogen pipeline network and thereby acts as the starting point of the liquefaction process. The zone is the connection point with external infrastructure, and therefore a hydrogen gas receiving point (or process control station)[76] is required within the airport premises. These stations are engineered to extract hydrogen from the pipeline and serve as nodes for monitoring flow rate, pressure and quality of hydrogen, ensuring safe and efficient distribution to the airport's liquefaction plant or other onsite users. Figure 7 offers a visual example of such infrastructure provided by the hydrogen receiving station designed by Bilfinger for Gasunie in the Netherlands. This zone typically requires a modest footprint but must be strategically located near

Figure 7 Bilfinger standardised design for hydrogen receiving stations
Source: Gasunie/Bilfinger

the airport perimeter to connect with external hydrogen pipelines.

Transporting hydrogen via pipelines is well established, with Europe's network totalling around 1,500km as of 2023.[77] Air Liquide operates a 964km cross-border hydrogen pipeline system across the Netherlands, Belgium and northern France. Additionally, EU member states are encouraged to make a science-based assessment of the possibility of repurposing existing gas pipelines for the transportation of pure hydrogen and the underground storage of hydrogen.[78]

The EHB outlines a vision for a continent-wide hydrogen infrastructure, combining repurposed and newly built pipelines.[79] Depending on the design and origin of the infrastructure, operating pressures are expected to range from 30 to 100 bar, with repurposed pipelines at the lower end and new ones supporting higher pressures.[80] Over 31,500km of hydrogen pipelines are planned by 2030, forming a key part of Europe's hydrogen market development.[81]

Current European regulations lack comprehensive quality standards for hydrogen transmission networks. In response, the Netherlands, Belgium and Germany have initiated the development of a joint specification, proposing a hydrogen purity level of 99.5 per cent, which exceeds the commonly applied threshold of 98 per cent.[82] Purity of 99.5 per cent, however, is still insufficient for hydrogen liquefaction, which requires an even higher level. Consequently, a dedicated PSA system remains necessary at the airport, with complexity of the system depending on the feed gas quality. After purification, compressors installed at the facility play a crucial role in increasing the hydrogen pressure, especially for the cold return gas, to levels suitable for subsequent downstream processes such as pre-cooling and liquefaction. Current liquefiers typically use a pressure between 15 and 30 bar.[83] Planning this zone must be coordinated with the local hydrogen grid operator.

Pre-cooling zone

Pre-cooling hydrogen requires a refrigerant, with LN_2 being the most commonly applied in the industry. LN_2 can be supplied to the airport liquefaction facility via external delivery, typically by tank trailers, or produced onsite using an ASU.

A closed-loop system can recycle LN_2 to reduce losses, although occasional 'make-up' LN_2 is needed to offset evaporation losses. To support this, the facility must include a LN_2 delivery bay and LN_2 storage (see Figure 8), which must be easily accessible for tank trailers without interfering with airside operations. Additional installations such as reliquefication units and compressors further reduce evaporation losses and overall LN_2 consumption. Using delivered LN_2 lowers CAPEX by reducing the need for extensive onsite infrastructure.

When regular LN_2 deliveries are impractical, an onsite ASU is required. This adds significant infrastructure, including air intake and compression systems, purification filters (absorbers), heat exchangers and a cryogenic distillation column for the separation of atmospheric gases (see Figure 9). ASUs are most cost-effective when operated at full capacity.[84] The pre-cooling zone typically requires a compact but insulated area, occupying several hundred square meters depending on delivery versus onsite production and the total needed capacity. This zone should be located close to the main liquefaction unit to

Figure 8 LN$_2$ tank trailer and fixed storage tank
Source: Air Products

Figure 9 Cryogenic distillation column by Linde as part of an air separation plant
Source: Linde

minimise cryogenic pipeline lengths and thermal losses of the refrigerant.

Once LN_2 is onsite, either delivered or produced, cryogenic pipelines transfer it to the hydrogen liquefaction system, where it functions as the working fluid in a closed-loop refrigeration cycle. Pre-cooling occurs within a cold box that houses the components necessary for further cooling, such as heat exchangers and expansion turbines. The physical dimensions of these cold boxes vary by design and capacity: Chart Industries offers a 10 tpd cold box with a diameter of ≈ 3m and a height of ≈ 12m,[85] while Linde offers a range of cold boxes in sizes of up to 5m by 7m and a length up to 40m[86] (see Figure 10).

Main liquefaction zone

Hydrogen is further cooled and condensed into its liquid state in the main liquefaction zone. This zone includes a cold box designed to reach temperatures up to 20K. The number, capacity and size of these cold boxes differ given the needed production capacity. Ideally, this zone should be located near the hydrogen receiving station and upstream of the storage zone to minimise pipeline lengths and thermal losses. Proximity to electrical substations is also critical due to high power demands.

Figure 10 Vacuum hydrogen cold box at Linde's liquefaction plant in Leuna, Germany
Source: Linde[87]

Liquefaction plants operate most efficiently under steady, continuous conditions. Intermittent operations can reduce thermal efficiency, increase equipment stress and affect economic viability. Liquefaction plants are reported to be able to operate at 30 per cent of their maximum production capacity. Modular designs, consisting of multiple smaller production units, offer flexibility and can be advantageous in terms of phased development at the airport. This setup allows to scale production up or down based on demand fluctuations while preserving the benefits of continuous operation. The Incheon facility (Figure 3), with three 30 tpd liquefaction trains, exemplifies this modular approach. At airports, modularity is essential given demand fluctuations driven through changes in flight schedules and seasonal patterns. This flexibility, however, may come at the cost of reduced economies of scale, potentially affecting overall plant efficiency.

After expansion, the hydrogen stream will enter the phase separator following its final expansion in the cold box, after which LH_2 and hydrogen vapour will be separated. The LH_2 is then transferred through vacuum-insulated pipelines to onsite LH_2 storage tanks located in the airport's storage zone.

Storage zone

This zone serves as the intermediate step between LH_2 production and distribution. LH_2 is stored in cryogenic tanks designed to limit heat ingress, typically using vacuum insulation. Storage is ideally located close to the liquefaction unit to minimise pipeline length and corresponding thermal losses, but must also be positioned with sufficient separation from passenger areas, operational areas on the airport and fuel storage areas to meet safety zoning requirements.

The storage zone plays a crucial role in the overall efficiency and economics of the liquefaction plant. Buffer capacity at the airport allows continuous operations by storing excess LH$_2$ during periods with lower demand, reducing shutdown frequency and improving operational flexibility.

LH$_2$ is commonly stored in cylindrical (horizontal or vertical) or spherical tanks. Boil-off rates depend on tank size, shape and insulation and are proportional to the surface-to-volume ratio of the storage tank.[88] Spherical storage tanks in general demonstrate lower boil-off rates compared to cylindrical tanks[89] and minimise land requirements when space constraints are present at the airport. Table 4 provides some examples of operational LH$_2$ storage tanks.

The world's largest LH$_2$ tank, a 4,700m^3 (≈ 334 t) storage tank at NASA Kennedy Space Center, features an integrated refrigeration and storage (IRAS) system that will minimise boil-off losses and maintain the cryogenic conditions inside the tank.[90] CAPEX for this system is said to have a payback time of less than a year, assuming a boil-off rate of 0.06 per cent per day.[91] The development of this specific storage tank shows potential for scaling storage capacities to large-scale storage (up to 10,000m^3 or ≈ 700 t) and mega-scale storage (100,000m^3 or ≈ 7,000 t) systems.[92]

Airport-based LH$_2$ storage must integrate boil-off management systems to reuse evaporated hydrogen as feed gas and minimise losses. Typical boil-off rates tend to be in the range of 0.05 per cent (optimistic) to 0.25 per cent (pessimistic) per day, with NASA indicating a loss of 0.03 per cent per day.[93]

The number, type and size of LH$_2$ tanks will depend on the on the local hydrogen demand and the chosen liquefaction strategy. Storage design should balance system efficiency (from production to distribution), cost-effectiveness and the ability to match LH$_2$ supply with the airport's LH$_2$ demand. LH$_2$ tanks must also be surrounded by safety buffers, typically defined by national or international standards (eg EIGA, ISO), to account for potential venting, emergency access and separation from critical airport infrastructure (see Figure 11).

Distribution and loading zone

The LH$_2$ distribution zone facilitates the transfer of LH$_2$ from fixed storage tanks to either LH$_2$ trailer loading bays or a hydrant system. Currently, trailer-based distribution is a common method in the industry. This zone should be located adjacent to the LH$_2$ storage tanks to minimise transfer distances and thermal

Table 4 Overview of a selection of operational LH$_2$ storage tanks

Country	*Location*	*Operator*	*Tank type*	*Total storage capacity*	*Tank footprint (m^2)*	*Coordinates*	*Source*
Netherlands	Rotterdam	Air Products	Spherical	≈ 70 t	≈ 320	51.876270, 4.259658	
South Korea	Incheon	Incheon Green Energy Co	Cylindrical	≈ 120 t	≈ 1250	37.508643, 126.653395	
United States	North Las Vegas	Air Liquide	Spherical	≈ 125 t	≈ 400	36.316269, –114.988511	
Japan	Kobe	Hystra	Spherical	≈ 175 t	≈ 400	34.641419, 135.235969	[94]
United States	Kennedy Space Center	NASA	Spherical	≈ 334 t	≈ 500	28.630045, –80.618529	[95]

Note: The footprint is an approximation and includes the area occupied by the storage tank excluding any additional needed areas for safety zoning or support infrastructure

Figure 11 70 t spherical LH_2 storage at Air Products in Rotterdam, The Netherlands
Source: Air Products

losses, while remaining accessible for trailers without interfering with existing airport operations.

A loading bay includes staging areas for LH_2 trailers and dedicated filling stations at each trailer position (see Figure 12). The stations are equipped with the necessary vacuum-insulated components to facilitate the filling process, such as valves, transfer hoses, pressure relief mechanisms and control systems. Flexible hoses allow LH_2 transfer and boil-off gas recovery. Depending on demand and the amount of loading bays and trailers, this zone may require several hundred square meters. The zone must be integrated with apron logistics to avoid congestion and ensure safe routing on the airport terrain.

LH_2 filling typically relies on natural flow mechanisms, using gravity and pressure differentials. To facilitate this, the pressure in the main storage is built up through intentional pressurisation of LH_2 via heat exchangers,[96] a process that can take several hours. LH_2 transfer pumps can significantly reduce bunkering time

Figure 12 LH_2 loading bays at Plug Power's liquefaction plant in Georgia, USA
Source: Plug Power, Inc.

but require additional components and energy. Due to frequent handling and personnel activity, this zone has a higher risk profile, although detailed design requirements for LH_2 loading bays are still lacking.

Hydrant systems, less common nowadays, require an underground LH_2 pipeline system at the airport. Advancements in LNG are accelerating LH_2 pipeline development. A concept at Amsterdam Schiphol (AMS) airport modelled a centrifugal pump system distributing LH_2 from onsite storage to aircraft via pipeline, requiring continuous recycling to maintain subcooled conditions.[97] The system's boil-off is subject to pump operation and pressure drops, and the amount of subsequent refuelling operations at the airport. If implemented, the distribution zone must include pump stations and subcooled LH_2 circulation infrastructure, coordinated with airside planning.

While LNG pipelines of 1–5km are operational, LH_2 pipelines are still emerging. Most noticeable is probably the development of a 15m LH_2 underground pipeline prototype system by ITP Interpipe under the Cryo PIP LH_2 project.[98] The choice between hydrant system and trailers depends on airport layout and overall economics. Highly constrained airports might prefer a LH_2 hydrant system and less traffic on the apron over slightly lower LH_2 supply pathway costs.[99]

Into-plane refuelling, direct transfer of LH_2 to the aircraft, is outside the scope of this study, but remains a critical research gap. Aviation can learn from current LH_2 refuelling operations in the automotive and maritime sectors, where procedures, equipment and safety measures are already in use. Aviation-specific projects such as TULIPS, GOLIAT and ALRIGH2T, are exploring the technical feasibility and operational integration of LH_2 refuelling at aircraft stands.

BoP zone

Utility and power infrastructure

Hydrogen liquefaction is highly energy-intensive. The specific energy consumption (SEC) — the energy needed to produce 1kg of LH_2, of current plant — ranges from 10–15kWh/kgLH$_2$,[100,101] equivalent to 30–45 per cent of hydrogen's lower heating value. Smaller systems that produce less than 3 tpd, using a Helium Brayton Cycle and LN_2 pre-cooling, report SECs of 12.3–13.4kWh/kgLH$_2$,[102] while larger plants that produce between 2 and 15 tpd, using a Claude Cycle and LN_2 pre-cooling, achieve 10.8–12.7kWh/kgLH$_2$. Future targets by the EU aim for 6–8kWh/kgLH$_2$ by 2030[103] and 7kWh/kgLH$_2$ in the US by 2028.[104]

Liquefaction costs can be significantly reduced through process optimisation and scaling. Ohlig and Decker suggest that SEC values of 7.5–9kWh/kgLH$_2$ are achievable in the near future through readily available technologies. Air Liquide projects that the efficiency of hydrogen liquefaction plants will increase over time from >12kWh/kgLH$_2$ for small-scale systems to <7kWh/kgLH$_2$ for systems over 100 tpd.[105] These studies highlight the potential of energy-efficient designs and capacity scaling to lower SEC. The IDEALHY project, for example, developed a conceptual 50 tpd plant with a SEC of 6.4kWh/kgLH$_2$.[106] Cardella *et al.* propose further process development for large-scale plants that can push SEC below 6kWh/kgLH$_2$.[107] Other modelling studies suggest even lower SEC values may be possible in the future.[108,109,110] Figure 13 compares actual and conceptual SECs.

The adoption of LH_2 in aviation may justify investments in larger, more efficient liquefaction plants, on or off the airport; however, airport operators must consider the spatial and electrical demands. Ensuring sufficient grid capacity and access to the regional or national electricity grid to support liquefaction at the airport is essential and can be challenging for airports. As an example, at least 13.3MW electrical input would be needed for a future 50 tpd plant with a SEC of 6.4kWh/kgLH_2, given that the SEC will improve in the upcoming years. This additional demand may place further pressure on airports' ongoing electrification initiatives, such as the (in some cases even mandatory) electrification of ground support equipment (GSE) and the deployment of electrical power units and pre-conditioned air systems.

In addition to electrical infrastructure, onsite water-cooled or air-cooled systems are essential to manage heat from compressors. Air-cooled systems typically require more space and energy consumption than water-cooled systems, often involving cooling towers. Warm air plumes from these systems may affect air traffic and should be addressed in the plant design. Reliable water access must also be considered. Auxiliary equipment such as air compressors or vacuum pumps

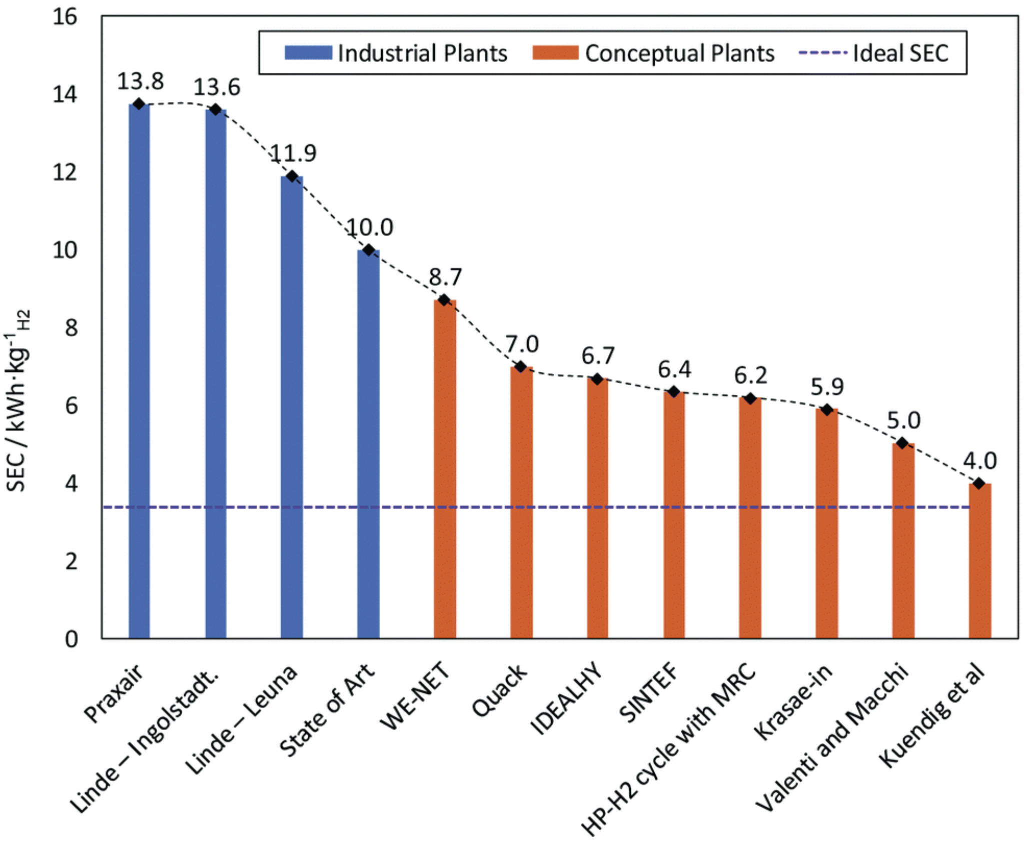

Figure 13 Specific energy consumption of actual hydrogen liquefaction plants (in blue) and conceptual hydrogen liquefaction plants (in orange)
Source: Al Ghafri *et al.*[111]

for cold boxes can add up to 6 per cent to total energy use.[112] To support future growth in electrification and potential hydrogen demand at airports, utility zones should be modular and scalable.

Safety and emergency systems

Components in this zone are integrated in the plant's design to prevent, detect and mitigate potential hazards. Safety systems are installed in several parts of the facility, including leakage sensors, gas detection systems and safety vent systems to prevent overpressure. Vents are often installed at elevated and more remote locations to minimise risks to personnel, and, in some cases, connected with flare systems to safely combust vented hydrogen gas, reducing the risk of hydrogen cloud formation near the airport. This potential hazard must be thoroughly assessed prior to site selection and design.

To ensure safe operations, high-risk systems such as storage tanks, compressors and vent systems require physical separation from adjacent airport operations. In this context, safety buffers are designed to protect individuals not directly involved in plant operations, such as passengers. In contrast, ATmosphere EXplosible (ATEX) zones define areas where explosive atmospheres may occur and apply to those working within or near the core process equipment. Both zoning types must be carefully defined and integrated into airport master planning and the facility layout to ensure regulatory compliance and operational safety.

While spatial separation will increase the overall footprint of the facility, it significantly reduces incident risks. Airport operators must ensure hydrogen-related installations do not interfere with critical airport functions or compromise operational continuity, especially near aircraft stands, where ground handling staff, GSE and passengers are present.

The introduction of onsite hydrogen (liquefaction) facilities, involving both GH_2 and LH_2, requires robust incident response protocols. Many of these are not yet standardised for airport environments. Emergency preparedness should be coordinated with airport rescue and firefighting (ARFF) teams and local safety authorities to ensure rapid, effective and well integrated response capabilities.

Administrative facilities

This zone serves as the operational heart of the liquefaction facility and is typically situated outside the main process zone to enhance safety and ensure business continuity. It generally houses control rooms, offices and rest areas for personnel who oversee plant operations but are not directly exposed to high-risk equipment. Given the continuous presence of staff, this zone must be carefully positioned with sufficient safety buffers from the process zone.

Financing and ownership

The design of a hydrogen liquefaction plant involves a trade-off between cost and efficiency. According to IRENA, the main CAPEX drivers are economies of scale, the upscaling of the plant capacity and project costs as a function of the scope.[113] For example, a 40 tpd hydrogen liquefaction plant requires an investment of approximately €90.5m, while a 50 tpd plant costs around €105m.[114] The 30 tpd liquefaction plant in North Las Vegas and the 90 tpd liquefaction plant in Incheon are reported to have cost respectively ≈ €221m and ≈ €442m (note: the

North Las Vegas figure includes a SMR). Specific liquefaction costs decrease with scale, by 50 per cent at 25 tpd and 67 per cent at 100 tpd[115] compared to a 5 tpd plant. This illustrates how CAPEX scales with capacity, but not linearly. It should be noted that current plant capacity is not limited by engineering capabilities, but by lack of market demand and need for a larger plant.

CAPEX typically includes core process equipment (eg pipeline systems, compressors, cold boxes), civil works, control systems, safety infrastructure and contingency. While CAPEX tends to dominate early investment decisions, OPEX, in the form of the levellised cost of liquefaction (per kg LH_2), eventually also plays a significant role in life cycle economics.

At airports, CAPEX may be influenced by land availability, permitting complexity, integration with existing infrastructure and safety zoning requirements. Additionally, financing and ownership models, whether airport operator owned, third party operated, public–private partnerships or consortium models, can affect capital cost structures and risk exposure for airport operators.

Ownership models influence not only the upfront investment but also long-term operational control, risk allocation and stakeholder coordination. In an airport operator owned model, the airport has full responsibility for financing, construction and operation, which allows for greater integration with airport systems, but requires — besides significant capital — a vast amount of technical expertise, which airport operators currently lack. A third party operated model, often involving energy or infrastructure companies, can reduce financial burden and leverage external expertise, although it may limit direct control over operations and pricing. Public–private partnerships offer a hybrid approach, distributing investment and risk between public authorities and private entities, and are increasingly used to accelerate infrastructure deployment while maintaining strategic oversight. Additionally, a consortium model, whereby the airport collaborates with airlines and energy providers, enables shared investment and operational alignment across the aviation and energy value chain. This model fosters joint decision making and ensures that infrastructure meets the operational goals of the airlines(s) involved.

CONCLUSION

This study has examined the infrastructure and supply chain configurations necessary for delivering LH_2 to airports, with a primary focus on the feasibility of onsite liquefaction as a foundation for hydrogen-powered aviation. Through a comparative analysis of centralised and decentralised supply models, the paper outlines the technical, spatial and operational impacts of each pathway, highlighting trade-offs between capital expenditure, operational complexity and supply security. These insights provide airport operators and planners with a decision support framework for strategic infrastructure development and airport master planning.

As airports prepare for the transition to zero-emission aviation, the readiness of hydrogen infrastructure will be a determining factor in the pace and scale of LH_2 adoption. This study contributes to that readiness by establishing a technical and spatial foundation for onsite hydrogen liquefaction, supporting informed decision making and coordinated planning across aviation, energy and regulatory domains.

A generalised layout for airport-based liquefaction facilities is introduced, structured into distinct zones: the main process zone (including hydrogen reception, purification, liquefaction, storage and distribution) and the balance of plant zone (supporting utilities and safety systems). These zones serve as a foundational tool for airport master planning, enabling early-stage spatial assessments, safety zoning and integration with existing infrastructure.

Real-world examples from operational liquefaction facilities in South Korea, the US and Canada have demonstrated the technical viability of hydrogen liquefaction technology at scales up to 90 tpd. These capacities are in theory sufficient to meet the projected LH_2 demand of many airport categories during the ramp-up years following hydrogen aircraft EIS and can continue to serve medium and large airports up to 15 years after EIS. The implementation of hydrogen liquefaction infrastructure at airports faces a range of practical challenges, however, including gaining access to GH_2 via backbone networks, high energy demands, constrained land availability, strict safety zoning protocols and complex regulatory requirements.

Addressing these challenges will require close coordination between airport operators, energy suppliers, infrastructure developers and regulatory authorities. Moreover, successful integration of liquefaction infrastructure must align with existing airport operations, including apron logistics, fuelling procedures and safety protocols. In many cases, a phased implementation strategy, beginning with offsite LH_2 delivery and evolving toward onsite liquefaction, may offer a practical pathway to infrastructure readiness.

Future research should focus on the techno-economic optimisation of liquefaction systems at airports, ownership and financing models, and the integration of into-plane refuelling operations. In particular, airport-specific case studies are needed to assess the feasibility of onsite hydrogen liquefaction under varying spatial, regulatory and energy system conditions, including access to gaseous hydrogen via pipelines and the availability of sufficient and reliable electrical power to support liquefaction operations. Recent demand projections and infrastructure modelling efforts, such as those by Hoelzen *et al.*,[116] provide a valuable starting point for such localised assessments and should be expanded to include operational constraints and master planning implications.

Building on these findings, a follow-up study will assess favourable and unfavourable conditions for onsite hydrogen liquefaction across multiple airport case studies, further supporting localised infrastructure planning.

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