Version 1.0

Hydrogen Infrastructure Feasibility Study

Groningen Airport Eelde

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The Hydrogen Infrastructure Collaborative Partnership:

Groningen Airport Eelde

Airbus Netherlands

Fokker Next Gen

Cranfield University

Cranfield Aerospace

RWE Generation NL

Engie Energie NL

Shell NL Verkoopmaatschappij

Groningen Seaports

Rijksuniversiteit Groningen

HyNetwork Services

NOM

NLR

Provincie Drenthe

AirportCreators

KLM Royal Dutch Airlines

Beyond Aero

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Date: May 6th, 2025
Authors: Joris Stolwijk; Stefan Rooze (AirportCreators)
Contributors:
Groningen Airport Eelde
NLR
Engie
Shell
RWE
Gasunie / HyNetwork Services
Fokker NG
Cranfield Aerospace
Airbus
KLM
Beyond Aero

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Nomenclature

Abbreviation	Term
GAE	Groningen Airport Eelde
ATM	Air Traffic Movement
CASK	Cost per Available Seat Kilometer
H2	Hydrogen
LH2	Liquid Hydrogen
GH2	Gaseous Hydrogen
MTOW	Maximum Take-Off Weight
MZFW	Maximum Zero Fuel Weight
PSA	Pressure Swing Adsorption
SAF	Sustainable Aviation Fuel
SMR	Steam Methane Reforming
WP	Work Package

1 | Introduction

This report explores the transition to hydrogen-powered aviation at Groningen Airport Eelde (GAE) as a pivotal part of the broader shift toward sustainable aviation. To evaluate the feasibility and potential benefits of integrating hydrogen as an aviation fuel, the report examines key aspects such as aircraft technologies, hydrogen infrastructure, and operational strategies. The research and analysis were organized into work packages, each focusing on a specific topic and distributed among the consortium members, leveraging their collective expertise. This collaborative approach ensured comprehensive coverage of the subject matter while identifying the challenges associated with safety regulations, cost implications, and evolving industry standards.

The report explores the supply chain dynamics of hydrogen, including on-site and regional production options, as well as the logistics of delivery and distribution to end users. Projections of traffic volumes, hydrogen adoption rates, and cost per available seat kilometer (CASK) provide critical insights into this transition's economic and operational impacts. Stakeholder interviews offer industry perspectives on hydrogen adoption, highlighting the factors influencing its integration into scheduled airline and business aviation operations.

Infrastructure requirements are assessed through analyses of safety standards, scalability, and the spatial demands of hydrogen storage and refueling systems. The report also considers the interplay between hydrogen-powered flights and existing operations.

This assessment provides insights into how GAE could integrate hydrogen technology into its operations, supporting the broader goals of sustainable aviation. It explores potential pathways to align hydrogen adoption with future environmental targets while exploring economic viability and operational efficiency. It provides actionable insights for stakeholders to align infrastructure development, regulatory compliance, and technological advancements with the growing demand for green aviation solutions.

Note: *This feasibility study has been prepared using data and insights sourced from project contributors as well as publicly available information over the course of 2024, with some updates made as of May 1st, 2025. The hydrogen sector is undergoing rapid evolution, driven by technological advancements, regulatory shifts, and market dynamics. As such, the information presented herein represents a point-in-time assessment. While every effort has been made to ensure accuracy and relevance, readers should recognize that key variables and outcomes are subject to change or deviate from what is presented in this study.*

2 | Aviation Factors Influencing Hydrogen Demand

This chapter explores the potential of hydrogen-powered aircraft at GAE through three critical perspectives. It examines the future hydrogen aircraft that could serve GAE, analyzes adoption rates based on industry stakeholder insights, and evaluates the Cost per Available Seat Kilometer (CASK) for hydrogen-powered operations. Together, these sections provide a concise overview of hydrogen aviation's technological, operational, and economic implications for GAE.

2.1 Hydrogen Aircraft

Main contributors: Cranfield Aerospace Solutions, Beyond Aero, Fokker Next Gen, Airbus

As the aviation industry moves toward more sustainable solutions, several companies, such as Fokker, Cranfield Aerospace Solutions (CAeS), Airbus, and Beyond Aero, are developing hydrogen-powered aircraft that could revolutionize air travel. These aircraft aim to significantly reduce carbon emissions by utilizing hydrogen as a primary fuel source through fuel cells or hydrogen combustion engines. This paragraph presents the highlights of these aircraft in development; detailed specifications of the aircraft can be found in Appendix A.

Aircraft fitted with Cranfield Aerospace Hydrogen Fuel Cell System

CAeS is developing a hydrogen fuel cell powertrain, the initial design of which is designed for integration into the Britten-Norman Islander BN2B-26, a twin-engine aircraft known for its utility and short-haul capabilities. Because this would be a retrofit of an existing aircraft, it is expected to enter service in 2027. The powertrain requires Gaseous Hydrogen (GH2) stored at 350 bar. This aircraft will be available with two variants of MTOW: around 3 tons or 3.2 tons, allowing for flexibility in payload and performance.

The aircraft, when fitted with the CAeS hydrogen fuel system as designed, can carry between 6 and 8 passengers, with a payload capacity ranging from 700 to 900kg (excluding the pilot). Its hydrogen fuel capacity will be between 37 and 60 kg, enabling a range of 200 to 400 km with an additional 45-minute reserve. These performance metrics apply to all proposed MTOW variants, making the Islander ideal for regional flights with moderate distances. The hydrogen consumption is between 18-21 per block hour depending on conditions and if the flight profile includes taxiing, illustrating the aircraft’s efficient fuel use in short-haul operations.

Refueling will adhere to current automotive hydrogen standards, using GH2 at 350 bar to ensure safety and compatibility with future refueling infrastructure. Regarding hydrogen purity, the system will follow ISO 14687 Grade D in the demonstrator models, while nozzle and refueling protocols are based on established automotive standards (J2600, J2601, and J2799). While safety protocols and refueling zone requirements are still under development, this hydrogen-powered Islander represents a significant step towards sustainable aviation for short-range flights.

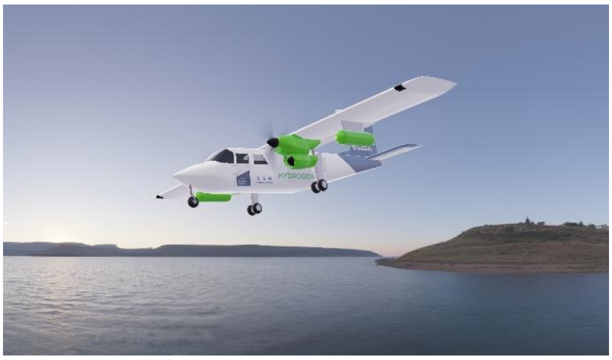

Figure 1: Impression of Britten-Norman Islander BN2B-26 aircraft with CAeS hydrogen powertrain integrated

Beyond Aero BYA-I

The Beyond Aero BYA-I aircraft is a light jet under development as a hydrogen-powered business aircraft designed for up to 8 passengers. The business jet is a clean-sheet design, specifically engineered and optimized for hydrogen-powered flight, with entry into service anticipated by 2030. The BYA-I features a GH2 fuel cell-based propulsion system (ISO 14687 Grade D purity standard). This aircraft boasts an MTOW of 8,616 kg. With a maximum fuel capacity of 250 kg of GH2 stored at 700 bar, the aircraft can achieve a range of up to 1,500 km, whether carrying a full payload or maxing out fuel capacity. This range allows the BYA-I to cover 80% of the main routes in Europe and 86% of the main routes in the United States.

With dimensions of 18,59 meters in length and a wingspan of 17 meters, the BYA-I business jet features a compact, streamlined design suited for a range of operational needs. Designed with compatibility in mind, this aircraft can utilize standard ground support equipment (GSE) for most operational tasks; however, specific safety protocols will be required for handling and refueling with GH2.

Figure 2: Impression of BYA-I

Fokker Next Gen

The Fokker Next Gen is a dual-fuel (SAF+Hydrogen) combustion-powered regional airliner expected to enter service in 2035. The aircraft is designed to accommodate 120 passengers in a single-aisle configuration. It operates using both Liquid Hydrogen (LH2) and Sustainable Aviation Fuel (SAF), allowing for increased range and flexibility. The aircraft's maximum takeoff weight (MTOW) is 54,000 kg, with an operating empty weight (OEW) of 36,000 kg and a maximum zero-fuel weight (MZFW) of 49,000 kg.

When fueled solely by LH2 with SAF reserves, the aircraft can cover up to 2,600 km, whilst a combination of LH2 and SAF extends the range to 4,000 km. Its maximum fuel capacity includes 2,300 kg of LH2 and 5,000 kg of SAF, providing flexibility for both short- and long-haul flights. The aircraft’s propulsion system relies on a combustion engine using LH2, offering the potential for reduced emissions compared to conventional fuel-based systems.

Regarding hydrogen refueling and ground support, the aircraft is compatible with standard ground support equipment (GSE) for non-hydrogen-related tasks. However, airports must accommodate specific safety considerations for refueling with gaseous and LH2. The refueling system must also handle gaseous helium, which is used to cool the hydrogen tanks. The integration of hydrogen in the propulsion system marks a significant step towards greener aviation whilst still maintaining operational flexibility and performance.

Figure 3: Impression of Fokker Next Gen aircraft

Airbus ZEROe Hydrogen-powered aircraft

Airbus has provided the following information regarding their hydrogen-powered aircraft:

"Airbus is pioneering sustainable aerospace. Airbus has the ambition to bring a commercially viable, fully electric, hydrogen-powered commercial aircraft into service. Airbus believes fuel cell technology to be the most promising to fulfil this ambition, which would significantly reduce emissions when compared to conventional jet engine configurations.

The scaling up of the hydrogen ecosystem is challenging and is progressing at a slower pace than previously anticipated. The scalability of fuel cell technologies towards a commercially viable product will also require more time. A commercially viable product is now expected to come later than 2035. Airbus will use this additional time to further develop the performance of the fuel cell propulsion and liquid hydrogen system technologies that are expected to enable the development of the Company's first fully electric commercial aircraft, as part of its ambition to pioneer sustainable aerospace.

The latest iteration of this new generation aircraft is a fully electric concept powered by hydrogen which has four propulsion systems highlighting a higher power density system than what we originally communicated in 2020.

This architecture offers a unique balance of performance and operational efficiency. Fewer engines mean a lower-cost aircraft, while still targeting a capacity of 100 passengers and a range of 1,000 nautical miles. It also translates into lower operating costs, reduced maintenance, and an easier-to-assemble design.

At the same time, this is a concept that will continue to evolve as we mature the key technologies needed for hydrogen-powered flight. Every breakthrough we achieve in the coming years will shape and refine this vision, ensuring we make the right choices when the time comes to launch the aircraft commercially.

We have now chosen to focus our efforts on the fuel cell propulsion system and liquid hydrogen storage and distribution system technologies. The combination of these technologies integrated into an aircraft would allow us to offer a fully electric commercial aircraft. The fuel cells and hydrogen storage can be considered like a battery which supplies electricity to electric motors which subsequently power a propeller or a fan. We believe this is a huge value proposition for passengers, airlines, and society at large. And with the new technologies we will do another loop and are going to try to push the seating capacity upwards from the 100-seat we initially targeted.

As a fully electric aircraft, it will emit neither CO_2 nor NOx during flight, achieving the lowest environmental impact of any propulsion system to date.

For decades, the aviation industry has pursued the ultimate goal: an aircraft that flies with no emissions. Until now, this has remained beyond reach. But with fuel cells, we believe we have found the right technology to turn this ambition into reality."

Figure 4 Airbus ZEROe aircraft concept (source: Airbus.com)

2.2 Adoption rate of Hydrogen-Powered Aircraft: Industry perspectives

Main contributors: NLR, Evia Aero, KLM, Beyond Aero

In assessing the adoption rate of hydrogen-powered aircraft, interviews were conducted by NLR with three key industry players: Evia Aero, represented by Suell Mues, KLM, represented by Jolanda Stevens, and Beyond Aero, represented by Irwin Kerboriou. These interviews provided insight into their strategies, challenges, and expectations regarding the transition to hydrogen aviation and their views on electric and conventional fuel alternatives.

Evia Aero: Reviving Regional Aviation with Hydrogen

Suell Mues, CTO of Evia Aero, brings a wealth of experience from his previous roles in consultancy and at Airbus, where he worked on hydrogen and electric aircraft technologies. His company is committed to reactivating regional aviation, which has diminished since the early 2000s due to rising fuel costs and restrictions on shorter routes. Mues highlighted that while demand for regional aviation remains high, particularly for business trips over distances of 200-1,000 kilometers, the aviation sector has struggled to adapt due to the financial burden of fuel and outdated infrastructure at smaller airports.

Aircraft Choices and Financial Implications

Evia Aero aims to fill this gap by offering hydrogen-powered flights that target business travelers, with routes that connect secondary airports and cities. The company's long-term vision includes helping regional airports transition to sustainable aviation by collaborating with OEMs to develop hydrogen infrastructure, such as power stations and refueling systems.

Evia Aero's aircraft strategy initially focuses on retrofitted Britten-Norman Islanders, which will be powered by GH2. According to Mues, GH2 is preferable over LH2 in the short term because it requires less infrastructure investment. However, it comes with challenges like a lower energy density than LH2 and NOx emissions when GH2 is combusted. Nevertheless, for shorter regional flights, the use of GH2 is operationally feasible and aligns with the company's mission to keep costs manageable. The operational costs of hydrogen, particularly for GH2, are expected to be lower than those of kerosene as the technology matures.

The choice of the Islander is also influenced by its proven track record as a small, reliable aircraft suitable for short routes. Evia Aero plans to take 15 Islander aircraft to market by 2027, two years before the expected launch of the Eviation Alice, an all-electric aircraft. The Islander will be the backbone of their early operations, flying short regional routes like Groningen-Den Helder, where the demand for small aircraft is sufficient to operate profitably without the need for extensive market research.

Mues emphasized that while early ticket prices for hydrogen flights will be around 20% higher than conventional business-class fares, economies of scale will drive prices down as the technology becomes more established and the market grows. Additionally, once hydrogen infrastructure becomes widespread, the business case for hydrogen aviation will become even more compelling.

However, the transition to hydrogen is not without its challenges. Evia Aero is already encountering political and infrastructural barriers, particularly from airports that are hesitant to invest in hydrogen-related upgrades. While major airport operators like Fraport and VINCI are exploring hydrogen independently, smaller airports lack the financial and political support needed to make significant strides. Mues argues that more substantial governmental and policy-driven incentives will be essential for the hydrogen transition to succeed.

KLM: Balancing Caution with Ambition in Hydrogen Adoption

Jolanda Stevens, KLM's Program Manager for Zero Emission Aviation, outlined the airline's cautious yet ambitious approach to hydrogen-powered aviation, emphasizing that any transition must align closely with KLM's current operational framework. Hydrogen is seen as a key solution for reducing emissions, especially for regional flights, but KLM is pragmatic about the timeline. Stevens explained that the airline's first steps toward hydrogen-powered aviation would likely start small, eventually aiming at fleet replacement in the late 2030s. For KLM to have a substantial hydrogen-powered fleet by 2035, it would already need to be in the testing and processing phase. KLM plans to conduct test flights with ZeroAvia, a British/American hydrogen-electric aircraft developer, in 2026 to assess hydrogen's commercial viability.

Aircraft Choices and Financial Implications

KLM's decisions regarding hydrogen-powered aircraft are strongly driven by a thorough cost-benefit analysis, with a critical emphasis on ensuring that the analysis does not yield a negative result. For any aircraft to be considered, it must meet sustainability goals and demonstrate clear operational and economic benefits. Smaller hydrogen aircraft (less than 50 passengers) may work well for niche markets, but for KLM, the aircraft type introduces operational inefficiencies. Replacing a single Embraer with several smaller hydrogen-powered planes would require additional pilots, airport slots, and infrastructure, straining the airline's resources at Amsterdam Airport Schiphol (AMS). These inefficiencies make such options unviable for KLM, underscoring the importance of solutions that maximize operational efficiency without incurring disproportionate costs.

While not expressing direct interest, Stevens considers aircraft with a seating capacity of over 100 passengers and a range exceeding 2,500 km as potentially suitable for its Cityhopper routes. The type of hydrogen propulsion system will also play a role in determining the suitability of an aircraft for KLM's fleet. While both combustion-based and fuel-cell hydrogen aircraft offer substantial emissions reductions, aligning with KLM's sustainability goals, hydrogen combustion still produces NOx emissions and causes non-CO_2 effects at high altitudes. These effects must be carefully considered in an environmental impact assessment. These factors, alongside cost implications, will influence the overall evaluation. Ultimately, any decision to adopt hydrogen-powered aircraft will require a careful balance between environmental benefits and operational practicality, with a clear condition that the cost-benefit analysis must show a positive outcome to ensure feasibility within KLM's business model.

Considerations for Future Aircraft

KLM is also open to exploring where it can innovate and where it needs to adapt to stay ahead in sustainable aviation. Stevens emphasized that although the airline wants to retain as much of its current operational model as possible, there are areas where KLM is willing to diverge to make a meaningful difference. This openness to research and innovation, particularly in hydrogen, reflects KLM's long-term vision of becoming a frontrunner in sustainable aviation.

However, the decision to transition to hydrogen-powered aircraft involves numerous factors, extending beyond passenger capacity and fuel efficiency. KLM must also consider noise reduction, a significant parameter in their sustainability framework, alongside other factors such as the turnaround time for hydrogen aircraft, refueling infrastructure, and heat management systems. If refueling or maintenance takes longer than for conventional aircraft, it could disrupt KLM's tight schedules, reducing fleet utilization and affecting profitability. This meticulous framework of requirements must be addressed before the airline can commit to hydrogen.

Strategic Planning and the Role of Infrastructure

Stevens also emphasized that supporting infrastructure is critical to KLM's hydrogen strategy. Airports must be equipped with hydrogen refueling capabilities, and both political support and regulatory frameworks are essential for a smooth transition. KLM plans to adopt a phased approach, waiting until the economic case for hydrogen becomes clearer. For the airline, early adoption must be justified by a clear business case, which includes not just the cost of aircraft and fuel but also the long-term impact on efficiency and sustainability. KLM will likely make final decisions about hydrogen adoption in the next few years as the costs, benefits, and technological advancements become more apparent.

Beyond Aero: Pioneering Hydrogen in Business Aviation

Irwin Kerboriou, Beyond Aero's lead H2 airport operations manager, shared insights into the company's vision of leading the shift towards hydrogen-powered aviation within the business aviation sector. Beyond Aero has as its mission to realize the first certifiable and profitable electric light jet design with hydrogen propulsion, slated to enter the market by 2030. The company recently closed a funding round to advance this vision, focusing initially on smaller, short-range aircraft that can achieve market readiness more rapidly.

Business Focus and Adoption Strategy

Beyond Aero has identified business aviation as an ideal entry point for hydrogen aircraft, as it combines strong decarbonization needs, mission profiles well-suited for hydrogen aviation, and aircraft sizes that facilitate streamlined development and certification. The flexibility inherent to business aviation also supports a smoother integration of new technologies: with less stringent turnaround times than commercial flights, hydrogen-powered business jets can meet performance expectations without sacrificing convenience or safety. Beyond Aero's technical approach involves initially using GH2, which has a higher technology readiness level and will ease regulatory approval and early market entry.

Challenges Ahead

Despite the promising outlook, Beyond Aero faces several technical and infrastructural challenges. A key technical hurdle is cooling the fuel cell, as the high electric output generates significant heat, requiring efficient dissipation. Additionally, the company aims to store GH2 at around 700 bar. This will require either innovative storage solutions or collaboration with airports capable of supporting such high-pressure systems. Certification for transporting GH2 at these pressures is advancing in the U.S., but global standards remain under development.

Conclusion: Strategic Choices for Hydrogen Adoption

The interviews with Evia Aero and KLM reveal two distinct approaches to hydrogen-powered aviation, each shaped by the size and scope of their operations. Evia Aero focuses on smaller, nimble aircraft to fly underserved regional routes, confident that hydrogen’s operational costs will eventually outcompete kerosene and electric alternatives. Their strategy is focused on early market entry and developing infrastructure partnerships with airports willing to invest in hydrogen.

KLM, on the other hand, is proceeding cautiously, driven by the need for larger aircraft that fit within its current network and operational constraints. While the Fokker NextGen shows promise, KLM is carefully evaluating the costs and risks of early adoption. Before committing to a large-scale hydrogen transition, the airline must weigh operational efficiencies, infrastructure readiness, noise considerations, and long-term environmental impacts. Their success will depend not only on aircraft technology but also on external factors like airport infrastructure, regulatory support, and the broader cost-benefit analysis of hydrogen versus other sustainable solutions like SAF.

Beyond Aero takes a pioneering stance in business aviation, planning to introduce a hydrogen-electric aircraft by 2030. Their smaller aircraft focus provides greater flexibility for early adoption, with a target market of operators looking to align with decarbonization goals and seeking long-term, high-performance alternatives to conventional aircraft. Early challenges, such as the cooling of the fuel cell system and the integration of the hydrogen storage system in the aircraft, are balanced by the opportunity to be first to market, leveraging business aviation’s flexibility and growing hydrogen support from airports.

Together, these insights underscore the complexity of the aviation industry's shift towards hydrogen, where both technological advancements and financial feasibility will dictate the pace of adoption.

2.3 Cost per Available Seat Kilometer (CASK)

Main contributions: AirportCreators (literature study)

The CASK is a critical metric when evaluating the feasibility and economic impact of hydrogen-powered aviation. Hydrogen's production costs are a central driver of its impact on CASK, accounting for 54% of the total cost. Figure 5 shows the relative contribution of hydrogen production, distribution and liquefaction, airport infrastructure and aircraft development to the total costs for the baseline scenario.

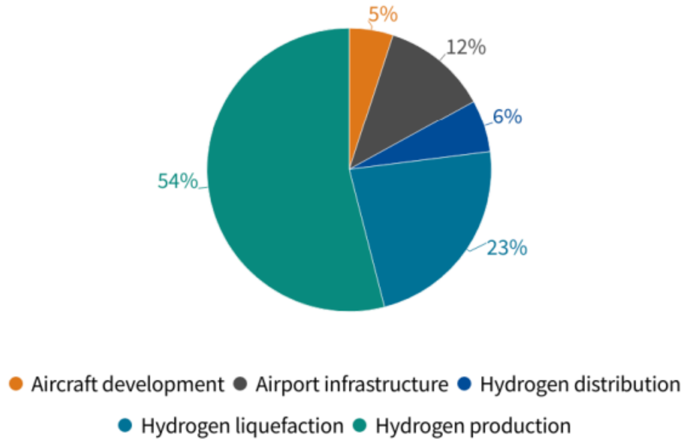

Figure 5: Distribution of Cost Contributors Hydrogen Supply Chain (Transport & Environment, 2023).

Hydrogen Production Cost

Hydrogen production costs vary significantly depending on the production method, and these costs directly affect its competitiveness in aviation and other sectors. Steam Methane Reforming (SMR), currently the most common method of hydrogen production, and renewable energy-based electrolysis present contrasting cost dynamics that will affect the future cost of hydrogen as a fuel.

The European Hydrogen Observatory (2024) provided an overview of the cost of GH2 production across Europe. In 2023, the production cost of H2 produced via SMR in Europe was, on average, 4.76 €/kg H2 (-2.47 €/kg H2 compared to 2022). When carbon capture technologies are added to SMR processes, production costs rise slightly to 4.41 €/kg H2 (down 1.97 €/kg H2 compared to 2022). On the other hand, hydrogen production costs using grid electricity vary widely, ranging from 4.06 to 17.36 €/kg H2, with an average of €7.94 €/kg H2 (down -1.91 €/kg H2 compared to 2022). Electrolysis directly connected to a renewable energy source, which avoids electricity grid fees and taxes, has lower unit costs, ranging from 4.13 to 9.30 €/kg H2 in 2024, with an average of €6.61 €/kg H2 (down -0.25 €/kg H2 compared to 2022).

Additional cost expectations from literature are provided in Appendix C. Literature expects hydrogen production costs to be 1.50—3.90 €/kg H2 between 2030 and 2040 and drop even further to 1.00—3.45 €/kgH2 in 2050. Considering the required infrastructure investment, the unit cost will increase to 2.20—3.97 €/kg H2 in 2050.

Although these figures suggest a promising decrease in costs, hydrogen is still expected to be more expensive per revenue passenger kilometer than untaxed kerosene during this period, as shown in Figure 7 (Steer, 2023). However, when factoring in carbon pricing, which is expected to rise from €127 per ton in 2035 to €200 per ton in 2050, hydrogen could become more competitive, particularly as carbon taxes and fuel taxes are increasingly applied to fossil fuels. Figure 7 also shows that compared to biofuel SAF and eFuel SAF, hydrogen is expected to have the lowest cost per revenue passenger kilometer.

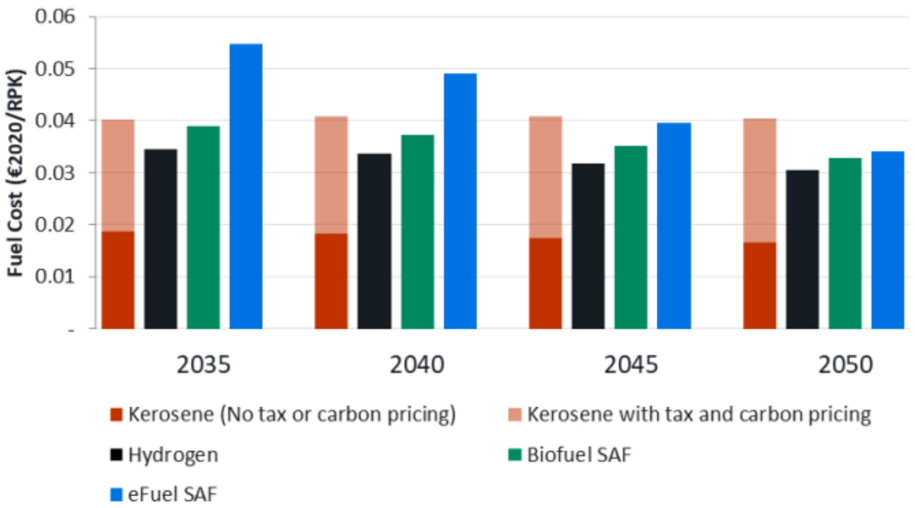

Figure 6: Expected Fuel Prices for Different Fuel Types (Steer, 2023).

Transport & Environment (2023) expects hydrogen fuel costs per revenue passenger kilometer to be lower than untaxed SAF blends and taxed SAF blends between 2035 and 2050. Hydrogen is still expected to be 8.8% more expensive per passenger revenue kilometer in 2035, as shown in Figure 9. When factoring in taxes on top of the carbon pricing for fossil fuels, hydrogen aircraft would be 18% less costly. By 2050, this cost difference narrows, with hydrogen-powered aircraft projected to be 17% less expensive than untaxed kerosene/SAF blends and 3.3% more costly than taxed fuel blends.

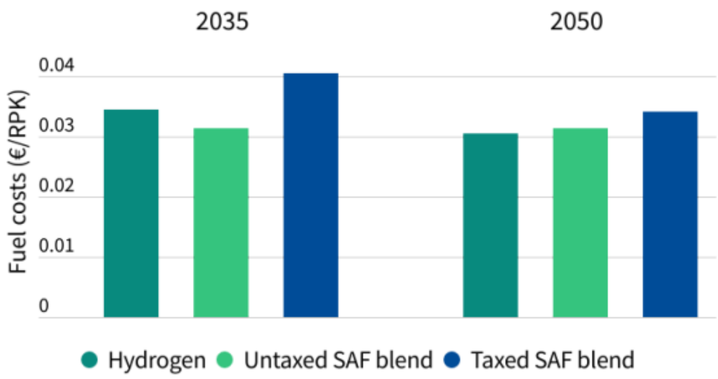

Figure 7: Fuel cost comparison 2035 and 2050 (Transport & Environment, 2023)

Operational Cost

Hydrogen-powered aircraft are expected to face higher operational costs than traditional kerosene-powered aircraft (Steer, 2023). An overview of the cost breakdown for LH2 is given in Figure 8. Limited studies have been done on the operational cost of GH2 aircraft. The fuel cost for LH2-powered aircraft is projected to be 82% higher than JetA1 fuel without carbon pricing or fuel taxes by 2050. Additionally, airport and handling charges are expected to rise by 11%, driven by the significant investments airports must make to accommodate hydrogen infrastructure. Ownership costs are also expected to increase by 19% as manufacturers pass on first-generation hydrogen aircraft development costs to customers. Altogether, these cost increases are projected to raise total operating costs by 27%, with potential variations ranging from 12% to 40%, depending on specific scenarios. Depending on the feedstock and method used to produce SAF, the unit cost of SAF can be between 120 and 700% higher than that of conventional Jet1A fuel (Watson et al., 2024). For biofuels and efuel, the expected increase in operational cost is 24 and 25%, respectively, because of the increase in fuel cost (Steer, 2023).

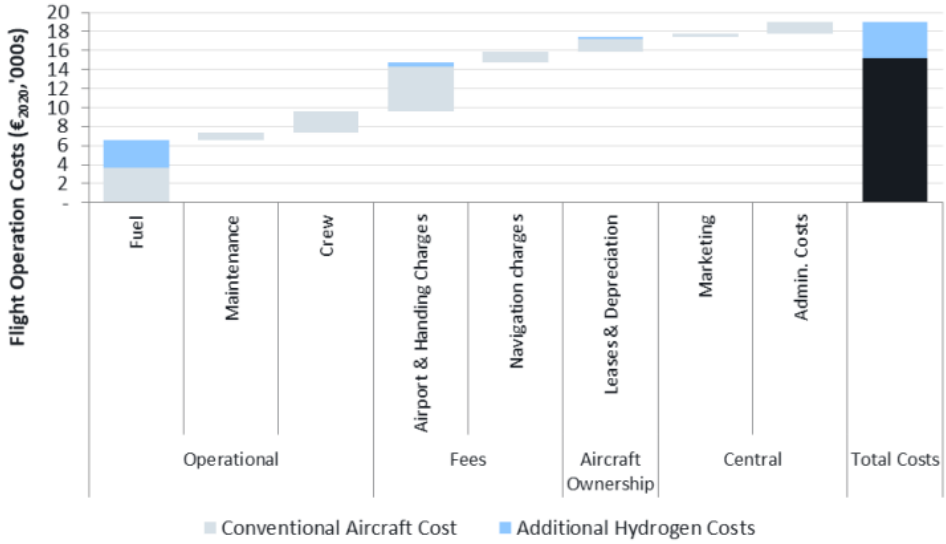

Figure 8: Operational Cost Breakdown (Steer, 2023).

A similar breakdown is made by McKinsey & Company et al. (2020), showing a more favorable outlook for hydrogen aviation. When comparing a short-range (2,000 km with 165 pax) H2 aircraft to a 2035-technology-adjusted kerosene aircraft (3.6 USD cents per CASK), additional costs in fuel (9% of CASK), CAPEX (7% of CASK), maintenance (6% of CASK), and other costs (3% of CASK) result in an overall increase of 0.9 USD cents per CASK (25% of CASK) in 2040. This is less than for synfuel aircraft, for which the cost is expected to increase with 1.1 USD cents (32% of CASK).

Similar comparisons are made for aircraft in other categories in 2040. Particularly, the CASK is only likely to be between 0 and 5% higher for small commuter aircraft because while fuel costs are higher, maintenance and purchasing costs are expected to be lower than for kerosene aircraft (McKinsey & Company et al., 2020). Compared to synfuel aircraft, the H2 commuter would be between 10 and 15% less expensive. For regional aircraft, the CASK is expected to be between 5 and 15% more expensive than kerosene aircraft but 10% less costly than synfuel aircraft (McKinsey & Company et al., 2020; Mancini & Constanza, 2022).

Using the expected fuel prices of hydrogen in 2035 (1.50–3.90 €/kgH2) to determine this scenario, Hoelzen et al. (2022) expect the CASK to increase by 10% for short-range aircraft (1500 NM with 180 pax single class layout) and by 15% for medium-range aircraft (4,000 NM with 290 pax two-class layout). Rau et al. (2024) expect a 12% increase in CASK for both fuel-cells and combustion hydrogen-powered aircraft in 2035 compared to conventional aircraft.

Transport & Environment (2023) offers a similar projection to McKinsey & Company et al. (2020). For a 1,000-nautical-mile flight, they estimate a 25.1% increase in total operating costs in 2035 compared to 100% fossil kerosene aircraft with no tax and no carbon pricing, which would decline to 20.0% by 2050. The operational costs are derived from fuel costs, airport charges, and ownership costs. When comparing hydrogen aircraft operating costs to kerosene-powered aircraft with SAF blend, hydrogen is expected to be 7.7% more expensive and 2.1% less expensive compared to untaxed and taxed SAF blended, respectively, in 2023. The difference decreases by 2050 to 3.0% more expensive and 0.5% less expensive than untaxed and taxed SAF blends, respectively.

3 | External Factors Influencing Hydrogen Demand

The demand for hydrogen in aviation is shaped by a complex interplay of external factors that extend beyond airport operations. This chapter examines these influences through two key lenses: policy impact and environmental factors, and industry-specific factors. These topics provide a comprehensive understanding of the broader forces shaping hydrogen demand in the aviation sector.

3.1 Impact of Policy and Environmental Factors

Main contributors: AirportCreators (literature study)

Policy frameworks and environmental factors aimed at reducing carbon emissions and promoting sustainable fuels heavily influence the demand for hydrogen in the European aviation industry. European Union (EU) policies, such as the European Green Deal and the Fit for 55 package, are key drivers in the push for hydrogen adoption. These initiatives set ambitious targets for reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels and achieving carbon neutrality by 2050. Aviation is a crucial sector in which emissions reductions must be established to reach these European emission goals. The International Civil Aviation Organization (ICAO) has forecasted that by 2050, international aviation emissions could triple compared to 2015 (International Civil Aviation Organization [ICAO], n.d.). The aviation sector is responsible for 3.8% to 4% of European GHG emissions and 13.9% of transportation emissions (European Commission, n.d.a).

ReFuelEU

One of the regulations aimed at reducing emissions from the aviation sector is ReFuelEU aviation, which is part of the Fit for 55 legislative package which in itself is part of the Green Deal. The ReFuelEU aviation regulation mandates using SAF to reduce CO2 emissions (European Commission, n.d.b). From 2025 onwards, airlines need to use at least 2% SAF, which will increase to 70% by 2050. Furthermore, it states that 1.2% of all aviation fuels must be synthetic aviation fuel by 2030, which will increase to 35% by 2050. Currently, the maximum SAF blend is 50%, but research and innovation initiatives are devoted to increase this to 100%. It allows airlines and aviation fuel suppliers to comply with the minimum share of SAF by using renewable hydrogen for aviation or low-carbon hydrogen.

European Emission Trading System

The European Union Emissions Trading System (EU ETS), part of the Fit for 55 legislation, continues to be a primary force driving decarbonization within the aviation sector, with the progressive reduction of allowances adding pressure to cut emissions. In 2024, the EU ETS cap amounts to 1.39 billion allowances (European Commissions, 2023). The upcoming reduction in aviation allowances, dropping by 90 million in 2024 and by 27 million in 2026, will intensify the cost of emissions compliance. Currently, 82% of all aviation allocated allowances are allocated for free, with 15% auctioned and 3% reserved for new entrants. From 2024 onwards, the number of auctioned allowances will increase, and from 2026, free allowances will be phased out. Over the 2024-2030 period, 20 million allowances from the aviation cap are reserved to support the uptake of alternative fuels. The emissions allowances only apply to flights operating within the European Economic Area (European Commission, n.d.a). This might be expanded to all flights originating or departing Europe from 2027 onwards. Allowance prices fluctuated between €50 and €100 per metric ton of CO_2 in the last two years, depending on market dynamics, making the case for transitioning to low-carbon solutions like hydrogen increasingly compelling.

In addition to the EU ETS, the Carbon Border Adjustment Mechanism (CBAM) is set to be implemented in 2026, which will place a carbon price on imports of certain goods to ensure fair competition between EU products and those from countries with less stringent climate regulations. Hydrogen is one of the first sectors to be covered under CBAM. Non-green hydrogen imports will require CBAM certificates, adding further compliance costs for companies looking to import hydrogen that is not produced through sustainable methods. This mechanism is designed to protect EU industries from carbon leakage while promoting the use of low-carbon technologies like green hydrogen.

Furthermore, the Alternative Fuels Infrastructure Regulation (AFIR) mandates national targets for deploying alternative fuel infrastructure across the EU, covering road vehicles, vessels, and stationary aircraft. However, the regulation does not specifically address hydrogen infrastructure for airport refueling, posing a significant policy gap.

Other Policies

Several other policies are also shaping a favorable landscape for hydrogen in Europe. The EU Hydrogen Strategy, part of the broader European Green Deal, outlines ambitious targets for the production and use of green hydrogen across multiple sectors, including aviation. The strategy suggests policy action points in five areas: investment support, support production and demand, creating a hydrogen market and infrastructure, and international cooperation. Furthermore, it specifies producing 10 million tons and importing 10 million tons of hydrogen by 2030, significantly reducing reliance on fossil fuels.

Hydrogen Valleys, such as HEAVENN in the northern Netherlands, have emerged as key drivers in the European hydrogen economy, particularly under the RePowerEU plan. The European Commission, recognizing the potential of these hubs, allocated an additional €200 million through RePowerEU to the Clean Hydrogen Partnership, intending to double the number of Hydrogen Valleys by 2025 (Clean Hydrogen Partnership, n.d.). This support has already materialized, with 13 new Hydrogen Valley projects initiated through 2022 and 2023. Currently, the Clean Hydrogen Partnership supports 16 Hydrogen Valley projects across 15 European countries, representing more than €1 billion in investments, with nearly €200 million directly funded by the Clean Hydrogen Joint Undertaking (JU).

The Dutch government recognizes the importance of a robust legislative framework to foster the hydrogen economy, particularly for its integration into the aviation sector. The State Vision for the Development of Markets for the Energy Transition, written in June 2020, emphasizes transitioning the natural gas infrastructure toward green gas and low-carbon hydrogen. This transition involves the national gas infrastructure company, Gasunie, which will play a crucial role in facilitating the hydrogen chain. Although specific hydrogen legislation is lacking, existing laws governing gas, energy, transport, and heating sectors currently apply. The Dutch Authority for Consumers and Markets DACM has issued guidelines clarifying the roles of network companies in alternative energy markets, allowing them to enhance their involvement in shaping the hydrogen economy.

Key initiatives to promote hydrogen include the innovation subsidy instrument (SDE++ regulation) for green hydrogen production and developing large-scale infrastructure projects to encourage consumption. Furthermore, the Netherlands has launched a Hydrogen Safety Innovation Programme, emphasizing identifying and mitigating safety issues related to hydrogen use, ensuring a safe integration of hydrogen technologies into the broader energy landscape.

3.2 Industry Factors Influencing Hydrogen Demand

To assess the factors influencing hydrogen demand at GAE, it is essential to examine both the hydrogen supply chain and the potential ancillary applications within the airport environment. This analysis includes supply chain maturity, cost, availability, and the specific airport-related applications that could drive demand.

Hydrogen Supply Chain Development

A critical factor shaping hydrogen demand at GAE is the maturity of the hydrogen supply chain. Currently, the hydrogen supply chain is still in the early stages of development. This includes production methods, transportation, storage infrastructure, and distribution networks. A more robust and reliable hydrogen supply chain will directly impact demand at GAE, as airlines and other airport stakeholders need to be assured of the constant and affordable supply of hydrogen.

Currently, green hydrogen production relies on renewable energy sources like wind and solar to power electrolysis. Production costs remain relatively high, but as renewable energy becomes cheaper and more widespread, hydrogen production costs are expected to decrease. Additionally, ongoing innovations and efficiency improvements in hydrogen production technologies, such as more efficient electrolyzers and optimized processes, are increasing production capacity while reducing costs. These advancements will further encourage airlines at GAE to consider hydrogen as a competitive alternative to jet fuel.

Hydrogen's low energy density per volume and its need for cryogenic or compressed storage add complexity to its distribution. Currently, cryogenic storage faces relatively high boil-off rates, which reduces efficiency, and every touchpoint in the hydrogen supply chain introduces excessive losses. However, advancements in storage technologies and more efficient handling processes can significantly reduce these losses. As these processes become more efficient and losses are minimized, the operational costs of using hydrogen will decrease. The potential integration of hydrogen pipelines or transport infrastructure at airports like GAE can further help overcome these challenges, making hydrogen a more viable option for aviation.

Industry and Ancillary Applications of Hydrogen

Beyond airline use, ancillary hydrogen applications at GAE could be crucial in creating an overall hydrogen ecosystem. Areas that can play a vital role in the hydrogen ecosystem are, for example, a landside hydrogen hub, hydrogen ground support equipment, and functioning as a hydrogen node for the region.

The global hydrogen economy will require extensive deployment of refueling stations, pipelines, and storage facilities. By 2050, over 163,000 truck refueling stations are projected globally, alongside 40,000 kilometers of hydrogen pipelines in Europe alone. A similar scale-up is expected in aviation to ensure smooth hydrogen distribution. Developing a hydrogen hub at the landside of GAE could serve as a fueling station for road transport, particularly hydrogen fuel cell electric vehicles (FCEVs), including trucks, buses, and taxis. This initiative would boost hydrogen demand at the airport and support regional decarbonization efforts.

Hydrogen-powered ground support equipment (GSE), such as baggage tractors, aircraft tugs, and refueling trucks, would be important in GAE's airside operations. Transitioning to hydrogen-powered GSE can help reduce carbon emissions and operational costs, creating a model for other airports. The increased use of hydrogen in GSE will naturally drive up demand for hydrogen fuel at GAE.

GAE can potentially serve as a strategic hydrogen distribution node for the surrounding region, benefiting the aviation industry, local businesses, and potentially residential areas. By developing a centralized hydrogen storage and distribution infrastructure, the airport could facilitate hydrogen supply to nearby industrial parks, logistics hubs, and other commercial entities, creating a regional hydrogen ecosystem. Additionally, GAE could act as a key point in a broader hydrogen network, supplying hydrogen to transportation sectors, such as freight and public transport, and eventually, residential areas as hydrogen technology matures. This would streamline access to hydrogen, drive demand, and support the energy transition across multiple sectors, positioning the airport as a central player in regional decarbonization efforts.

4 | Projected Hydrogen Flights at GAE

Main contributors: Groningen Airport Eelde

The projected flight network at GAE offers a detailed look into the future of sustainable aviation, relying on both hydrogen and electric propulsion systems, while conventional fuels phase out over time. This vision is based on several key assumptions about broader aviation trends and local infrastructure developments, reflecting a shift toward greener, more efficient travel modes. The table summarizing the projections can be found below. The extended version can be found in Appendix B.

4.1 Demand Drivers

One of the primary drivers of this transformation is the anticipated capacity restrictions at Amsterdam Schiphol Airport (IATA: AMS). Growth at Amsterdam Schiphol Airport (IATA: AMS) is constrained by movement limitations and ongoing political uncertainty surrounding its future expansion. These factors are expected to lead to a redistribution of air traffic to other regional airports, including Groningen Airport Eelde (IATA: GRQ) and Maastricht Aachen Airport (IATA: MST). Unlike Schiphol, GRQ currently faces no limiting constraints related to noise, emissions, or slot availability, providing it with the capacity to accommodate growth in the foreseeable future. While the vision for GAE accounts for some of this spillover, the model largely focuses on organic growth within the GQR catchment area, projecting how the airport will naturally evolve as a hub for sustainable regional aviation. Additionally, the planned extension of GAE's operating hours, from the current 06:30 - 23:00 hrs to 06:00 - 00:00 hrs starting in 2025, is another crucial assumption that will help create a more competitive playing field within the Dutch airport market.

4.2 Development in Movements and Passengers

A key assumption in this growth is that most scheduled flights from GAE will be short to mid-range regional routes (up to 2,600 km), which are expected to be gradually replaced by electric and hydrogen-powered aircraft. Current battery-electric aircraft offer a limited range of approximately 140 km, with future advancements expected to extend this range to around 400 km (Mukhopadhaya & Graver, 2022; Wolleswinkel et al., 2024). Hydrogen-powered aircraft are projected to achieve significantly greater range improvements over the coming decades, with next-generation technologies enabling ranges between 3,000 and 3,400 km by 2035 and a potential increase to as much as 7,000 km by 2050 (Mukhopadhaya & Graver, 2022; O'Callaghan, 2020). Notably, this vision does not account for the presence of a fixed-base carrier, a scenario that GAE actively supports. Introducing a fixed-base carrier at GAE would significantly alter the expected development in air traffic movements (ATM) and passengers and the sustainable transition. In this vision, SAF is considered a direct replacement for Kerosene-based long-range / leisure-oriented flights rather than the regional services GAE expects to offer with Hydrogen-based flights.

A significant element of GAE's future lies in adopting electric regional air mobility. By 2030, electric aircraft will begin operations with 9-19 seaters, mostly on domestic routes and a few international connections, such as to Denmark. These flights are expected to grow rapidly, reaching a peak of 13,500 annual flights by 2040 as the route network expands to include major European cities like Paris, Munich, and Berlin. This rapid flight increase from 2030 through 2045 is also reflected in the significant rise in electric air travel passengers, as shown in Table 1. Although the number of electric flights will taper off to 8,200 movements by 2050, the shift in routes will reflect a transition from primarily domestic flights to more international (Schengen) destinations. The evolution of electric aviation introduces a new transportation modality akin to regional bus services, driven by anticipated advantages in cost-efficiency, reduced maintenance, and competitive seat prices. By 2040, electric aircraft seating capacity is expected to grow, with planes carrying more than 30 passengers becoming a standard option.

Hydrogen aviation utilizing GH2 and LH2 will further expand GAE's flight network. GAE's hydrogen network will focus on short-haul regional routes, but as technology matures and hydrogen infrastructure becomes more widespread, the range and payload capacity of these aircraft will likely increase. In traffic vision, Hydrogen flights commence with GH2 operations, starting in 2030, with 1,900 ATMs on routes to Hamburg and Rotterdam. Although no new GH2 routes are added, the number of flights will rise to 2,800, serving around 58,800 passengers by 2050. The first LH2 flights are envisioned to begin in 2035, with initial routes to London and Copenhagen using 50-seater aircraft. Over time, the number of routes will increase significantly, reaching 25 by 2050, with more than 17,900 flights annually.

Currently, only airline-based movements are considered; movements of Business Aviation, General Aviation, and other flight sectors are not yet part of the traffic vision. Business aviation, in particular, has the potential to increase the number of hydrogen flights significantly. For instance, Beyond Aero's hydrogen aircraft, with a range of 1,500 km, could cover 74% of current flights from GAE and 92% of flights within Europe are under 1,500 km. In 2023, GAE saw 147 departures below 1,500 km with passenger numbers that align with Beyond Aero's capacity. However, it remains uncertain how business aviation will evolve in the coming years at GAE and how the transition from kerosene to hydrogen, electric, or SAF-powered flights will occur. Therefore, the number of hydrogen business aviation activities in the future is currently excluded from the GAE hydrogen vision.

In parallel to these developments, regular jet-fuel flights will continue operating at GAE but slowly phase out over time. The peak for these conventional flights is projected for 2035 with 2,300 annual movements, a number that will remain stable until 2040. However, a steady decline will follow, with only 520 jet-fuel flights expected by 2050. The remaining routes will primarily serve high-demand southern European destinations, especially during the summer.

The vision envisions a dramatic shift in its flight operations, with LH2 and electric aircraft progressively replacing traditional fuel-powered planes. The integration of electric aviation as a cost-effective, short-haul transportation mode and the eventual growth of hydrogen-powered flights for medium-haul routes underscores the airport's potential to become a leader in green aviation. This transformation is further supported by external developments, such as the restricted growth at AMS and the expected non-opening of Lelystad Airport for commercial scheduled services, which could redirect traffic toward regional airports like GAE. With these factors in place, GAE is well-positioned to capitalize on the growing demand for sustainable travel solutions, making it a leading player in the future of European regional aviation.

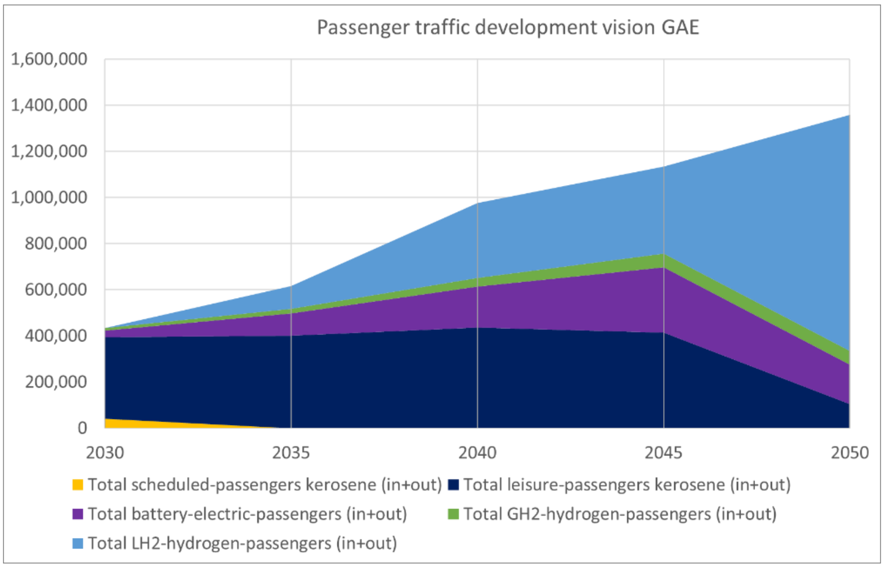

Figure 9: Passenger traffic development vision GAE 2030-2050. Excludes General Aviation and Business Aviation

	2030	2035	2040	2045	2050
Total scheduled-passengers (Kerosene/SAF) (in+out)	40,320	0	0	0	0
Total leisure-passengers (Kerosene/SAF) (in+out)	354,564	401,436	435,492	414,324	103,932
Total battery-electric-passengers (in+out)	27,720	95,760	177,380	283,500	172,200
Total GH2-hydrogen-passengers (in+out) (excl. Business Aviation)	11,970	19,880	37,240	58,800	58,800
Total LH2-hydrogen-passengers (in+out)	0	98,000	325,920	377,020	1,024,280
Total commercial passengers (in+out)	**434,574**	**615,076**	**976,032**	**1,133,644**	**1,359,212**

Table 1: Hydrogen growth scenario for the years 2030-2050. Excludes General Aviation and Business Aviation

4.3 Hydrogen Consumption at GAE

Main contributions: AirportCreators

Based on the demand and network assessment, reference figures are derived for the expected consumption of hydrogen at GAE. It is important to note that business aviation is excluded from these estimates, as the hydrogen adaptation and unpredictability in the number of hydrogen flights per year make it challenging to accurately project hydrogen consumption for this sector.

In the initial years of hydrogen adoption within the aviation industry, it is anticipated that only small GH2 aircraft will be operational at GAE. By 2030, approximately 19 GH2 flights per week are expected to depart. The GH2 estimation is based on the aircraft capacity (6-8 passengers) and fuel tank size (37-60 kg) of the Britten Norman Islander BN2B-26, fitted with the Cranfield Aerospace hydrogen fuel cell powertrain. It is assumed that this aircraft will depart with a full GH2 fuel tank to be able to fly the return leg, as refueling at the destination airport may not be possible. For a 9-seater aircraft flying to Rotterdam, a consumption of 60 kg of GH2 is projected, while a 19-seater aircraft traveling to Hamburg is expected to consume 100 kg of GH2 (from Appendix A – WP2). With these assumptions, the estimated GH2 consumption is calculated yearly and daily and presented in Table 2. The reference year 2030 is hereafter referred to as Tier 1.

Seat capacity	Flight movements (yearly)	Consumption m3 (yearly)	Consumption kg (yearly)	Consumption m3 (daily)	Consumption kg (daily)
19	500	1,054	25,000	2.9	68.5
9	1,400	1,771	42,000	4.9	115.1
Total	1,900	2,825	67,000	7.7	183.6

Table 2: Required GH2 in 2030. Note. The GH2 volume of the GH2 is calculated for a pressure of 350 bar. ***Tier 1***

From 2035 onwards, the number of LH2 flights will rapidly take off. A small regional aircraft is estimated to consume approximately 1 ton of LH2 per flight to establish the required LH2 consumption at GAE (Airport Council International [A

CI], 2021). In contrast, a narrow-body medium-haul aircraft consumes around 5 tons per flight (ACI, 2021; Fuel Cells & Hydrogen 2 Joint Undertaking, 2020). Furthermore, the aircraft is assumed to operate with maximum fuel capacity on board, again because of the assumption that the aircraft will not be able to refuel at the destination. The reference year 2035 is hereafter referred to as Tier 2. By 2050, the envisioned number of LH2 flights is projected to reach 17,920 at GAE. Tables 3 and 4 provide a detailed distribution of these flights according to aircraft size. Aircraft with seating capacities of 50 and 80 are categorized as regional aircraft, whereas those with seating capacities of 120 and 150 are classified as narrow-body medium-haul aircraft. The reference year 2050 is hereafter referred to as Tier 3.

Seat capacity	Flight movements (yearly)	Consumption m3 (yearly)	Consumption kg (yearly)	Consumption m3 (daily)	Consumption kg (daily)
50	1,400	98,000	6,948,200	58.1	4,120
Total	1,400	98,000	6,948,200	58.1	4,120

Table 3: Required LH2 in 2035 ***Tier 2***

Seat capacity	Flight movements (yearly)	Consumption m3 (yearly)	Consumption kg (yearly)	Consumption m3 (daily)	Consumption kg (daily)
120	1,450	101,500	7,196,350	280	19,900
50	4,400	66,000	4,679,400	180	12,900
80	2,750	41,250	2,924,625	110	8,100
150	360	25,200	1,786,680	70	4,900
Total	8,960	233,950	16,587,055	650	45,900

Table 4: Required LH2 in 2050 ***Tier 3***

5 | Hydrogen Production and Delivery

Having a reliable hydrogen supply chain is a cornerstone of GAE vision for sustainable aviation. With hydrogen-powered aircraft set to play a potential pivotal role in the airport's future operations, determining how hydrogen is produced and delivered is critical to ensuring both feasibility and efficiency. This chapter examines two primary approaches—on-site hydrogen production and regional hydrogen production with delivery to the airport. Each approach comes with its own set of benefits and challenges, influenced by factors such as demand levels, technological advancements, and cost considerations. On-site production allows for localized control and potentially lower transportation emissions, while regional production benefits from economies of scale but requires robust delivery systems to meet airport needs. The chapter focuses on the trade-offs between these strategies, offering insights into how GAE can align its hydrogen supply chain with its operational and sustainability goals.

5.1 On-site Hydrogen Production and Delivery

Main contributions: Engie

The on-site production of hydrogen offers a practical solution for meeting the initial demand for hydrogen at GAE, particularly as the industry transitions toward greener energy sources. Starting in 2030, only a small quantity of GH2 will be required to supply the initial hydrogen flights, making large-scale hydrogen supply chains unnecessary and potentially cost-prohibitive at this early stage. Producing hydrogen directly at the airport allows for a flexible, scalable, and more sustainable approach during the first years after hydrogen flight is introduced.

Production

A scenario is developed to assess the technical feasibility of hydrogen application at GAE in the early stages of its implementation, as shown in Figure 10. The scenario outlines a setup that includes a 1 MW electrolyzer capable of producing 430 kg of hydrogen per day (55.8 kWh per kg of hydrogen), equating to approximately 140 tons per year, powered entirely by renewable electricity. This initial small-scale hydrogen production setup is similar to the HYPORT initiative in Toulouse, which cost approximately 7.2 million Euros (Engie, 2023). This on-site production unit would deliver a steady hydrogen supply that is sufficient to provide the required GH2 aviation operations at GAE, making it a sustainable solution for early-stage needs.

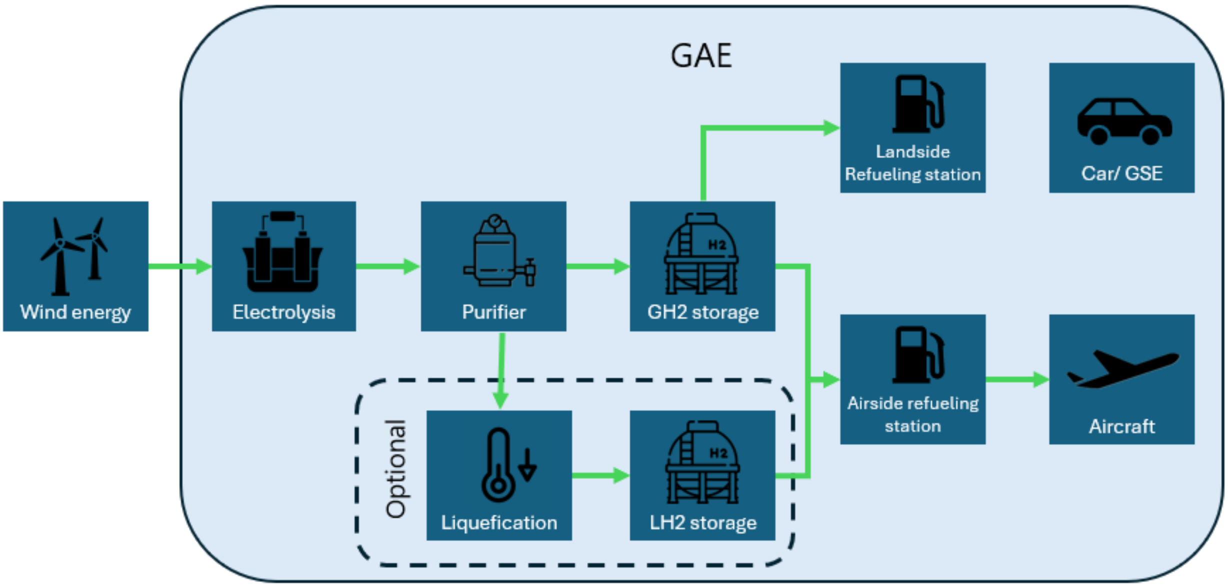

Figure 10: Schematic Representation of Hydrogen Production and delivery at GAE.

Two dedicated refueling stations are proposed to support hydrogen refueling operations. One station would be located airside on the tarmac to serve both aircraft and potentially ground support equipment (GSE), offering refueling at 350 and 700-bar. The dual pressure levels accommodate different hydrogen tank design specifications—such as Cranfield Aerospace's aircraft, which stores GH2 at 350 bar, and Beyond Aero's aircraft, which requires 700 bar—enabling GAE to meet various operational needs. Because of the low number of GH2 operations at GAE in Tier 1, the refueling will be done at a fixed fuel station instead of using bowsers or a hydrant system. A second refueling station on the public side would also provide 350 and 700-bar refueling for landside vehicles, including buses, trucks, and cars. This dual-capability setup demonstrates hydrogen's potential to power aviation and ground transportation, positioning the airport as a leader in clean energy infrastructure.

Storage

In terms of storage, the plan includes a GH2 storage facility with a capacity of 450 kg. The storage tank can be increased to a maximum of 1 ton because of the health, safety, security, and environmental (HSSE) permitting process. The hydrogen storage facility also serves as a buffer to ensure uninterrupted operations during supply chain disruptions. The specific buffer size for hydrogen has yet to be finalized but is assumed to be one day. For comparison, the current buffer requirement for kerosene is equivalent to three days of operations at 90% of the regular flight schedule. Airside hydrogen demand is projected to stabilize at around 400 kg per day after 2040. Accounting for a one-day buffer, a storage tank with a capacity of 600 to 800 kg (depending on the flight schedule) would be sufficient to meet airside demand through 2050. An estimation for landside/public demand will be necessary to determine the appropriate tank size by 2050.

Investing in a larger GH2 storage tank in Tier 1 may be advantageous, potentially eliminating the need for additional upgrades in Tier 2 or 3. However, this will ultimately depend on the long-term strategy selected for these future phases. The storage is divided into three pressure levels — 30 bar, 250 bar, and 900 bar — allowing for flexible distribution of hydrogen depending on the application. In the event of an electrolyzer breakdown or higher-than-expected demand, an import facility is also included, allowing a tube trailer or container to be integrated into the system to ensure uninterrupted hydrogen supply. Depending on the purity levels produced by the electrolyzer, a purification unit may be required to ensure hydrogen meets the necessary purity standards for operational use.

Liquification

In Tier 1, a liquefier with a capacity of 100 kg per day and a 200 kg LH2 storage facility can be included if there is sufficient demand. With this relatively low production rate, the generated LH2 would primarily support landside operations or ground support equipment, as it would not be adequate for larger aircraft—such as a 50-seater—typically requiring around 1,000 kg of LH2 per flight. However, it is important to note that both the liquefaction and storage capacities are scalable to meet future demand. The liquefaction unit can be expanded to produce up to 10 tons of LH2 per day, and hydrogen storage could be increased to a maximum of 20 tons, with an ideal target of 5 tons to simplify the permitting process. This scalability ensures that, as hydrogen demand grows, the infrastructure can be adapted to accommodate larger-scale LH2 operations, supporting the airport's long-term hydrogen strategy.

Hydrogen liquefaction demands substantial energy due to the multi-stage process required to cool hydrogen to cryogenic temperatures. This energy-intensive process involves compression, pre-cooling, and final cryogenic cooling stages. Currently, the energy required to liquefy hydrogen is approximately 10-13 kWh/kg of LH2, though this can vary depending on the scale and efficiency of the liquefaction facility (ACI, 2021; Hunt et al., 2023; United States Department of Energy, 2008). However, technological advancements are expected to decrease this energy requirement, moving closer to the theoretical minimum of 3.7 kWh/kg of LH2, significantly reducing liquefaction costs (Hunt et al., 2023).

5.2 Regional Hydrogen Production and Delivery

As the demand for hydrogen increases, particularly for LH2, the feasibility of sourcing hydrogen directly from regional production facilities becomes increasingly attractive. While initial efforts in Phase 1 focus on modest hydrogen production installations, primarily serving early adopters and smaller-scale applications, Phase 2 introduces the potential for substantial economies of scale. This development tier aligns with the larger quantities required for aviation, particularly for LH2, which necessitates a significant expansion of production capabilities. The shift to Phase 2 reflects the increasing viability of off-taking hydrogen directly from regional facilities, where larger-scale operations can deliver the volumes required to meet growing demand.

Availability of Green and Blue Hydrogen in the Region

Main contributions: AirportCreators and RWE

The Northern Netherlands is rapidly establishing itself as a key sustainable energy hub. Demand for hydrogen has been increasing due to regulatory requirements for companies using more than 0.1kt of hydrogen yearly. These companies expect to use more low-carbon or RFNBO hydrogen in their production processes as mandates for utilizing hydrogen will likely come into force in the coming years. This shift is critical for hard-to-abate sectors where electrification is not feasible, making low-carbon hydrogen essential for decarbonization.

The increasing hydrogen demand drives significant offshore wind energy investments to produce green hydrogen in the region, with projects like the Gemini wind farm generating 600 MW annually and the Eneco-Shell joint venture, CrossWind, contributing 759 MW annually. In addition, the Dutch government plans to install a 500 MW electrolysis plant in the North Sea wind farm area, further increasing green hydrogen output. The NorthH2 initiative by Shell, RWE, Eneco and Equinor is set to produce 800,000 tons of green hydrogen annually by 2040 in Eemshaven, with potential expansion into the North Sea. Similarly, the HyNetherlands project at Eemshaven by Engie is expected to scale up to over 200,000 tons of green hydrogen annually by early 2030. These large-scale initiatives provide GAE with a clear and reliable pathway to secure sustainable hydrogen for its operations.

In terms of blue hydrogen, Equinor, in partnership with Linde Gas, is developing a blue hydrogen production facility in Eemshaven, which is expected to be operational by 2029. This plant will use natural gas as its primary feedstock, combined with advanced carbon capture and storage (CCS) technologies to significantly reduce CO_2 emissions, offering a lower-carbon alternative to traditional hydrogen production methods.

In addition, the Northern Netherlands' technical infrastructure is well-positioned to support blue and green hydrogen, as the existing network of natural gas pipelines can be repurposed to transport hydrogen. This is further supported by the HyStock initiative, which provides large-scale, cost-effective hydrogen storage using salt caverns. These caverns offer significant storage capacity, which is critical for balancing supply and demand fluctuations, especially in a market requiring flexible and scalable hydrogen solutions over time.

The growing investments in regional hydrogen projects make it highly feasible for GAE to access green and blue hydrogen. With the Eemshaven green and blue hydrogen plants and extensive renewable energy infrastructure, GAE will benefit from a diverse and secure hydrogen supply chain. This flexibility allows GAE to meet varying hydrogen demands, as it can source green hydrogen when abundant and cost-effective and blue hydrogen when green hydrogen production is constrained or when a lower-cost option is needed. Combining green and blue hydrogen options gives GAE a strategic advantage in ensuring a reliable and scalable hydrogen supply as demand grows while aligning with broader sustainability goals.

Regarding green hydrogen production, it must be considered that electrolysis plants will have limited running hours due to Renewable Hydrogen Delegated Acts of the European Commission, stating that the energy source for hydrogen production must be at least 90% renewable to classify the hydrogen itself as renewable. Once the electricity mix reaches >90% renewable, running hours will not be limited. This mix requirement is not expected to be met before 2035.

Regional Hydrogen Supply

Main contributions: AirportCreators, Engie, and RWE

Local production becomes less feasible in the long run due to increasing hydrogen demand and the complexity of on-site safety measures and associated permitting. In addition, large-scale production is needed for the increased demand to drive the cost down. Therefore, two regional supply options can be considered in the second phase: GAE is connected to the NL H2 backbone, or delivery is done via road tankers.

The first option involves connecting GAE to the NL H2 backbone, with GH2 supplied directly through a pipeline from regional production centers like Eemshaven or the Port of Rotterdam. Initial liquefaction capacity could be set at 1 ton/day, but a larger 10 tons/day unit could be installed as demand grows. The first estimation for the energy needed for the liquefaction of GH2 to LH2 is around 12 kWh/kg LH2. This value may vary depending on the size of the liquefaction unit, with smaller units requiring more energy per kg LH2 while larger installations of 10 tons/day may require 10 kWh/kg LH2. This would be accompanied by buffer storage of LH2 on-site. The storage size would be determined by daily demand but ideally kept below 5 tons for easier permitting, though it could scale up to a maximum of 20 tons if required. Both gaseous and LH2 storage would feed into the hydrogen refueling station to meet aviation and ground service equipment needs. However, it should be noted that on-demand liquefaction is not yet technically feasible and requires buffer storage.

The second option is off-site liquefaction, where GH2 or LH2 is produced at a regional hydrogen facility and transported to GAE by truck, train, or boat. The ideal transport method depends on factors such as distance, volume, and site accessibility by each mode. Upon arrival, if the hydrogen is in gaseous form, an on-site liquefaction plant will be necessary to meet the LH2 demand and storage systems for both GH2 and LH2. If the hydrogen arrives in liquid form, there is flexibility in storage options: LH2 can either remain in its transport container or be transferred to a dedicated storage tank, depending on operational needs.

Hydrogen Purity

Main contributions: Shell

Hydrogen purity is critical in successfully adopting hydrogen-powered aviation operations at GAE. Ensuring the appropriate purity levels throughout the hydrogen supply chain is essential to meet the stringent requirements of fuel cell-based powertrains and other hydrogen propulsion systems. These purity standards must address challenges related to production, transportation, storage, and delivery, all of which can introduce impurities that compromise the performance and safety of hydrogen-powered aircraft. This section explores the current and anticipated purity requirements, the potential challenges associated with maintaining these standards, and the purification technologies that can ensure the hydrogen delivered to GAE meets aviation-grade specifications.

Purity Considerations Regional Hydrogen

If GH2 is delivered to GAE via the hydrogen backbone, the quality specifications of the hydrogen will be established by Hynetwork Services (HNS). Based on these specifications, additional purification may be required to ensure the hydrogen meets the stringent quality standards necessary for use as aviation fuel, particularly for fuel cell-based power trains. According to the HNS General Terms and Conditions – Connection Agreement (HyNetwork, 2023), "Connected Party warrants to HNS that the Gas as (to be) made available at a Connection complies with (i) the specifications as set out in Annex 3 (Quality and pressure specifications) or (ii) if accepted under Article 4.2.2(b) below, the specifications described in the notice mentioned in Article 4.2.1 below."

Table 1: Indicative quality specifiaction Hydrogen Network Netherlands

Constituents	Unit	Min.	Max.
Hydrogen (H_2)	mol/mol %	99.5	
Total sum of hydrocarbons including CH_4 (C_XH_Y)	mol/mol %		0.5
Oxygen (O_2)	μmol/mol (ppm)		10
Total sum of inerts (N_2, He, Ar)	mol/mol %		0.5
Carbon dioxide (CO_2)	μmol/mol (ppm)		20
Carbon monoxide (CO)	μmol/mol (ppm)		20
Total sulphur including H2S (S)	μmol/mol (ppm)		3
Formic acid (CH_3OOH)	μmol/mol (ppm)		10
Formaldehyde (CH_2O)	μmol/mol (ppm)		10
Ammonia (NH_3)	μmol/mol (ppm)		10
Halogenated compounds	μmol/mol (ppm)		0.05
Water dewpoint (H_2O)	ºC @ 70 bara		-8
Hydrocarbon dewpoint	ºC @ 1 - 70 bara		-2
Wobbe index	MJ/m³ (n)	45.99	48.35
All other impurities	Shall not contain solid, liquid or gaseous material that might interfere with the integrity or operation of pipes or any gas appliance		

Table 2: Temperature

Property	Unit	Min.	Max.
Gas temperature	ºC	5	30

Figure 11: Indicative Quality Specifications Backbone (HyNetwork, n.d.)

While Annex 3 is at the time of writing unavailable, HNS has published indicative quality and temperature specifications, as outlined in Figure 11. The Ministry of Economic Affairs and Climate Policy will make final decisions on the hydrogen quality and temperature standards. There is growing support in neighboring countries for a minimum purity requirement of 99.5% for GH2, which aligns with evolving European standards. The European Commission is expected to initiate a hydrogen standardization process, likely to take around three years. In the interim, several transportation companies across Germany, Belgium, and the Netherlands, including Gasunie, are collaborating to develop a joint hydrogen quality specification based on the 99.5% purity standard. The EZK will consider this joint specification before finalizing national regulations, with no definitive decision expected before the end of 2024.

The quality of the imported hydrogen will depend on new supply projects and infrastructure development. Both HNS and HyStock, which are key to the northern hydrogen cluster relevant to GAE, currently maintain a GH2 quality standard of 98.0%. However, both entities have indicated that a hydrogen purity level of ≥ 99.5 % could be achievable in the future. A potential issue arises from the proposed reduction in sulfur content limits, currently set at 3 mol ppm, which may pose challenges if further tightened.

For LH2, purity levels vary depending on the production method. Electrolysis, classified as green hydrogen, can generate hydrogen with a high purity of 99.99% (Polman et al., 2022), making it suitable for fuel cells and other high-purity applications. In contrast, LH2 produced through blue hydrogen methods, which utilize natural gas, generally has a lower purity between 95 and 97% (Polman et al., 2022). The involvement of natural gas in blue hydrogen production introduces additional contaminants, reducing overall hydrogen purity.

Transportation

Hydrogen can be delivered to GAE via pipeline (the hydrogen backbone) or road. Its small molecular size and particular chemical properties present transmission and distribution challenges and trade-offs. One significant issue is the risk of gas impurities creeping in during transportation or storage and reducing the gas purity. Furthermore, compressing GH2 for transport can result in traces of oil in the gas.

Transporting hydrogen by pipeline also presents challenges, such as the need to odorize the gas for safety reasons. This is due to the propensity for hydrogen embrittlement, which could lead to leakage. Including sulfur-containing odorants (e.g., mercaptans) could be an issue as these need to be removed before usage. This is a hydrogen fuel cell catalyst that can be "poisoned" by these chemicals. It is also likely that contaminants picked up from the inside of even brandnew pipelines will need to be removed prior to use in high-purity applications. Furthermore, leaks can allow air and moisture to enter the pipeline, further reducing hydrogen purity. These contaminants would require additional purification at the point of use, increasing the complexity and cost of the overall hydrogen supply system. Ensuring hydrogen purity, particularly for aviation, will therefore involve addressing these challenges and implementing rigorous testing and purification processes throughout the supply chain.

Hydrogen Purity Standards

Hydrogen purity standards are internationally recognized guidelines that define the maximum allowable levels of impurities in hydrogen gas and outline methods to test its purity. Various standards apply to different sectors, but no specific purity standards have been developed for the aviation industry. However, several existing standards can serve as references:

- **ISO 14687**: This is the most widely used international standard for hydrogen gas, particularly in fuel cell vehicles. The standard does not specify the hydrogen fuel precursor or source. It limits impurities such as water vapor, carbon monoxide, and other gases, as well as methods for testing purity. Hydrogen fuel cell vehicles must comply with ISO 14687:2019 Grade D, which requires a minimum purity of 99.97%. Similar, or even higher, purity levels are anticipated for the aviation sector.
- **ASTM D4814**: Developed by the American Society for Testing and Materials (ASTM), this standard outlines purity requirements for hydrogen used in vehicles, specifying impurity limits and testing methods.
- **SAE J2719**: Issued by the Society of Automotive Engineers (SAE), this standard provides hydrogen fuel quality guidelines for PEM fuel cell vehicles, including permissible impurity levels and testing protocols.

Due to manufacturers' varying development stages, limited information is currently available regarding aviation's final hydrogen purity requirements. However, the designs proposed by Cranfield Aerospace and Beyond Aero require a minimum purity level of hydrogen conforming to ISO 14687 Grade D standards, mandating a minimum hydrogen purity of 99.97% at the point of transfer to the aircraft. Maintaining this purity level throughout the entire supply chain is essential, as any drop below the 99.97% threshold could compromise the performance and safety of hydrogen-powered aviation systems. A note has to be made that the purity standards for commercial use in aviation still need to be determined with the possibility of higher purity standard requirements. Aircraft that use a combustion method for propulsion, such as the Fokker NextGen and the Airbus ZEROe, do not have these stringent purity standards.

Purification

Purification must be considered as the GH2 delivered to GAE may not meet the required purity levels for its intended applications. Hydrogen purification encompasses a range of technologies used to remove impurities from hydrogen gas, which can vary depending on the production method—whether from petroleum, natural gas, electrolysis, or other sources. The specific application determines the required level of purity. For instance, ultra-high purity hydrogen is necessary for applications like proton exchange membrane fuel cells. Several purification technologies can be employed to achieve the necessary standards. Each purification method offers unique advantages depending on the required hydrogen purity levels and the operational context.

- Pressure Swing Adsorption (PSA): PSA is one of the most used methods for hydrogen purification. It is an industrial process suited primarily for stationary installations. PSA can remove contaminants such as methane, carbon monoxide, nitrogen, moisture, and, in some cases, argon from hydrogen. When necessary, PSA can achieve purity levels exceeding 99.97%. The energy requirement to achieve this purity level lies between 2.37 and 2.53 kWh/kg GH2 (Naquash et al., 2021; Naquash et al., 2023). The energy required depends on the purity level and the corresponding efficiency to achieve such purity. The efficiency to achieve 99.5% purity is 89%, while to achieve more than 99.9% purity, it reduces to 85% (Polman et al., 2022).
- Membrane Separation: In this process, permeable membranes separate and purify hydrogen in this process. These membranes allow hydrogen to pass through while blocking other gases, making them practical for specific purification needs. Energy requirements for membrane separation vary depending on the configuration from 3.94 to 7.95 kWh/kg GH2 (Nordio et al., 2021).
- Electrochemical Separation: This method utilizes palladium-coated membranes to purify hydrogen through an electrochemical process. These palladium membrane purifiers are compact and ideal for hydrogen mobility applications where space is constrained.
- Distillation: Distillation leverages the different boiling points of impurities and hydrogen to separate them in a distillation column. It is effective in isolating hydrogen gas from contaminants based on their thermal properties

- Low-Temperature Methods: These methods take advantage of hydrogen's extremely low boiling point of −253°C to purify it. Since most impurities have boiling points significantly higher than this, they can be removed during the cooling process. Low-temperature methods can be complemented by scrubbing to target specific impurities.

Financial feasibility

Main contributions: RWE

The financial feasibility of hydrogen production in the Northern Netherlands holds significant potential but is closely tied to large-scale investments and continued government subsidies, especially in the short to medium term. Hydrogen production, particularly green hydrogen, is still in its early stages, with high upfront costs for infrastructure, electrolysis units, and renewable energy sources posing substantial financial barriers. However, as the regional hydrogen market develops—driven by large-scale projects like NorthH2 and increasing offshore wind capacity—the economies of scale are expected to reduce production costs significantly.

A crucial factor in making green hydrogen financially viable is the price of electricity. Low-cost renewable electricity is essential for green hydrogen to be competitive, especially compared to blue hydrogen and fossil fuels. Current analyses show that, with electricity prices around USD 30 per megawatt-hour (MWh), green hydrogen could become competitive with blue hydrogen by 2030 (IRENA, 2020). Additionally, reductions in electrolyzer costs, improved efficiency, economy of scale, and increased operational hours will further lower costs, potentially allowing green hydrogen to be produced at less than USD 1 per kilogram by 2040, making it cheaper than fossil fuels before that time (IRENA, 2019). An effect of the economy of scale is visible in the liquefaction process. Increasing liquefaction from 100 to 1000 tons daily reduces the cost from 2 to 1 USD per kilogram of LH2 (Hunt et al., 2023). The price decline of hydrogen production will be driven by aggressive electrolyzer deployment, increased renewable energy output, increased demand, and continued innovation in hydrogen technology.

For GAE, the financial feasibility of using hydrogen follows a similar trajectory. The proximity of hydrogen production facilities like NortH2 and Equinor's blue hydrogen plant in Eemshaven reduces transportation costs, making local sourcing more attractive. However, in the near term, GAE will likely rely on government subsidies to offset initial investments in hydrogen infrastructure, including storage, refueling stations, and potentially retrofitting existing systems. As the hydrogen market matures and technology advances, these costs are expected to decline, improving the long-term financial sustainability of hydrogen as a fuel source for aviation and other applications at GAE. Ultimately, the region's growing renewable energy infrastructure and hydrogen projects provide a promising pathway for hydrogen to become a financially viable and sustainable option for the airport.

6 | Hydrogen Supply

Meeting the hydrogen needs of future aviation requires careful planning of how it is delivered and distributed at GAE. This chapter delves into two critical aspects: hydrogen supply to the airport and hydrogen supply to the end user. The supply to the airport examines transportation, safety standards, and cost, while supply to the end user focuses on infrastructure and operational efficiency. Together, these considerations lay the foundation for a reliable and efficient hydrogen supply chain, essential for the airport's sustainable transition.

6.1 Hydrogen Supply to the Airport

The hydrogen supply network comprises the following key subcomponents: hydrogen production, hydrogen liquefaction (for LH2), hydrogen transport, hydrogen storage, and hydrogen distribution. There are two viable options for transporting the required hydrogen from the production facility to GAE:

1. Hydrogen is produced, (liquefied off-site,) and delivered to the airport via road tankers.
2. Hydrogen is produced off-site and delivered to the airport in gaseous form through pipelines or compressed hydrogen trucks (, where it is subsequently liquefied on-site).

LH2 is often preferred in studies due to its superior volumetric density compared to GH2 (Degirmenci et al., 2023). When GH2 is stored under a pressure of 350 bar, its density is approximately three times smaller than that of LH2 (reducing to 1.79 times when compressed to 700 bar). Consequently, GH2 requires larger storage tanks and, depending on the transportation method, potentially more hydrogen trucks.

Transportation Feasibility

Main contributions: AirportCreators and Shell

Hydrogen can be transported by trucks, trains, boats, or pipelines. The most optimal mode depends on multiple factors, such as distance, accessibility, and quantity. Trains and boats are often used for transporting large quantities of hydrogen over long distances (3,000+ km) (Barckholtz et al., 2013; European Commission, 2021). Pipelines and road transport are more economically viable options for shorter distances (ENTOG et al., 2021; European Commission, 2021). With the assumption that regionally produced hydrogen will be imported from the North Netherlands Hydrogen Valley, road transport and pipelines are the two most viable options.

Road Transportation

There are two main types of road tankers: pressurized tube trailers and cryogenic liquid tankers. Pressurized tube trailers, which are designed for compressed GH2, typically transport at pressures between 250 and 500 bar, carrying between 500 kg and 1 ton of GH2, respectively. While higher pressures, up to 700 or even 1,000 bar, can increase the transportable quantity, this requires additional infrastructure and is costlier. The energy requirement for compressing 1 kg of GH2 from 20 bar to 350 bar is 1.05 kWh/kg GH2,1.36 kWh/kg GH2 to 700 bar, and 2.6 kWh/kg GH2 to 1.000 bar using ideal isothermal compression (Knop, 2022; United States Department of Energy; 2009). Loading a 500-bar GH2 trailer typically takes around four hours, with offloading taking approximately 45 minutes (depending on compressor capacity and other infrastructure) when using a trailer-swap system (Linde, 2020). Tube trailers are generally suited to shorter-distance deliveries, as costs become prohibitive over 300 km, as shown in Figure 14. With the Eemshaven just 50 km from GAE and the Port of Rotterdam 273 km away, transporting hydrogen in gaseous form for lower quantities is a viable option.

Cryogenic LH2 tankers offer a more economical alternative for medium quantities or longer transport distances between 300 and 900 km (but can be used up to 4,000 km (ANZ, 2024). Hydrogen is cooled to -253°C to enable transport in liquid form. These trailers have a typical capacity of up to 4 tons with about 5% ullage (Aerospace Technology Institute [ACI], 2021; Degirmenci et al., 2023). LH2 trailers have an approximately usable volume of 90%, accounting for retention needed to maintain cryogenic temperatures on return trips (Department of Energy, 2013). LH2 transport generally requires four hours to load fully and one hour to offload (Linde, 2020). However, energy losses through gradual warming lead to boil-off unless active cooling systems are in place.

LH2 offers significant potential for efficient storage and transportation due to its high gravimetric and volumetric energy densities and its ability to maintain high purity. Although LH2 provides greater energy density than GH2, the total energy required across the supply chain—from production to end-use delivery—remains nearly equivalent, with GH2 transported at 500 bar requiring about 60 kWh per kg and LH2 approximately 63 kWh per kg. A factor that should be considered with LH2 storage is that the cryogenic LH2 is susceptible to energy loss through gradual warming, which leads to the boil-off of GH2 unless actively cooled to maintain the required low temperatures.

Transporting hydrogen involves large, heavy-duty vehicles requiring sufficient access space at the unloading site or parking area. Efficient and safe transportation using tube trailers requires a well-coordinated infrastructure covering essential elements like off-loading stations, parking, safety, and logistics. The system must also be equipped with operator-controlled technology to monitor pressure and hydrogen levels, ensuring safe and efficient filling. Additionally, designated parking areas for both full and empty trailers are required, with sufficient space and adherence to regulated safety distances to mitigate risks. The tube trailers must carry ADR approval, certifying them for the safe road transport of high-pressure or cryogenic hydrogen. Routine inspections are necessary to verify structural integrity and pressure specifications. Additionally, strong logistics management is key to ensuring smooth trailer turnover and meeting the demands of a 24/7 operational schedule.

The impact of increased tanker traffic to meet hydrogen demand, both on and around the airport, requires careful consideration to avoid congestion. This consideration determines which state (gaseous or liquid) it is most beneficial to transport the hydrogen and with what transportation mode. A clearly defined point at which road transportation of hydrogen is no longer viable is not defined and is influenced by many factors (Steer, 2023; FCH, 2020). Assuming that the onsite production facility proposed for Tier 1 can (only) meet GH2 demand, LH2 must be imported. In 2035, one LH2 truck or four GH2 trucks per day will be necessary to meet projected demand (excluding boil-off losses). In 2040, this will increase to 3.2 LH2 or 12.5 GH2 trucks. By 2050, this will have further increased to approximately 11.5 LH2 trucks or 46 GH2 trucks per day. The number of trucks required in 2035 (both in gaseous and liquid state) and the number of LH2 trucks required in 2050 lay within the number of trucks feasible without creating excessive congestion based on the fact that Eindhoven Airport imports 15 trucks of kerosene per day during peak days and literature (FCH, 2020; Hoelzen, Silberhorn, et al., 2022).

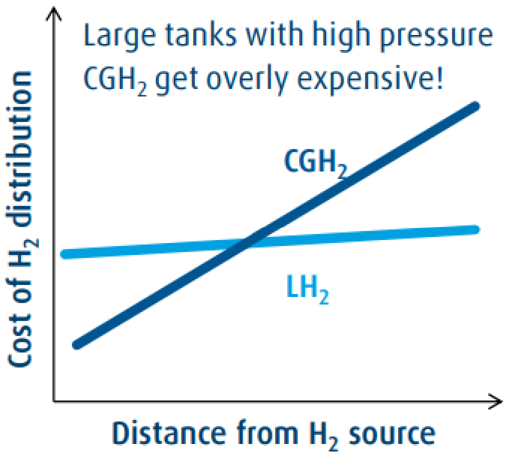

Figure 12: The Tipping Point Between GH2 and LH2 Road Transportation (Linde, 2020)

Pipeline

Transporting hydrogen through pipelines provides an efficient means to move large volumes of GH2 across medium distances (ENTOG et al., 2021; European Commission, 2021). GAE may benefit from integration with the Netherlands' planned hydrogen backbone. Led by Gasunie, this national infrastructure project aims to establish a network of hydrogen pipelines by repurposing existing natural gas lines and adding new, hydrogen-specific infrastructure.

The backbone will connect key industrial clusters, storage facilities, ports, and international borders, supporting large-scale hydrogen transportation and distribution. The initial phase, projected for completion by 2035, will focus on supplying industries with substantial hydrogen needs, around 10 tons per hour. A subsequent expansion phase will connect additional high-demand users (consuming over 100 kg per hour) based on their demand and strategic location. With GAE's hydrogen consumption expected to exceed 100 kg per hour between 2035 and 2040, the airport could be well-positioned for connection in this second phase, efficiently supporting its hydrogen supply needs as demand grows.

Hydrogen can be transported as pure gas at varying pressures or blended with natural gas with different blend ratios and pressure levels. While it's theoretically possible to move LH2 through pipelines, industry consensus discourages this due to significant safety concerns, particularly surrounding the risks associated with cryogenic temperatures and containment.

One of the promising options is leveraging the existing natural gas infrastructure by blending hydrogen into natural gas pipelines. This blend could then be deblended at specific points for high-purity hydrogen applications. However, although substantial research has focused on deblending, it remains a challenging and likely inefficient method for large-scale users who require pure hydrogen. Additionally, high-pressure natural gas transmission pipelines, typically made of steel, are vulnerable to hydrogen embrittlement, which increases the risk of leaks. However, the natural gas distribution networks have largely been upgraded from cast iron to polyethylene (PE), which is more compatible with hydrogen, making distribution networks closer to hydrogen-ready.

Safety measures may also be required, such as odorizing the hydrogen gas for leak detection. However, certain odorants, like sulfur compounds, would need removal before use in sensitive applications such as hydrogen fuel cells, where contaminants can degrade performance. Additionally, even new pipelines could introduce minor impurities, necessitating purification steps at delivery points for high-purity applications, adding complexity and cost to the overall supply chain. While technically feasible, implementing hydrogen transport through pipelines demands careful consideration of material compatibility, blending and deblending capabilities, and safety protocols to ensure it meets industry needs effectively.

Safety Standards

Main contributions: AirportCreators and RWE

The integration of hydrogen as an aviation fuel demands strict adherence to safety standards to address the unique risks associated with its storage, transportation, and handling. Hydrogen's properties, such as its flammability, small molecular size, and high pressures, require specialized regulations to ensure safe operations both during road transport to airports and within airport premises. This section explores the key safety standards relevant to hydrogen transportation and airport infrastructure, highlighting their critical role in supporting a safe and efficient hydrogen supply chain.

Road Transportation

The safe transportation of hydrogen requires adherence to various industry safety standards, which provide crucial guidelines for the design, operation, and maintenance of infrastructure and equipment involved in the hydrogen supply chain. Several essential standards apply to hydrogen transport, ensuring safe and efficient operations (Hydrogen Transport Economy for the North Sea Region, 2020).

ADR and ADR 2019: The European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) governs the safe transportation of dangerous goods, including hydrogen, by road. It provides comprehensive safety standards for classifying, packaging, and labeling hazardous materials. Specifically, hydrogen is classified as a dangerous good, and the ADR outlines detailed requirements for vehicles, storage conditions, and labeling to ensure safe transport. Furthermore, the ADR imposes restrictions on transportation routes for hydrogen, specifying that only specific maximum quantities may be transported through tunnels. Otherwise, additional tunnel restrictions apply. The ADR 2019 update includes enhanced provisions for transporting gases, such as hydrogen, under pressure, ensuring that vehicles and containers are appropriately equipped to handle the risks of transporting hydrogen.

PED and TPED: The Pressure Equipment Directive (PED) and the Transportable Pressure Equipment Directive (TPED) regulate the design, manufacture, and conformity assessment of pressure equipment used in hydrogen transport. The PED ensures that pressure vessels, such as those used for storing hydrogen on road tankers, meet strict safety and performance standards. It covers pressure equipment design, testing, and operation to prevent failures or accidents. The TPED specifically addresses the requirements for transportable pressure equipment, ensuring that hydrogen is transported in compliance with safety standards for containers, trailers, and cylinders that store the gas under high pressure.

TDG: The Transport of Dangerous Goods (TDG) Directive 2008/68/EC regulates the inland transport of dangerous goods within the European Union. This directive provides a framework for safely handling and transporting hazardous materials, including hydrogen. It ensures that hydrogen is transported safely and controlled, outlining safety provisions for vehicles, containers, and storage facilities and the labeling and documentation required for transport. The TDG is closely aligned with ADR but covers broader logistical aspects, such as route planning and emergency procedures.

CLP: The Harmonized European Standards No 1272/2008 on classification, labeling, and packaging (CLP) ensures that hydrogen is correctly classified as a hazardous substance and that appropriate safety measures are in place during transport. This regulation mandates the correct labeling of hydrogen containers, ensuring transport personnel are aware of the risks and equipped to respond to potential hazards. The CLP regulation also dictates the requirements for packaging and labeling hydrogen for transport, providing consistency across the EU in how hazardous materials, including hydrogen, are managed and communicated.

Together, these regulations form a comprehensive safety framework for hydrogen transportation, addressing the technical and operational safety requirements of vehicles, containers, and personnel involved in the supply chain. They ensure that hydrogen is transported in a manner that minimizes risks, meets industry standards, and complies with European safety protocols.

Within the Airport Premises

Establishing and operating hydrogen infrastructure at an airport requires adherence to specific safety regulations designed to mitigate risks associated with the storage, production, transfer, and handling of GH2 and LH2. The regulations encompass equipment standards, risk assessments, fire protection, and explosion prevention protocols to ensure safe operations across the hydrogen infrastructure, which includes storage areas, unloading/loading zones, and hydrogen production and liquefaction facilities.

PGS35: The PGS35 guideline provides specific safety requirements for the safe storage, handling, and use of hydrogen within designated infrastructure, such as production and storage facilities. This standard emphasizes the spatial separation of storage areas, ventilation requirements, and material compatibility, ensuring that hydrogen facilities are equipped to prevent leaks and minimize ignition risks. PGS35 also sets forth protocols for regular inspections and maintenance to support the long-term safety of hydrogen installations.

ISO 19880: ISO 19880 outlines essential safety and performance criteria for hydrogen fueling stations, which directly apply to loading and unloading zones at the airport where hydrogen transfers occur. This standard covers fueling system design, construction, and operational safety requirements, ensuring that infrastructure can support reliable hydrogen dispensing with minimized risk. It also addresses pressure control and emergency response protocols, facilitating safe handling during high-frequency operations.

PED WBDA 2016: The Pressure Equipment Directive (PED WBDA 2016) establishes safety standards for pressurized equipment involved in hydrogen infrastructure. This directive mandates that all pressure vessels, piping, and components used in hydrogen production and storage are engineered to prevent leaks and withstand high pressures without compromising structural integrity. Compliance with PED WBDA 2016 includes rigorous testing and certification, confirming that pressure equipment used for hydrogen meets EU safety and quality standards.

NPR 7910: The Dutch NPR 7910 standard focuses on risk assessment for hazardous installations and is particularly relevant for hydrogen infrastructure. It requires a thorough evaluation of risks associated with hydrogen production, storage, and transfer processes, facilitating the development of tailored safety measures. This standard guides operators in identifying potential failure points, evaluating explosion risks, and establishing mitigation strategies to ensure that any hazards are effectively managed within the airport environment.

NFPA 2 – Hydrogen Installations: NFPA 2 provides comprehensive requirements for the safe installation and operation of hydrogen infrastructure, covering fire protection and explosion control measures. It specifies fire suppression systems, minimum safe distances, and ventilation requirements for areas where hydrogen is stored or handled. NFPA 2 also mandates regular maintenance and inspection schedules to prevent accidental ignition, ensuring that hydrogen installations at the airport operate safely under all conditions.

ATEX 2014/34: The ATEX 2014/34 directive governs equipment used in explosive atmospheres, which is critical for hydrogen facilities where leak risks exist. ATEX requires that all equipment in areas where hydrogen is stored, produced, or transferred be rated for explosive environments to minimize the chance of ignition. Compliance with ATEX involves using explosion-proof equipment and appropriate material choices for safely handling hydrogen in environments where a flammable atmosphere may develop.

These safety requirements are fundamental to ensuring that hydrogen infrastructure at the airport is built, maintained, and operated to the highest safety standards, protecting both personnel and the surrounding environment. However, these regulations also impose specific constraints on the design, construction, and choice of equipment for hydrogen infrastructure, which can limit flexibility in terms of layout and technology options. While essential for minimizing risk, these constraints require careful planning and often necessitate additional investment, impacting both the feasibility and scalability of hydrogen infrastructure development at the airport.

Infrastructural Needs at GAE

Main contributions: AirportCreators, RWE and Shell

When evaluating the infrastructural requirements for importing hydrogen to GAE, it is crucial to consider the various hydrogen delivery methods, illustrated in Figure 15. The type of infrastructure needed will vary significantly depending on the transportation mode chosen for hydrogen importation. Two primary transportation scenarios are available:

hydrogen delivered via truck or hydrogen transported through a dedicated pipeline connection. Each scenario necessitates certain infrastructure to ensure safe, efficient, and reliable hydrogen delivery, storage, and distribution across the airport's facilities.

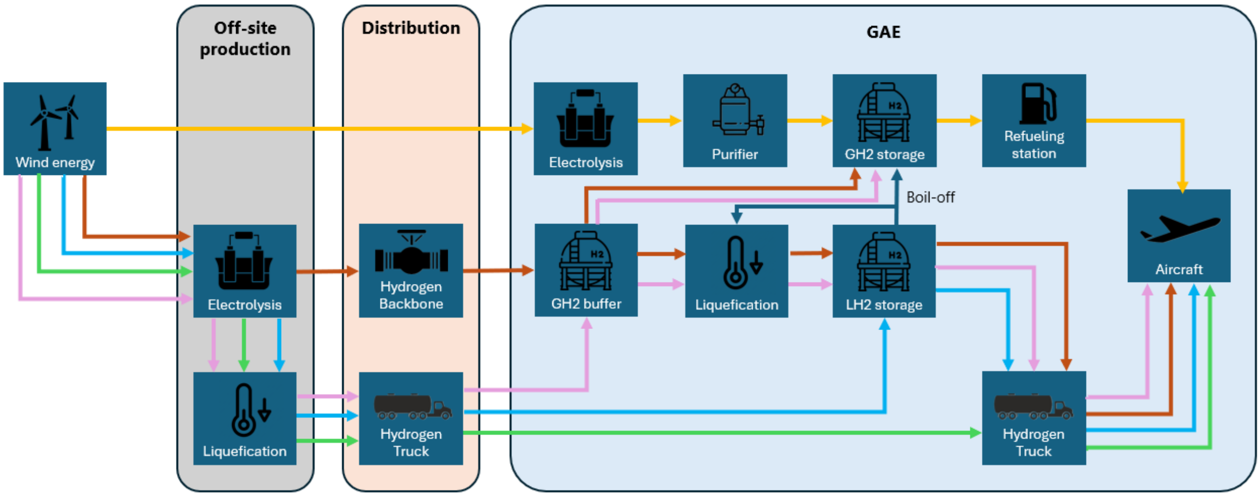

Figure 13: Schematic representation of hydrogen procurement at GAE.

Orange:	*Tier 1 onsite production*
Dark red:	*Hydrogen delivery by pipeline*
Blue:	*Liquid hydrogen delivery by truck, with permanent storage*
Green:	*Hydrogen transport by truck, temporary storage in truck*
Pink:	*Gaseous hydrogen delivery by truck, with permanent storage*

Roadside Import

When LH2 is delivered to the airport by truck, there are two primary scenarios for handling the fuel upon arrival: storing it in a dedicated storage facility (blue path) or keeping it in the trucks (green path). The choice of storage method has a direct impact on the infrastructure requirements.

The infrastructure needed is minimal if the hydrogen is stored directly in the trucks. In this case, only parking spaces are required where the trucks or bowsers can be safely parked (for extended periods). These parking areas must adhere to safety regulations, including proper spacing as outlined in PGS35, to ensure safe operation and minimize risk. Additionally, to ensure that the hydrogen quality meets the required standards, the hydrogen depot may need to be equipped with facilities for quality checks and testing. Moreover, the trucks must comply with temporary/permanent storage regulations, including venting requirements and provisions for regular maintenance and inspection.

In the second scenario, where LH2 is stored in a dedicated facility on-site, the infrastructure needs are more extensive. A designated unloading and loading bay is essential to facilitate the safe transfer of LH2 from the trucks to the storage tanks. The design of this bay should allow for smooth operation, accommodate the incoming trucks, and enable bowsers to refill as needed. The size and layout of these facilities will depend on factors such as the volume of hydrogen required, delivery frequency, and daily hydrogen flow. The unloading and loading areas should also include safety features like spill containment, emergency shutdown systems, and proper ventilation. Along with the storage tanks, the infrastructure may include integrated systems for quality checks, pressure monitoring, and temperature controls to ensure the hydrogen remains within specified safety and quality standards.

Pipeline Import

If hydrogen is delivered to the airport via pipeline (brown path), it will typically arrive in gaseous form. The hydrogen will enter the airport through a dedicated receiving station, which serves as the point of connection between the hydrogen pipeline (backbone) and the airport's infrastructure. This receiving station functions similarly to a gas receiving station, where the hydrogen is carefully controlled as it enters the site. The receiving station must be equipped with appropriate safety features, such as pressure regulation, flow measurement, and leak detection systems, to ensure secure and efficient operation.

Once the hydrogen has been received, it will undergo further processing based on its intended use. If the hydrogen is to be used in its gaseous state, it will typically undergo purification to meet the necessary quality standards for specific applications. Alternatively, additional infrastructure is required to liquefy the hydrogen if the hydrogen is intended for use in its liquid state.

The infrastructure required to support pipeline-delivered hydrogen at the airport should also include safety systems to manage the high-pressure gas, including emergency shut-off valves, pressure relief systems, and adequate ventilation to prevent the accumulation of hydrogen in confined spaces. Additionally, a robust monitoring and control system is essential to ensure the continuous operation of the pipeline and to detect any leaks or anomalies in the hydrogen supply chain.

Cost

Main contributions: AirportCreators

The various hydrogen transport options differ significantly in capital expenditure (CAPEX) and operational expenditure (OPEX). A hydrogen pipeline has a higher initial CAPEX than trucking but benefits from lower OPEX in the long term. Excluding CAPEX, transporting GH2 via a pipeline over 50 km costs approximately €0.12/kg (ANZ, 2024). In comparison, transporting a kg of GH2 in a truck costs around €0.64/kg per 50 km, while LH2 trucking costs €3.63/kg per 50 km (ANZ, 2024). Table 5 provides further details on the unit cost for single truck operations for both GH2 and LH2.

GAE has two main import options: the Eemshaven in Groningen, 50 km by road, or the Port of Rotterdam, 273 km by road. Transporting GH2 from Eemshaven to GAE by a GH2 truck costs €0.64/kg for each kg in the truck, whereas pipeline transport would cost €0.12/kg for the same distance. Transporting from the Port of Rotterdam raises the cost to €3.49/kg by a GH2 truck and €0.66/kg via pipeline.

For a direct comparison between GH2 and LH2 transport, liquefying GH2 is assumed to require 12.5 kWh/kg, with renewable energy priced at €0.083/kWh (ACI, 2021; Hunt et al., 2023; Trinomics, 2020; U.S. Department of Energy, 2008). This adds approximately €1.04/kg in energy costs alone. Including this liquefaction energy cost, the total cost of importing from Eemshaven would be €1.16/kg via pipeline, €1.68/kg in a GH2 truck, and €3.63/kg in a LH2 truck. Importing from Rotterdam would cost €1.69/kg via pipeline, €4.53/kg in a GH2 truck, and €19.82/kg in a LH2 truck.

OPEX comparisons should also account for the difference in capacity between GH2 and LH2 trucks: LH2 trucks carry 5-12 times more hydrogen than GH2 trucks (ANZ, 2024). As a result, LH2 trucking becomes more cost-effective for distances over 350 km due to reduced truck fleet requirements, highlighting a tipping point where LH2 transportation becomes favorable.

	Truck Cost (€)	**Capacity**	**OPEX (per 50 km)**
CGH2 truck	~€585,600	700 kg/H2	0.64 €/kg
LH2 truck	~€847,900	4,400 kg/H2	3.63 €/kg

Table 5: CAPEX and OPEX for Truck Import (ANZ, 2024).

6.2 Hydrogen Supply to the End-User

Main contributions: AirportCreators and NLR

Two primary methods are possible to provide the end user with GH2 or LH2. The first option uses H2 bowsers (refueling trucks), and the second one uses an H2 pipeline and hydrant system. Both methods can be applied to LH2 and GH2 (ATI, 2022) but the designs will differ depending on whether they are used for LH2 (low temperature) or GH2 (high pressure). However, the hydrant system cannot switch between LH2 and GH2. Each system's suitability depends on factors such as airport size, technological advancements, and the maturity of the hydrogen refueling infrastructure. The advantages and disadvantages of the bowsers and hydrant system are summarized in Figure 16.

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

Figure 14: Advantages and Disadvantages Bowser vs. Pipeline (ACI, 2021)

Hydrogen refueling infrastructure at airports faces different regulatory requirements for hydrant systems and bowsers. Hydrant systems require extensive permitting, regular safety assessments, and adherence to environmental and safety regulations such as the SEVESO Directive, NFPA 2, and PGS35 due to their permanent underground infrastructure (for safety requirements, see WP 3+4). Emergency response plans and local authority approvals are also necessary. In contrast, bowsers, being mobile fuel carriers, must comply with transport safety regulations like the ADR for hazardous materials and ATEX standards to prevent combustion risks. They require frequent inspections, explosion-proof systems, safety labeling, and emergency shutdown features as per CLP standards. However, if hydrogen-filled bowsers are parked for extended periods, they are considered permanent storage and face additional safety regulations similar to fixed storage tanks used in hydrant systems.

Figure 17 shows a high-level indication of which system is most advantageous for different airport sizes over time. Since GAE is categorized as a small airport, defined as handling approximately 7.5 million passengers by 2035 and 10 million by 2050, bowsers are considered the most appropriate option for delivering hydrogen to aircraft in both the near and far future (ATI, 2022; FCH, 2020; Hoelzen, Flohr, et al., 2022). This is in line with the airport's current delivery model for kerosene.

Airport Size	2035	2040	2045	2050
Large	Bowser	Consider Hydrant	Hydrant	Hydrant
Medium	Bowser	Bowser	Consider Hydrant	Hydrant
Small	Bowser	Bowser	Bowser	Bowser

Figure 15: Time Scale for the Introduction of Hydrogen Hydrant Refueling System (ATI, 2022)

Bowsers present several advantages for small-scale airports like GAE. Because of the low demand, especially in the early stages, the operational cost of using a bowser is expected to be lower than that of the hydrant system. Furthermore, bowsers provide operational flexibility as they can move between aircraft as needed, making them highly suitable for smaller airports or those with diverse aircraft types and varying refueling requirements. Finally, GAE anticipates supporting both LH2 and GH2 flights. Utilizing bowsers offers greater operational flexibility, making managing refueling operations for both fuel types easier. However, it is important to note that due to the lower density of LH2 compared to conventional kerosene, approximately two to four times more bowsers are required to deliver the same amount of fuel (ACI, 2021; FCH, 2020).

ZeroAvia, a British/American hydrogen-electric developer, is currently developing an LH2 bowser with a capacity of 10,000 liters (709 kg), with a design projected launch in May 2024 (May, 2024). This innovation aims to reduce hydrogen refueling times for hydrogen-powered aircraft to match the quick turnarounds of traditional Jet A-1 fuel refueling. Success in this endeavor would significantly streamline airport operations by reducing the number of required bowsers to achieve parity with current kerosene refueling rates. However, the 709 kg capacity would still require over three bowsers to fully refuel an aircraft like the Fokker NextGen. While larger LH2 trailers have capacities of up to 4 tons, they are not certified for airport operations. Thus, a combined approach of optimizing both refueling speed and bowser capacity is essential to meet operational demands and match the turnaround efficiency of conventional refueling. It is likely that the development of bowsers to meet these requirements will correlate with the increasing adoption of hydrogen-based flight.

7 | Required Hydrogen Infrastructure

Main contributions: AirportCreators and NLR

Based on the findings in Chapters 5 and 6, the key requirements for the hydrogen infrastructure at GAE have been identified. This chapter provides a descriptive specification of the system that needs to be developed and implemented per tier.

7.1 Tier 1

A comprehensive infrastructure system is essential to support hydrogen needs at the airport, addressing production, storage, and refueling, as shown in Figure 18. This setup includes a dedicated hydrogen production unit that utilizes renewable electricity, ensuring a sustainable and continuous hydrogen supply. Operating this unit will require significant energy input of around 55.8 kWh/kg H2. If necessary, a purification system is installed to ensure that hydrogen reaches the required purity levels for safe and efficient operational use. Depending on the purification method used, the energy requirement for the purification can range from 2.37 to 7.95 kWh/kg GH2.

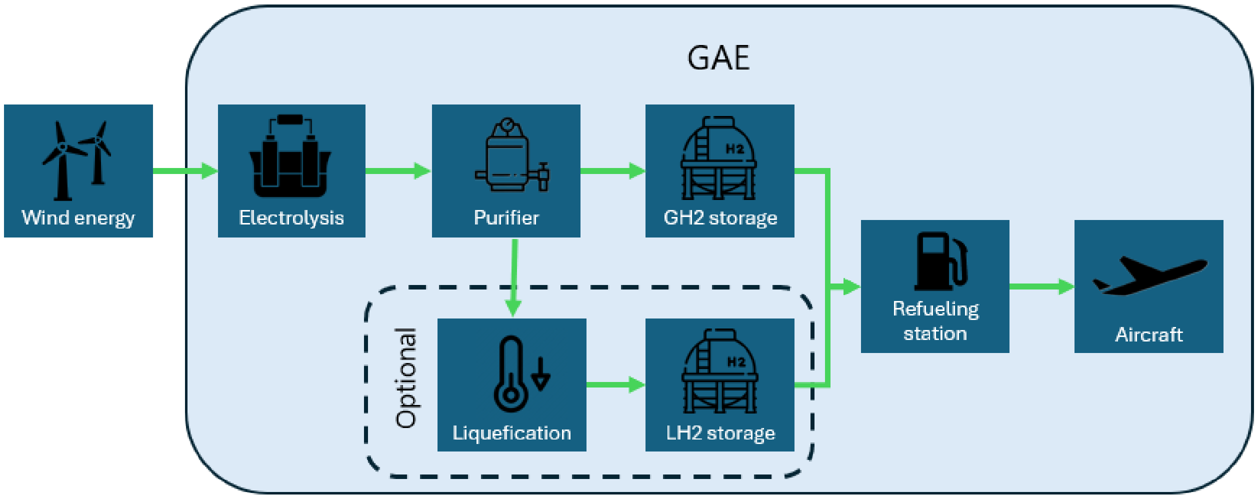

Figure 16: Schematic Representation of the Hydrogen Production system at GAE in Tier 1.

Two refueling stations are necessary to serve different sectors within the airport. One station, located airside, will be a fixed fuel station and supplies hydrogen for aircraft and ground support equipment, operating at 350 and 700 bars to match equipment specifications. The second station, positioned landside, serves hydrogen-powered vehicles, offering both lower- and higher-pressure refueling options. Each refueling station demands electricity to compress hydrogen, with consumption varying by pressure level. The energy consumption for compressing 1 kg of GH2 from 20 bar to 350 is 1.05 kWh/kg GH2, to 700 bar 1.36 kWh/kg GH2, and to 1,000 bar 2.6 kWh/kg GH2 (Knop, 2022; United States Department of Energy, 2009).

A liquefaction unit can also be installed to meet initial LH2 demand, with scalability options to accommodate future increases. This unit is energy-intensive, consuming between 10 and 13 kWh/kg LH_2 due to the cryogenic cooling facility (ACI, 2021; Hunt et al., 2023; United States Department of Energy, 2008). Hydrogen storage will be established for both gaseous and liquid forms, with GH2 storage divided into compartments at 30 bar, 250 bar, and 900 bar. The different pressure levels for GH2 storage will require additional energy for compression. LH2 storage may also involve added energy use if an active cooling system is employed to minimize boil-off losses. There will also be an import facility with the appropriate number of trailer connections for trailers to connect to the system. Finally, parking bays will be designated for bowsers and/or hydrogen trailers.

Initial operations are planned to produce 430 kg of hydrogen daily, with 100 kg of this amount to be liquefied daily. All produced hydrogen is assumed to require purification to meet operational standards. This setup will result in the following estimated energy consumption:

- **GH_2 Production**: ~24,000 kWh
- **GH_2 Purification**: 1,000–3,500 kWh
- **Compression for GH_2 Storage and Refueling (assuming a 50/50 distribution between 350 and 700 bar)**: ~500 kWh
- **LH_2 Liquefaction (optional)**: 1,000–1,300 kWh

This results in a total daily energy requirement of approximately 26.5 to 29.3 MWh, including liquefaction. Renewable offshore wind energy is the most likely supply source for GAE, currently priced at 83 €/MWh (Trinomics, 2020). With increased offshore wind farms and advancing technology, this cost is projected to decrease to approximately 41 €/MWh by 2040 (Ueckerdt et al., 2024). Assuming an average daily consumption of 27.9 MWh, the current daily energy cost would be €2,316, dropping to €1,144 by 2040, including the liquefaction of 100 kg of GH2. Excluding liquefaction, the average energy requirement would decrease to 26.75 MWh per day, resulting in a daily cost of €2,220 at current rates, reducing to €1,097 in 2040. Given a production rate of 430 kg of GH2 per day, the average energy cost per kilogram of GH2 is approximately €5.16, closely aligning with the current industry average of 5 $/kg GH2 for renewable hydrogen production (United States Department of Energy, n.d.a). It is noted that US prices may vary significantly from EU prices.

7.2 Tiers 2 and 3

In Tier 2, the introduction of larger LH2 aircraft will require a new type of fuel supply and a change in operational strategy. The most optimal strategy for Tier 2 and 3 depends on many factors, such as how hydrogen is imported at the airport, quantities, and technological advancements. The transition points between Tier 1 and Tier 2 will be due to the introduction of LH2 airliner aircraft in 2035. Because the required infrastructure for Tier 2 and 3 depends on the infrastructure decision in Tier 1, additional detailed system calculations, and large uncertainties, no definitive infrastructure can be established for these tiers. The different options for the required infrastructure and the distribution method used are illustrated in Figure 19, where the orange pathway represents the infrastructure from Tier 1.

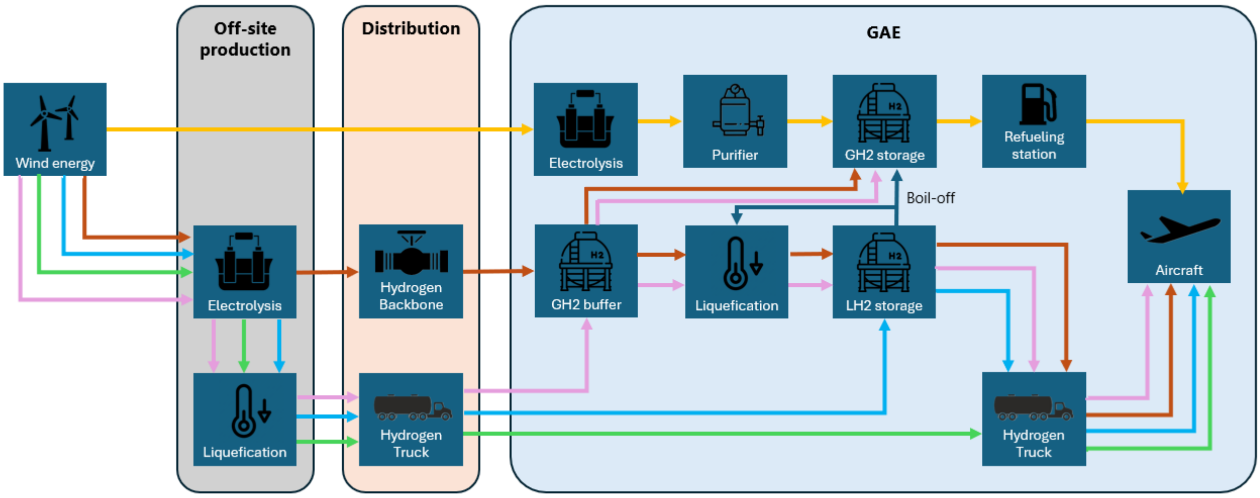

Figure 17: Schematic Representation of Different Infrastructure Requirements and Delivery Methods at GAE.

Orange: *Tier 1 onsite production*
Dark red: *Hydrogen delivery by pipeline*
Blue: *Liquid hydrogen delivery by truck, with permanent storage*
Green: *Hydrogen transport by truck, temporary storage in truck*
Pink: *Gaseous hydrogen delivery by truck, with permanent storage*

Hydrogen Import by Pipeline

The dark red pathway in Figure 19 represents hydrogen delivery by pipeline. An assessment of the Off-site supply chain is presented in Chapters 5 and 6.

Upon connection to the hydrogen backbone, GAE will receive hydrogen in gaseous form. To support continuous operations, a buffer storage system should be established downstream of the backbone connection to the GAE hydrogen infrastructure. This incoming GH2, supplemented by production from the existing Tier 1 electrolyzer, will need purification, which can be managed by either upgrading the existing purifier or installing a new one.

Most of the GH2 will be liquefied, requiring a large-scale liquefaction system capable of processing approximately 60 tons per day to meet demand. A tank with a 110-ton capacity (about 1,600 m^3) is recommended for storage. This ensures a one-day 90% operational buffer and accounts for a 0.1% boil-off rate, 8% loading/unloading losses, and three transfer points. A boil-off recovery system should also be installed to capture evaporated hydrogen, which can either be returned to GH2 storage or re-liquefied to reduce waste.

A loading area for LH2 bowsers will be connected to the LH2 storage for refueling. If customers' needs indicate demand for GH2 refueling in the future, a separate GH2 loading area for loading GH2 bowsers should be considered in addition to fixed refueling stations. The number of loading bays will depend on the anticipated number of simultaneous bowser refueling operations and the refill time, with current estimates at approximately one hour to fill a 4-ton LH2 trailer.

Hydrogen Imports by Truck

The second option for hydrogen delivery to the airport is by truck, which can be transported either in gaseous or liquid form. An assessment of the off-site supply chain is presented in Chapters 5 and 6.

Gaseous Hydrogen Delivery

Initially, GH2 transport is feasible during the early stages of Tier 2 when demand remains manageable at around four truckloads per day. The gaseous import by truck is depicted in pink in Figure 19. However, as hydrogen demand grows, the increasing number of GH2 truckloads required would make this method inefficient, prompting a transition to pipeline delivery.

The infrastructure requirements for both truck and pipeline delivery are largely similar, as both require components such as a liquefier, purification, LH2 storage (that needs to function as a buffer and for continuous operations), and a bowser loading area. For truck delivery, however, an unloading area replaces the pipeline connection, and GH2 trailers can serve as a temporary buffer, reducing the need for expanded GH2 storage on-site. The LH2 boil-off can be captured and either reused for liquefication or stored in the GH2 storage. Once the limitations of truck delivery are reached, the system can be smoothly upgraded to pipeline operations, aligning with the increased infrastructure capacity needed at higher demand levels.

Liquid Hydrogen Delivery

For Tier 2 and Tier 3, importing LH2 by truck offers a practical solution. Two options are available to create the required one-day fuel buffer. Initially, using the trucks as temporary storage could suffice, especially during Tier 2 and early Tier 3 operations, depicted by the green pathway in Figure 19. However, this option is only possible if the 4-ton LH2 trucks are modified and certified for aircraft fueling operations. In 2040, maintaining a one-day buffer would require around 3.2 trucks parked at the airport, a manageable number (not considering boil-off loss). However, by 2050, this buffer requirement would rise to approximately 11.5 trucks. From a safety and logistical standpoint, there is a tipping point between 2040 and 2050 where using the trucks is no longer viable. Therefore, while using trailers as storage is viable in early Tier 3, a transition to permanent storage should be planned as demand grows, depicted by the light blue pathway in Figure 19.

Though installing a permanent LH2 storage unit at the beginning of Tier 2 is an option, if designed for 2050 capacity, it may lead to underutilization, resulting in an oversized tank for several years. Alternatively, starting with trailers as a buffer and switching to permanent storage once demand surpasses a certain threshold could offer a more flexible, cost-effective approach. The timing of this switch would depend on several factors, including boil-off rates of LH2 in multiple trailers versus a single storage tank, hydrogen losses at loading and unloading points, and comparative operational (OPEX) and capital (CAPEX) costs. Additionally, regulatory and permitting requirements for long-term storage must be considered.

The infrastructure requirements remain relatively limited when trailers are used as buffer storage for hydrogen at GAE. A designated truck parking area and purity testing infrastructure will be needed primarily to ensure the hydrogen meets quality standards before use. The parking area must comply with safety and spacing requirements as outlined in WP3 and WP4 to minimize risks.

If GAE transitions to permanent storage, the capacity should be sufficient to meet one day of hydrogen demand plus a one-day buffer, requiring a tank size of approximately 110 tons (1,600 m^3 when assuming 0,1% boil off, buffer consisting of 90% of expected daily operations demand, and 8% load/unload loss and three touch points). Supporting infrastructure for this permanent setup would include a dedicated unloading area where trucks can safely transfer their LH2 into the storage system and a loading area where bowsers can refill for distribution. Additionally, sufficient parking for trucks and bowsers should be factored into the design to ensure smooth operations and accommodate traffic flow around the refueling areas.

Using permanent storage simplifies boil-off gas recovery, but it may also be feasible with trailers serving as temporary storage. Despite the hydrogen arriving in liquid form, GH2 demand will persist for both aviation and non-aviation use. The boil-off gas from stored LH2 can be captured and directed to GH2 storage established in Tier 1, supplementing the GH2 produced by the on-site electrolyzer. This integrated approach can help meet GH2 demand while maximizing efficiency by reusing boil-off hydrogen rather than letting it dissipate.

GAE can switch from importing via LH2 truck to gaseous pipeline operations once the opportunity arises to do so and once it is financially advantageous. This trigger point is currently difficult to estimate in terms of time, volume and cost. Much of the infrastructure used for trucking operations, such as storage facilities and bowser loading areas, can also support pipeline operations. However, additional investments for elements like a liquefier, expanded GH2 storage, and other supporting infrastructure will be required.

7.3 CAPEX Hydrogen Infrastructure

Main contributions: AirportCreators

To establish the required Tier 1 hydrogen infrastructure, a budget of approximately €7.2 million is estimated. This figure is based on a similar project (HYPORT) in Toulouse, France, which provides a reliable benchmark given its comparable scale and specifications. Nevertheless, inflation and other factors must be considered in later stages when cost estimates are further elaborated upon.

For Tier 2 and Tier 3 infrastructure, only an approximate investment range can be calculated. According to projections by the Aerospace Technology Institute (ATI, 2022), a small airport with anticipated hydrogen consumption levels of around 7 tons per day in 2035 and 50 tons per day in 2050 would need a total investment of about €26 million (+/- €13 million) to support LH2 flight operations up to 2050. The variation is based on the complexities, uncertainties, and risk involved in building new infrastructure at an airport. This estimate includes LH2 delivery by truck and a 35 and 177-ton storage tank as a two-day buffer. Although the storage tank in this scenario is larger than anticipated for GAE (which assumes only a one-day buffer), the daily LH2 consumption figures—5.2 tons in 2035 and 58 tons by 2050—align closely, providing a reliable preliminary estimate for the initial investment. If GAE opts for a pipeline connection to the hydrogen backbone and the on-site liquefaction of GH2, the investment would increase to around €33 million, with a potential deviation of +/- €13 million.

Airport size	**LH2 delivered to the airport**		**GH2 pipeline supply to the airport**	
	Median cost (m €)	+/-	Median cost (m €)	+/-
Large	430	298	827	662
Medium	132	79	265	199
Small	26	13	33	33

Table 6: CAPEX estimate assuming bowser operations (ATI, 2022)

8 | Spatial Considerations for Hydrogen Infrastructure

Main contributions: AirportCreators and Groningen Airport Eelde

Strategic considerations for size and location are essential to ensure the infrastructure is safe, efficient, and scalable while integrating seamlessly with the airport's broader master plan. The design must accommodate current operational requirements and anticipate future expansion, particularly as demand for hydrogen grows significantly.

This chapter explores the foundational aspects of hydrogen infrastructure at GAE, focusing on the spatial requirements for various phases of development and the careful selection of locations to comply with strict safety regulations. It highlights the interplay between operational efficiency, safety considerations, and scalability, addressing the unique challenges of integrating hydrogen into an airport environment. This chapter lays the groundwork for a sustainable and practical approach to hydrogen infrastructure development at GAE by analyzing the immediate and long-term needs.

8.1 Size

The strategic placement of hydrogen infrastructure at the airport is crucial for enabling safe, efficient, and scalable operations while aligning with GAE's overall master plan. The location of hydrogen facilities must minimize operational disruptions, support future scalability, and adhere to stringent safety standards. Key considerations include proximity to airside and landside operations to facilitate seamless access for aircraft and ground support equipment, compliance with safety regulations for refueling and storage in high-traffic areas, adequate distance from public buildings to mitigate potential risks, and a layout supporting future expansion.

The footprint for the Tier 1 hydrogen installation is estimated at approximately 2,600 m^2, including a fixed fueling station on the airside (860 m^2), a landside fueling station (950 m^2), and the main hydrogen installation itself (around 790 m^2). A slightly larger area—roughly an additional 100 m^2—may be necessary if GH2 storage capacity is doubled. Based on the reference installation in Toulouse (H2 HYPORT), the height of the installation is estimated to be around 4 m.

If LH2 is imported directly, operations will likely begin with parked trucks. These trucks are approximately 20 meters in length and 2.6 meters in width. According to the European Industrial Gases Association (EIGA, 2019) Code of Practice, a minimum safety distance of 3 meters is recommended between LH2 tankers. This requirement results in a footprint of roughly 129 m^2 per trailer and additional space for supporting infrastructure. When a fixed storage is included in Tier 3, the footprint required expands considerably due to the need for a large storage tank of around 110 tons (1,600 m^3). This scenario would require an additional 6,500 m^2, covering the storage area as well as loading and unloading zones for up to 13 daily truckloads of LH2 (Aerospace Technology Institute [ATI], 2022), bringing the total area for Tier 1 and this expansion to around 9,100 m^2.

If hydrogen is instead imported in gaseous form, the need for a liquefaction plant would increase the infrastructure footprint by approximately 4,000 m^2 (ATI, 2022). This results in a total estimated area of 10,000 m^2 for the second-phase expansion and approximately 12,600 m^2 for the entire Tier 1 installation and expansion combined, assuming pipeline operations.

8.2 Location

The primary factor to consider when selecting the location for hydrogen infrastructure is ensuring safe distances from other structures and areas due to strict regulations for explosive materials like hydrogen. The placement guidelines are based on the Code of Practice by the European Industrial Gases Association (2019), which, while primarily for LH2 storage, imposes more stringent safety distances than the PGS35 standards. According to EIGA's guidelines, there must be a minimum of 20 meters between any occupied building and the hydrogen storage tank and at least 10 meters between the storage tank and any road (EIGA, 2019). It should be noted that the proposed locations in this section for the hydrogen installation do not yet incorporate a safety assessment or input from the safety region or other relevant entities. These considerations must be addressed in subsequent planning phases to ensure compliance with safety regulations and alignment with stakeholder requirements.

In Figure 20, the runway strip is marked in blue, and the safety zone for the taxiway incorporates the clearance requirements of a Code E-aircraft, including a 10-meter separation per EIGA's guidelines. Considering GAE's land use plan and future developments, the red-marked area in Figure 20 is identified as a suitable location, balancing safety, operational efficiency, and accessibility. This area is adjacent to the existing kerosene fuel depot, slightly farther from the commercial aircraft stands, and close to the business aviation apron, reducing additional travel time for bowsers or small aircraft refueling at the fixed refueling station. Additionally, this location enables easy access for both airside operations and landside refueling, with only about 90 meters to parking area P3 and approximately 165 meters to the nearest public road. This minimizes the required piping to the landside refueling station, shown in green in Figure 20.

The designated area, as marked, covers approximately 7,000 m²—sufficient for Tier 1 requirements. However, height restrictions from applicable Obstacle Limitation Surfaces and ATC tower sightlines will apply. However, with an estimated height of 4 meters, these restrictions are unlikely to pose a significant limitation. The hydrogen infrastructure in Tier 3 will eventually require a space between 9,100 and 12,600 m². This will require the expansion of facilities elsewhere.

A more secluded and spacious location for the hydrogen infrastructure is indicated in pink. The proximity to the main access road is a clear benefit of this location; however, airside access is limited and will need to be improved by means of additional road infrastructure. Additionally, the travel distances to the main apron are significantly longer. This location is not hindered by height restrictions imposed by obstacle limitation surfaces or ATC tower sightlines.

Lastly, the green area is considered due to its proximity to the connecting infrastructure of the Solar Park. However, the practical use of this is potentially limited due to the fact that the energy supply by the airport solar park is not owned or controlled by GAE. Also, height restrictions are a concern in this location, especially since the new remote tower is placed in this area.

Figure 18: Initial Hydrogen Infrastructure Location (Red), Landside Refueling Station (Green), and Expansion Area (Orange). The star indicates the ATC tower.

9 | Safety Strategy

The regulatory framework for hydrogen-powered aircraft and associated ground-handling operations is still in the beginning stages (Hancock, 2023; ARUP, 2023), necessitating the development of comprehensive safety standards, certification processes, and operational guidelines. This effort requires close collaboration among industry stakeholders, international organizations, and government agencies to ensure harmonized and robust policies that address the unique challenges of hydrogen as an aviation fuel. Demonstrations of hydrogen operations involving all relevant stakeholders are critical to ensure that the resulting regulations are practical, effective, and applicable. Key considerations include safety protocols for fueling and storage, security measures to mitigate risks, and specialized training programs to equip personnel with the necessary skills for safe operations (Gu et al., 2023). The European Union Aviation Safety Agency (EASA) has outlined a timeline for developing these regulations, with the majority expected to be finalized between 2025 and 2030, reflecting the urgency and complexity of establishing a regulatory foundation for hydrogen-powered aviation.

9.1 Physical Properties of Hydrogen versus Jet A-1

Main contributors: AirportCreators (literature study)

When considering safety regulations for hydrogen in aviation, it is critical to account for its distinct physical and chemical properties compared to Jet A-1 fuel, as shown in Table 7. These differences influence ignition potential, storage requirements, and response strategies in case of leaks or spills.

	Jet A-1	**H2**
Boiling point (°C)	167–266	-252
Flammability limits (%)	0.6 to 4.7	4 to 75
Minimum ignition energy (mJ)	0.25	0.02
Burning velocity (cm/s)	18	265–325
Buoyancy	N/A	GH2: 14x lighter than air in gaseous form, rise at 20 m/s LH2: 55x heavier than air
Self-ignition Temp in air (°C)	210	585
Fire heat radiative fraction	30–40%	10–20%

Table 7: Properties comparison of Jet-1A and H2 (ATI, 2022; United States Department of Energy, n.d.b).

Flammability and ignition Energy

Hydrogen's flammability range (4–75%) is considerably broader than Jet A-1's (0.6–4.7%), enabling ignition under a wider variety of scenarios. Additionally, hydrogen requires significantly lower ignition energy—just one-tenth that of Jet A-1—making it highly susceptible to ignition from minimal sparks or static discharge. This necessitates eliminating ignition sources and meticulous attention to spark-free design around hydrogen infrastructure, particularly in environments where gas accumulation is possible.

Hydrogen flames pose a unique safety challenge because they are nearly invisible to the naked eye under normal daylight conditions. Unlike hydrocarbon flames, which produce soot and emit a bright yellow or orange glow, hydrogen burns with a pale blue flame that is often indistinguishable against a bright background. The near-invisibility of hydrogen flames increases the risk of accidental exposure, as personnel may not easily recognize the presence of a fire. Additional training for all personnel dealing with hydrogen operations is therefore recommended in preparation for the first hydrogen flight.

Buoyancy, Dispersion, and Vaporization

Hydrogen's buoyant nature (14 times lighter than air in its gaseous form) allows rapid dissipation in open environments, reducing the risk of prolonged accumulation of flammable gas. However, in its cryogenic liquid state (-252°C), hydrogen becomes denser than air, which can lead to the formation of low-lying flammable clouds in the event of a spill. These clouds can travel significant distances before dispersing, presenting localized fire and explosion hazards.

Hydrogen also vaporizes and burns much faster than Jet A-1, leading to shorter fire durations. For instance, a LH2 spill equivalent to 10 tons of fuel may burn completely in 10 seconds, compared to 2 minutes for Jet A-1. While shorter fire durations can reduce the time of exposure, the high heat release rate and rapid combustion of hydrogen necessitate swift response measures.

Fire Radiative Heat Flux

Hydrogen fires release only about 10% of their energy as thermal radiation, compared to 30–40% for Jet A-1 fires. This is because hydrogen combustion primarily produces water vapor, which absorbs much of the thermal radiation, whereas Jet A-1 fires emit radiation efficiently through soot particles. Consequently, hydrogen fires may pose a lower thermal radiation hazard to bystanders and structures under certain conditions. Studies have shown that hydrogen fireballs are shorter in height, smaller in diameter, and of shorter duration than Jet A-1 fireballs, potentially resulting in less severe heat doses to surrounding areas (Arthur D. Little Inc., 1982; Holborn, 2020). However, these conclusions depend on idealized conditions, and additional research is needed to understand how varying scenarios, such as un-ignited hydrogen spills during refueling, might influence risk.

Cryogenic Hazards (Liquid Hydrogen)

Unlike Jet A-1, which remains stable and manageable at temperatures above 160°C, LH2 must be stored at an extremely low temperature of -252°C to maintain its liquid state, introducing several unique hazards. Direct contact with uninsulated components such as pipes, tanks, or valves can result in severe frostbite or burns due to the extreme cold, necessitating advanced insulation materials and strict personnel safety protocols, including appropriate protective gear. Additionally, many conventional materials become brittle and lose their structural integrity when exposed to such low temperatures, requiring careful selection of materials designed to withstand cryogenic conditions without compromising safety. This challenge has been effectively addressed within the existing hydrogen industry. Even minor temperature increases can cause rapid evaporation of LH2, leading to significant pressure build-up within storage or transport vessels and increasing the risk of leaks or structural failures.

9.2 Safety Equipment

Main contributors: AirportCreators, Cranfield Aerospace Solutions

Hydrogen fuel operations require specialized safety equipment to protect personnel during routine and emergency situations. The unique properties of hydrogen, including its high flammability, cryogenic temperatures in liquid form, and potential for asphyxiation in confined spaces, necessitate careful planning and provision of appropriate protective gear (European Industrial Gases Association, n.d.; New Jersey Department of Health, 2016). The type of safety equipment required depends not only on whether GH2 or LH2 is being handled but also on the stage of the supply chain.

Handling LH2 generally involves more stringent safety requirements than GH2 due to its cryogenic properties and the greater potential for frostbite and material embrittlement. For example, personnel handling LH2 must wear cryogenic-resistant gloves and flame-resistant clothing to mitigate the risks associated with extremely low temperatures and flash fires. Safety goggles and face shields are also essential for protection against potential splashes of cryogenic liquid. In contrast, handling GH2 often requires less specialized equipment during certain supply chain stages. For example, individuals can refuel a GH2-powered vehicle, such as a hydrogen car, without needing additional safety equipment beyond the standard precautions outlined for public use.

However, some safety recommendations apply universally to both GH2 and LH2 operations. For instance, using anti-static footwear and properly grounded equipment is critical to prevent the accumulation of static electricity, which poses a significant ignition risk for both forms of hydrogen. Grounding is particularly important during operations that involve transferring hydrogen, such as fueling or loading processes, where the potential for static discharge is heightened. Grounding is a practice that is also currently applicable to kerosene operations.

In addition to these standard measures, emergency scenarios demand enhanced protective equipment and protocols to address the specific risks associated with hydrogen. Although inhaling small amounts of hydrogen is not harmful, longer exposure can lead to strokes or cardiac arrest (Shimouchi et al.,2013). Therefore, self-contained breathing apparatus (SCBA) is crucial in environments where hydrogen leaks may lead to oxygen displacement or the accumulation of potentially harmful gases. Thermal-insulating protective suits are necessary for managing cryogenic spills or exposure to extreme temperatures, while advanced detection systems, such as UV or infrared sensors, play a critical role in identifying hydrogen flames, which are nearly invisible under normal lighting conditions. Portable hydrogen detectors should also be deployed to alert personnel to leaks in their immediate surroundings. Furthermore, portable ventilation systems may be required to disperse hydrogen gas accumulations, and intrinsically safe communication devices ensure effective coordination without posing an ignition risk. Firefighting equipment, including fire blankets and suitable extinguishers, must be readily available to address secondary fires, even though extinguishing hydrogen flames themselves can be challenging

9.3 Fuel Safety Zone

Main contributors: AirportCreators (literature study)

One critical aspect of hydrogen safety is the establishment of appropriate safety distances to mitigate hazards associated with leaks, fires, or explosions. Separation distances are essential for preventing the accumulation of flammable gas near ignition sources and ensuring safe operation near equipment sensitive to hydrogen.

Gaseous Hydrogen

GH2 is already used in various industries and even as fuel for cars and trucks. This provides a solid foundation of safety practices and standards that can inform its adoption in the aviation sector. While the aviation industry has unique requirements, existing safety guidelines for GH2 offer a reliable starting point for ensuring safe operations.

Current standards for GH2 systems specify separation distances ranging from 5 to 8 meters for common installations, such as storage tanks, pipelines, and other operational areas, and outdoor exposures, such as open flames, buildings, and storage (European Industrial Gases Association [EIGA], 2021). A maximum separation distance of 15 meters is recommended to prevent hydrogen ingress into equipment like air compressors, ventilator intakes, or similar infrastructure. These distances, such as valves, flanges, or removable connections, are measured from points where hydrogen escapes may occur and are calculated in plan view. Safety distances must also consider the direction of potential hydrogen release, especially from vents or relief devices. Pipelines are assessed only at potential leakage points, such as connections or valves, rather than along their entire length. In situations where national codes or regulations specify greater distances, those precede EIGA guidelines.

Safety distances may be reduced by implementing fire-resistant barrier walls. The effectiveness of these walls in reducing distances depends on various factors, including the conditions at the hydrogen source, the nature of the exposure, and specific parameters such as pressure and pipe size. The placement of these barriers must also account for potential hazards such as jet flame impingement or the risk of fire spreading due to rebounding or deflected flames.

The safety distances are based on empirical data and practical experience in sectors where GH2 is widely used, such as industrial processes and energy applications. While these guidelines may require some adjustments for aviation-specific conditions, they provide a robust initial planning and implementation framework.

Liquid Hydrogen

Establishing safety distances for handling LH2 is vital to its integration as an aviation fuel. Unlike GH2 , LH2 use is less common, with limited regulatory frameworks across industries and none specifically tailored to the aviation sector. This lack of established guidelines underscores the importance of adopting cautious, research-driven approaches to defining safety zones.

Drawing on existing standards from industries experienced with LH2, such as NASA's operations for space travel and the European Industrial Gases Association, preliminary safety recommendations for LH2 in aviation suggest zones ranging from 20 to 60 meters, as shown in Table 8. These distances account for the unique hazards associated with LH2, including its cryogenic temperatures, rapid vaporization, and flammability, along with the potential risks posed by proximity to the public.

Description	**Separation distance per standard [m]**				
	BCHA	BSi	EIGA	NFPA	NASA
Place of public assembly			20	23	22.9
Public establishment			60		
Compressor, ventilator, and air conditioning intake	15	15	20	23	22.9
Any combustible liquids			10	30.5	30.5
Other LH2 fixed storage			1.5	1.5	1.5
Other LH2 tanker			3		
Vehicle parking storage				7.6	
Electricity cable and pylons	1.5	10	10		
Applicability	LH2 ≤ 5,000 kg	LH2 ≤ 5,000kg		4,032 – 20,157 kg	4,032 – 20,157 kg

Table 8: Current recommended minimum separation distances for LH2.

Initial research conducted by the UK Health and Safety Executive (HSE) for FlyZero indicates that safety zones for LH2 fueling could be adjusted based on specific operational conditions. For instance, during the connection and disconnection of fueling hoses, a 20-meter safety zone is recommended to manage the associated risks effectively. However, once the connection is securely established and fueling is underway, reducing the safety zone to 8-10 meters may be possible, provided this reduction is validated through comprehensive testing and risk assessments (ATI, 2022). The potential impact of such adjustments is illustrated in Figures 21 and 22, where the red circle represents a 20-meter safety zone and the green circle an 8-meter safety zone. This reduction is particularly significant for smaller regional jets, where a 20-meter safety zone could pose logistical challenges and affect ground operations, emphasizing the importance of optimizing these parameters to balance safety and efficiency.

Given the limited use of LH2 and the absence of aviation-specific regulations, these preliminary findings emphasize the need for rigorous testing and validation. They also highlight the potential for adapting safety distances to different phases of the fueling process, balancing operational efficiency with stringent safety requirements. As experience with LH2 handling grows, further research and collaboration with industries already using LH2 will be crucial to developing practical and effective safety guidelines for aviation applications.

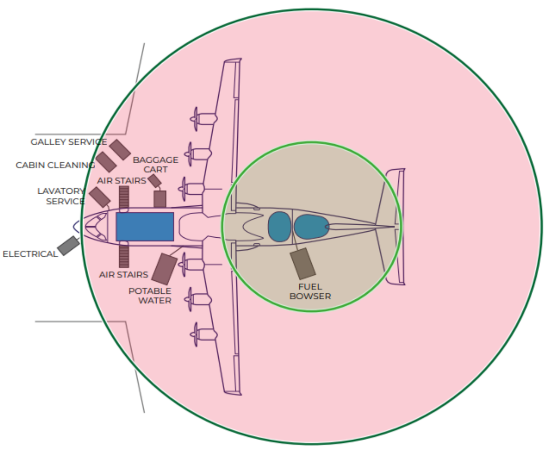

Figure 19: Fuel Safety Area Narrowbody Aircraft (ATI, 2022).

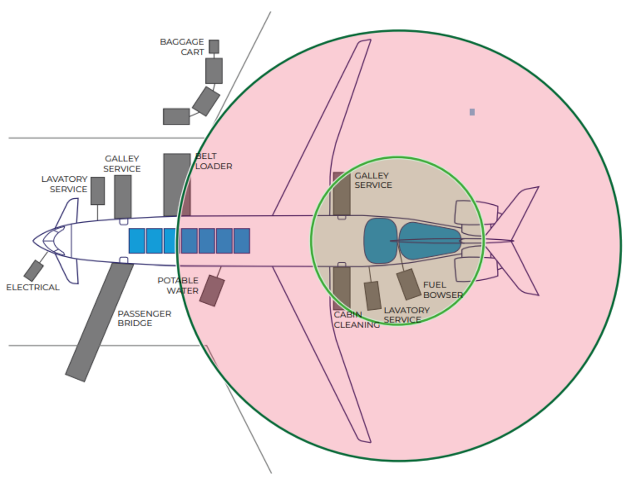

Figure 20: Fuel Safety Area Regional Aircraft (ATI, 2022).

Managing Leaks and Spills

Main contributors: AirportCreators (literature study)

Effective leak and spill management is critical to ensuring the safety of hydrogen operations in aviation. Hydrogen's unique properties, including its wide flammability range, low ignition energy, and cryogenic temperature requirements, necessitate a comprehensive and multi-faceted safety strategy.

Leak Detection Instrumentation

Hydrogen leak detection systems must prioritize early identification to minimize gas accumulation or cryogenic exposure hazards. Leaks are most likely to occur at joints, glands, and couplings, so these components should be the primary focus of monitoring systems. Integrating advanced detection technologies throughout the transportation, storage, and refueling process is essential for maintaining safety.

Ultrasonic gas leak detection sensors are particularly effective in outdoor environments like airport ramps. By detecting the high-frequency sound waves emitted by gas escaping under pressure, ultrasonic sensors enable the rapid identification of leaks, even under adverse weather conditions. Unlike traditional gas detectors, they are not influenced by wind direction or dispersal patterns, making them reliable for hydrogen monitoring in open spaces.

Leak detection tape offers a localized and highly visible method for identifying hydrogen leaks. This tape can be applied to high-risk areas such as pipes, flanges, valves, and access panels. When exposed to hydrogen, the tape undergoes a permanent color change, clearly marking the leak's location. This provides a straightforward visual indicator for maintenance teams and complements automated detection systems.

Integrated Monitoring Systems consisting of sensors and gauges installed across the hydrogen infrastructure—storage tanks, pipelines, and fueling equipment—should provide real-time data to control centers. These systems must be capable of detecting pressure drops, temperature fluctuations, or hydrogen concentrations indicative of leaks, triggering automated shutdown protocols if necessary.

Spill Containment Measures

In the event of a LH2 spill, the extremely low temperature of the cryogenic liquid will rapidly cool the surrounding air, causing water vapor in the atmosphere to condense and form a visible white cloud. This cloud, comprised of low-temperature water vapor, is denser than air and will remain localized near the ground, potentially moving horizontally depending on wind conditions. While the condensed vapor poses minimal direct hazard, it may obscure visibility and create a localized zone where hydrogen gas is present as it warms and vaporizes.

As LH2 warms, it transitions into a gaseous state and rapidly dissipates, rising due to its low molecular weight. This upward dispersion reduces the risk of prolonged accumulation near the ground, but during the initial spill phase, containment measures must address the potential for the flammable gas to remain within the white cloud's boundary.

To mitigate risks during such spills, containment strategies should focus on controlling the localized hydrogen cloud and preventing it from spreading to areas with ignition sources. Designated spill zones should include barriers or trenches to channel LH2 away from critical infrastructure and personnel, ensuring vaporization occurs in a controlled and well-ventilated area. Advanced ventilation systems designed to disperse hydrogen gas efficiently and safely are essential in spill-prone areas, mainly where the cloud could accumulate near the ground. Emergency response teams should be equipped to manage the visibility challenges posed by the condensed vapor cloud, ensuring safe evacuation and containment procedures.

Safety Strategies for Hydrogen Leak and Spill Management

Early detection is the cornerstone of hydrogen safety, and a layered approach that combines ultrasonic sensors, detection tape, and real-time monitoring systems ensures leaks are identified before they escalate into significant hazards. Integrating automated controls capable of isolating affected components and shutting down operations upon leak detection is equally essential for mitigating risks; these systems should be connected to centralized control panels that provide operators with immediate feedback.

To complement these technological measures, personnel must be thoroughly trained to recognize the visual and auditory cues of hydrogen leaks and understand the appropriate response procedures. Regular drills and safety briefings reinforce these protocols to ensure readiness in emergencies. Finally, clearly defined emergency response plans must include detailed procedures for evacuation, containment, and the safe shutdown of fueling systems, with close collaboration between airport safety teams and local emergency services to ensure coordinated and effective responses.

9.4 Weather Conditions

Main contributors: AirportCreators, Cranfield Aerospace Solutions

Safety considerations during hydrogen fuel operations must account for varying weather conditions, as these can significantly influence the risks associated with its handling. Hydrogen's unique properties, including its low ignition energy, high buoyancy in gaseous form, and the cryogenic nature of LH2, interact with environmental factors such as temperature, wind, humidity, and precipitation, requiring tailored safety measures for different scenarios.

In windy conditions, the dispersion of hydrogen gas may occur more rapidly, reducing the risk of flammable gas accumulation near the ground. However, strong winds can complicate leak detection by dispersing gas beyond the range of standard sensors or creating unpredictable vapor trails. Ultrasonic gas detectors, which are unaffected by wind, are particularly valuable in such environments to ensure leaks are identified promptly. Additionally, personnel must be cautious when operating in open areas, as wind gusts can affect equipment stability or dislodge connections during fueling.

High temperatures can accelerate the evaporation of LH2, increasing pressure within storage systems and fueling hoses. Pressure relief systems must be fully operational to prevent over-pressurization and potential failures. Heat can also amplify static charge buildup, particularly in dry environments, increasing the likelihood of ignition. Anti-static grounding and bonding systems are critical in such conditions, and personnel must be vigilant about avoiding spark-generating activities near fueling zones.

Precipitation, such as rain, snow, or hail, can introduce further complexities. Hydrogen operations during heavy rainfall or snow may require additional shielding to protect fueling equipment from water ingress or contamination, which could lead to operational inefficiencies or hazards. Similarly, snow accumulation or ice formation around fueling stations may block essential sensors or vents, necessitating regular inspection and maintenance during such conditions. In addition, visibility may be reduced during heavy precipitation, making it more challenging to detect hazards such as vapor clouds or equipment malfunctions. Adequate lighting and visual indicators, such as color-changing tapes for leak detection, are critical in these scenarios.

Electrical storms present a unique risk for hydrogen fueling operations due to the potential for lightning strikes to ignite hydrogen gas. During such conditions, fueling activities must be immediately suspended, and all personnel evacuated from the fueling zone until the risk subsides. Grounding systems must be inspected regularly to ensure they can effectively dissipate electrical surges.

10 | Airport Operations

Main contributors: AirportCreators, Cranfield Aerospace Solutions, and NLR

The ICAO Aerodrome Design Manual (Doc 9157) and the ICAO Airport Planning Manual (Doc 9187) provide detailed guidance on the physical characteristics of airport infrastructure, such as runways, taxiways, parking aprons, and aircraft stands. The integration of hydrogen-powered aircraft will necessitate significant operational changes at airports, driven by changes in infrastructure, regulations, and differences in aircraft design. A non-exhaustive list of eight critical aircraft characteristics has been identified to assess the compatibility of future hydrogen-powered aircraft with existing airport operations and infrastructure. These characteristics, shown in Table 9, derived from a qualitative assessment conducted by Airport Council International (ACI) and Airbus as part of Airbus' Zero-e program, aim to pinpoint potential impacts on airport design and operations (Airport Council International [ACI], 2021). Based on preliminary hydrogen aircraft designs, the assessment provides an early framework for evaluating the implications of hydrogen-powered aviation on airport infrastructure and operations. Still, it acknowledges that results may evolve significantly as designs mature.

	Likely to change		**Unknown if it will change**	**Unlikely to change**
	Will need special infrastructure considerations	**Will not need special infrastructure considerations**		
Wingspan				X
Maximum take-off weight		X		
Maximum landing gear weight		X		
Fuselage length	X			
Electric power demand				X
Required runway distance			X	
Engine blast production				X
Servicing design (position of the cargo and passenger doors, refueling port, etc.)			X	

Table 9: Identification of possible required changes in infrastructure because of hydrogen aircraft operations (ACI, 2021).

Hydrogen-powered aircraft are expected to have larger fuel tanks, possibly increasing aircraft length by 5 to 10 meters, as predicted by Clean Sky 2 for narrow-body designs. This could impact gate compatibility and require adjustments to existing gate operations and infrastructure or aircraft parking procedures. Operational workflows around gate management, particularly at airports with limited space, will need to adapt to accommodate these longer aircraft.

In addition, the cryogenic nature of LH2, stored at -253°C, will necessitate new refueling protocols. Ground staff will require training to handle cryogenic systems safely, and specialized equipment will need to be deployed for refueling operations. These changes may also affect the sequencing and timing of other activities during the turnaround process, introducing new coordination challenges between fueling, cargo handling, and passenger services.

Overall, while hydrogen-powered aircraft are expected to be compatible with existing airport infrastructure from a structural perspective, the operational adjustments required for fueling, ground handling, and gate management represent significant changes. Airports must implement new procedures, invest in specialized equipment, and provide comprehensive training for ground-handling staff to ensure a seamless transition to hydrogen-powered operations.

10.1 Refueling

Hydrogen refueling is one of the most challenging operational elements. This is because of the safety procedures and regulations for hydrogen refueling and the safety zone that needs to be established during fueling times. Turnaround time is an important parameter for airline operations and to maximize utilization of the aircraft. Airlines will often aim to minimize turnaround times. The refueling time is based on two parameters that differ between Jet-1A and hydrogen: refueling rate and the safety zones.

Hydrogen Refueling Operations

Refueling hydrogen-powered aircraft using GH2 or LH2 involves a series of specialized steps that differ significantly from conventional kerosene operations due to hydrogen's unique physical and chemical properties. These processes are designed to ensure safety, maintain operational efficiency, and protect equipment from potential damage caused by hydrogen's cryogenic temperatures and high flammability.

The process begins with grounding the aircraft and the refueling system just as for kerosene operations to eliminate the risk of static electricity buildup, which could ignite hydrogen. This step is particularly critical for hydrogen refueling due to hydrogen's low ignition energy compared to kerosene. Grounding ensures that all connected components, including the aircraft, fueling equipment, and the fueling vehicle or station, are at the same electrical potential. This process is identical for both GH2 and LH2 refueling operations.

Once the fueling system is prepared, a secure connection is established between the aircraft and the fueling hoses. Hydrogen connections require advanced locking mechanisms to manage the high pressures of GH2 or the extreme cold of LH2. After connecting the hoses, the system performs checks to verify the integrity of the seals and ensure no leaks are present. Communication and checks between the aircraft and the fueling system continue throughout refueling. Real-time data exchange monitors and manages key parameters such as pressure, temperature, and flow rate, ensuring safe and efficient hydrogen transfer following the aircraft's specifications and entering the aircraft's tanks.

Next, purging is a key step unique to hydrogen refueling and is performed to eliminate oxygen or other contaminants from the fueling lines, reducing the risk of ignition or combustion. For GH2, purging is typically done using inert gases such as nitrogen to displace oxygen in the system. For LH2, helium may also be used, particularly when purging cryogenic lines, as helium's lower boiling point minimizes the risk of freezing. This process ensures that the hydrogen is introduced into a clean, inert environment, preventing unwanted chemical reactions and preserving system integrity.

For LH2 operations, the chill-down process is a critical additional step. Before full fueling begins, small amounts of LH2 are gradually introduced to pre-cool the fueling lines and tanks. This reduces their temperature to match hydrogen's cryogenic state (-253°C), preventing thermal shock that could damage the equipment or cause leaks. The initial contact with the warmer surfaces causes the hydrogen to vaporize, absorbing heat from the surrounding material and cooling it down. This vaporized hydrogen is either vented safely or returned to the storage system. This step prevents thermal shock, which could damage equipment or cause leaks, and minimizes the formation of vaporized hydrogen ("boil-off") during full-scale fueling.

The aircraft can be refueled after purging for GH2 and chill-down for LH2. When refueling is done, a final leak test is performed to ensure no hydrogen is escaping from the aircraft's tanks, fueling lines, or connections. Advanced sensors verify system integrity, and any detected leaks are promptly addressed. After this, the fueling lines are purged with inert gas to remove any residual hydrogen or the fuel lines are flared, depending on operational requirements and situational needs. Flaring is employed when larger quantities of hydrogen cannot be safely returned to storage or vented, ensuring that the gas is burned off in a controlled manner. This process minimizes environmental risks and prevents the accumulation of hydrogen in hazardous concentrations. While this step is essential for both GH2 and LH2 refueling operations, it is more frequently required for LH2 due to the management of boil-off gases generated during cryogenic handling. These measures ensure safe and efficient post-fueling procedures, mitigating potential hazards associated with residual hydrogen.

Once the purging or flaring is complete, the fueling hoses are disconnected, and all valves are secured. Grounding connections are removed, and the aircraft is inspected for any abnormalities from the refueling process. After these steps, the aircraft is cleared and prepared for its next operational activities, ensuring a smooth and safe transition from refueling to regular operations.

Figure 21: LH2 refueling steps with estimated duration (Mangold et al., 2022).

Refueling Rate

In liquid form, hydrogen has a significantly lower density than kerosene, leading to operational challenges in refueling hydrogen-powered aircraft. Although hydrogen aircraft are expected to have smaller overall fuel tank sizes compared to their kerosene counterparts, refueling LH2 using hoses with the same diameter and flow rate as kerosene would result in longer refueling times. This issue becomes increasingly pronounced for larger, long-range aircraft, where extended fueling durations could significantly impact turnaround times. For instance, refueling a long-range kerosene aircraft from 25% to 100% capacity using two hoses with a flow rate of 900 liters per minute currently takes approximately 65 minutes (Fuel Cells and Hydrogen 2 Joint Undertaking [FCH], 2020). Refueling the same tank size with the current LH2 refueling rate of 500 liters per minute and four hoses, the refueling time could extend to 140 minutes (FCH, 2020; Abel & Allroggen, 2023).

To address this, advancements in refueling technology are essential to optimize turnaround times and ensure the operational viability of hydrogen-powered aviation. Increasing the flow rate is one promising solution. According to FlyZero, analyses of higher flow rates reveal no significant concerns related to heat transfer in the lines, erosion of the inner walls of pipelines or fittings, or the generation of electrostatic charge, all of which are critical factors for safety and efficiency (ATI, 2022). Progress in this area is exemplified by ZeroAvia, which is actively developing innovative refueling solutions, including a bowser designed to match the refueling times of conventional kerosene aircraft, thereby addressing one of the key operational challenges associated with hydrogen-powered aviation.

Other potential solutions involve increasing the diameter of refueling hoses or using multiple hoses simultaneously. However, the primary challenge with larger hoses is their reduced flexibility and increased weight, which could complicate handling during refueling operations. Balancing these physical constraints with operational efficiency will be crucial for developing practical refueling systems for hydrogen aircraft.

Table 10 illustrates the effects of increased hose diameter and flow rate on refueling times. As the industry progresses toward adopting hydrogen as an aviation fuel, addressing these refueling challenges will be a key factor in ensuring seamless integration into existing airport operations and maintaining competitive turnaround times.

Aircraft design	**LH quantity (kg)**	**Fill time (2.5 m/s)**		**Fill time (5 m/s)**		**Fill time (7 m/s)**	
		10.16 cm diameter	15.24 cm diameter	10.16 cm diameter	15.24 cm diameter	10.16 cm diameter	15.24 cm diameter
Midsize	11698	175 min	78 min	87 min	39 min	62 min	28 min
Narrowbody	2718	41 min	18 min	20 min	9 min	15 min	6 min
Regional	1300	19 min	9 min	10 min	4 min	7 min	3 min

Table 10: Estimated LH2 refueling times using single hose operations (ATI, 2022).

Safety Zone and Simultaneous Activities

Hydrogen refueling has the potential to significantly impact aircraft operations and turnaround times, with the extent of the impact depending on whether GH2 or LH2 is being used. For GH2-powered aircraft, the effects are expected to be less severe due to the smaller safety zones, typically ranging from 5 to 8 meters. These relatively compact safety zones may allow for simultaneous turnaround processes, depending on the specific aircraft and regulatory requirements set up in the future, thereby minimizing disruptions to standard operational workflows.

In contrast, LH2 refueling imposes stricter safety requirements due to its cryogenic nature and larger safety zones. The first and most conservative scenario, likely to be implemented during the initial phases of LH2 operations, mandates safety zones of 30 to 60 meters, as discussed in Section 2.3. These zones encompass almost the entire aircraft. As a result, no turnaround activities can occur simultaneously with LH2 refueling, including connection and disconnection of fueling hoses, purging, and chill-down procedures. Additionally, passengers cannot be on board during refueling operations under this scenario for safety reasons. This strict approach prioritizes safety but significantly extends turnaround times.

The second scenario aligns with recommendations from the Health and Safety Executive (HSE), introducing a more flexible safety framework. In this procedure, a 20-meter safety zone is required during the connection and disconnection of fueling hoses, which is then reduced to 8 meters during active refueling after the connection is secured, as illustrated in Figure 21 and 22. Importantly, regulations in this scenario allow staff to be on board during refueling, enabling certain turnaround activities to proceed simultaneously. The extent of permissible activities will depend on factors such as aircraft design, regulatory approval, and the optimization of ground handling processes.

The third and most streamlined scenario envisions a level of operational freedom similar to that of kerosene refueling. In this case, safety zones are reduced to a level that permits all turnaround activities to occur concurrently with LH2 refueling, including the presence of passengers on board throughout the process. Achieving this scenario would require significant advancements in safety standards, technology, and regulatory frameworks, ensuring that refueling operations can be conducted with minimal disruption to aircraft schedules while maintaining the highest safety standards.

Current turnaround times for kerosene-powered aircraft are approximately 60-90 minutes for midsize aircraft, 25-30 minutes for narrowbody aircraft, and 20-25 minutes for regional aircraft. For hydrogen-powered aircraft to be a viable option for airlines and encourage their adoption, it is essential that their turnaround times as closely match or even fall below those of kerosene aircraft. Figure 24 illustrates the projected turnaround times for regional, narrowbody, and midsize LH2 aircraft under the three safety scenarios outlined earlier (ATI, 2022).

The analysis reveals that under current safety zone regulations, where no simultaneous activities are possible during refueling, turnaround times for all hydrogen aircraft types far exceed those of kerosene aircraft. This extended downtime is largely due to the inability to perform other processes while refueling, severely impacting operational efficiency. In scenarios where some simultaneous activities are allowed, such as under reduced safety zone conditions, turnaround times approach the upper limit of kerosene turnaround times, making operations more competitive. Finally, with full simultaneous activities permitted during refueling, hydrogen aircraft could achieve turnaround times nearing the lower range of those currently achieved by kerosene-powered aircraft, significantly enhancing their operational appeal.

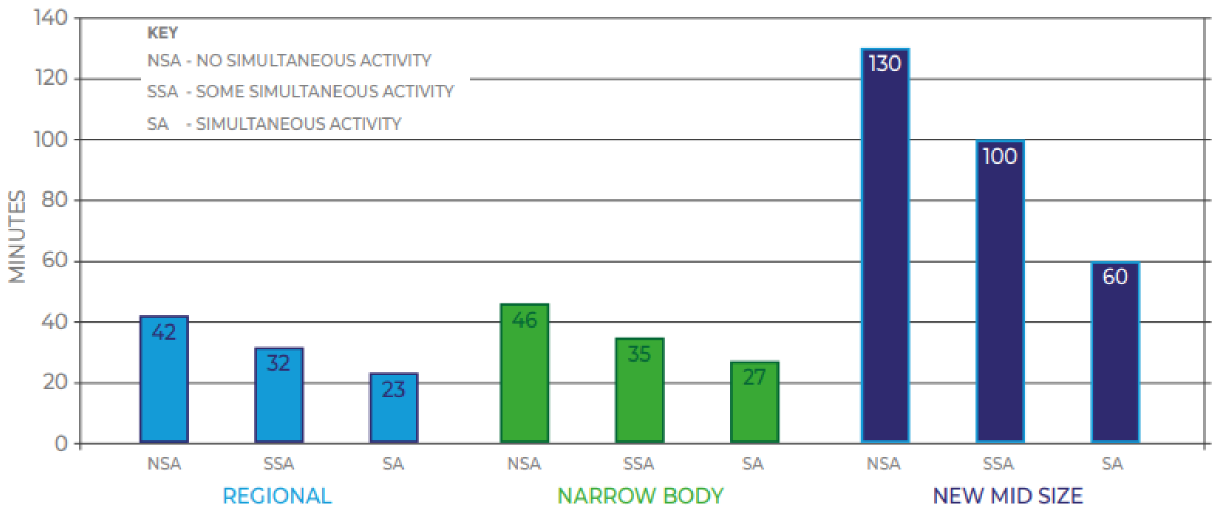

Figure 22: Estimated Turnaround Times (1x 6" hose for regional and 2x 6" hose for narrowbody and new mid-size, all with fill velocity of 5 m/s) (ATI, 2022).

Refueling Process Flow Diagram

Hydrogen refueling operations differ based on the type of hydrogen fuel used—GH2 or LH2—and the infrastructure tier. Figures 25 and 26 present conceptual process flow diagrams for these refueling scenarios, emphasizing the key steps and operational considerations.

Figure 25 illustrates the GH2 refueling process at a fixed refueling station, as envisioned for Tier 1 operations. At this stage, GAE operations are expected to use GH2 predominantly. A critical consideration is whether passengers can remain onboard during refueling, which will depend on future safety regulations. If regulations permit, the refueling process could be similar to current kerosene operations, allowing passengers to be onboard the aircraft during refueling, after which it can directly depart. However, if passengers cannot remain onboard, the process becomes more complex: the aircraft would need to deboard passengers, taxi to the refueling station, refuel, return to the stand, board passengers, and then depart. All ground handling activities, such as baggage loading, cleaning, and maintenance, are performed before or after refueling. This would introduce additional logistical challenges and potentially extend turnaround times.

The delivery of GH2 to the fixed refueling station—whether via bowser transport or pipeline—will depend on its location and require further analysis to determine the most efficient and cost-effective approach.

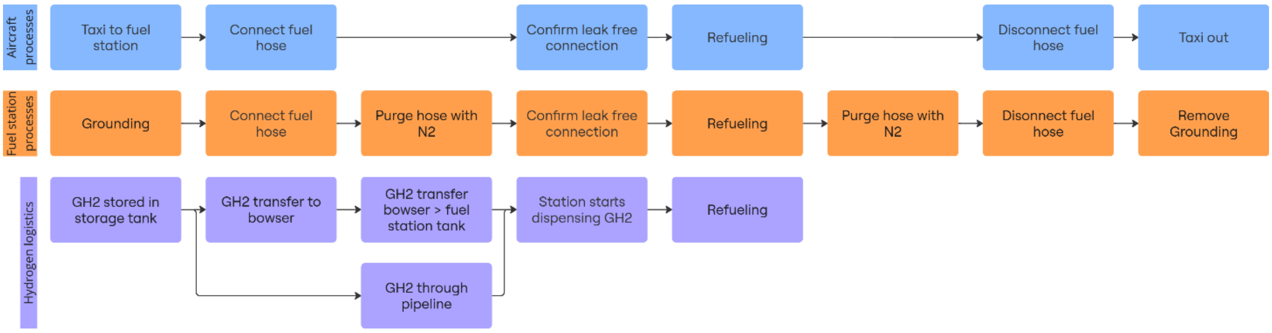

Figure 23: Concept process flow diagram for gaseous hydrogen refueling at a static hydrogen fuel station

Figure 26 depicts the refueling process for LH2, where a bowser delivers the fuel directly to the aircraft as expected in Tier 2 and 3. Although the fixed GH2 refueling station will still be operational, it is possible to do GH2 bowser operations. A similar approach applies for GH2 refueling using a bowser, though with key differences, such as the absence of the chill-down step for GH2. The concept of operations assumes that some simultaneous activities, such as baggage unloading, cleaning, and minor maintenance, are allowed once the safety zone is reduced after the fueling connection is established.

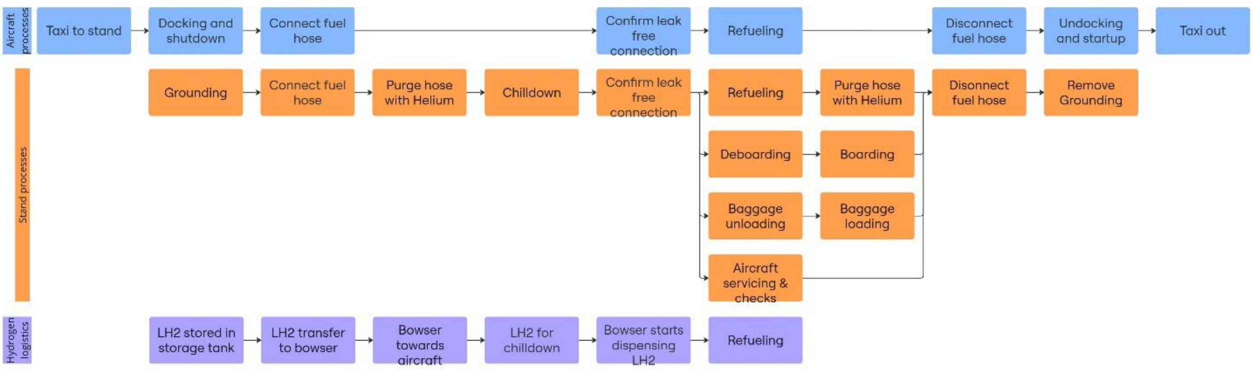

Figure 24: Concept process flow diagram for liquid hydrogen refueling at the aircraft stand

10.2 Fire Fighting

Rescue and firefighting operations will need significant adaptation to address the unique challenges hydrogen-powered aircraft pose. Hydrogen fires, characterized by rapid combustion and short duration, may consume all the fuel before emergency responders arrive at the incident site. This could alter the traditional role of firefighting crews, shifting their focus from extinguishing fires to managing the aftermath, securing the area, and addressing potential secondary hazards such as explosions from high concentrations of hydrogen in confined spaces.

New training programs and specialized equipment tailored to hydrogen-related emergencies will be essential to meet these challenges. Projects like HyResponder are pioneering efforts to prepare first responders for hydrogen-specific incidents (HyResponder, n.d.). The HyResponder initiative aims to develop a sustainable "train-the-trainer" program in hydrogen safety, providing responders across Europe with state-of-the-art knowledge and tools to handle hydrogen fires and accidents effectively. This program supports the commercialization of hydrogen technologies by enhancing responder preparedness, improving resilience, and ensuring appropriate accident management and recovery.

HyResponder is revising the European Emergency Response Guide to include updated strategies and tactics specific to liquefied hydrogen applications as part of its objectives. By incorporating these advancements, responders will have access to operational, virtual reality, and educational training materials that reflect the latest developments in hydrogen safety. A Pan-European Network of Responder Trainers will be established, involving trainers from at least ten countries attending bespoke courses and adapting training materials to reflect regional needs. These resources will be translated into eight languages and disseminated through an e-platform, ensuring European accessibility.

To address the invisibility of hydrogen flames, advanced flame detection technologies, such as ultraviolet or infrared sensors, will play a critical role in identifying hydrogen fires quickly and safely. Combined with enhanced responder training in using such tools, these systems will ensure that firefighting crews can respond effectively even in challenging visibility conditions.

To support national readiness, National Training Clusters will link the hydrogen safety community with responder organizations, facilitating the delivery of workshops tailored to local requirements. Additionally, an International e-forum will provide a platform for knowledge exchange, further consolidating a unified and sustainable approach to hydrogen safety training.

These efforts will ensure that firefighting and rescue crews are equipped to manage incidents involving hydrogen aircraft with the highest levels of safety and efficiency in hydrogen-powered aviation.

10.3 General Staffing

The introduction of hydrogen-powered aircraft necessitates adjustments to airport staffing requirements to accommodate the unique demands of hydrogen as an aviation fuel. These changes span across various operational roles and require enhanced training, additional personnel, and adjustments to existing workflows to ensure safety, efficiency, and compliance with emerging regulations.

In the public domain, refueling GH2 vehicles is straightforward enough that individuals are currently permitted to perform the task themselves. However, the aviation sector operates under far stricter safety regulations, and such practices may not be allowed in the same way for refueling hydrogen-powered aircraft. Pilots may not be permitted to refuel their own aircraft, particularly for LH2 operations, because of the safety complexities due to LH2's cryogenic properties and heightened risks.

Even airports with stationary hydrogen refueling stations will require a dedicated team to oversee operations, perform regular inspections, and manage safety compliance. This shift could mean that pilots of smaller (general aviation) aircraft, who are often allowed to refuel their aircraft under conventional fueling systems, may no longer be permitted to do so without undergoing extensive specialized training. Regulations governing hydrogen fueling often mandate additional oversight during critical operations, which may require staffing levels to exceed those typically allocated for kerosene refueling. Instead, the aviation industry will likely require a specialized team trained in hydrogen refueling procedures to manage these operations. For GH2 aircraft, such a team would ensure compliance with strict protocols. For LH2 aircraft, their role would be even more critical, addressing the added challenges of extreme temperatures, material handling, and potential boil-off. Scenarios where pilots might be allowed to refuel their aircraft would almost certainly involve extensive specialized training and strict oversight from a dedicated hydrogen safety team during all critical operations.

Ground handling teams will also need additional training to safely operate in proximity to hydrogen-powered aircraft. This includes understanding the operational restrictions imposed by hydrogen safety zones, recognizing potential hazards unique to hydrogen, and coordinating with refueling staff to ensure smooth turnaround processes. This requirement is similar to current kerosene operations, where baggage handlers, maintenance personnel, and catering teams must coordinate activities around refueling schedules. However, with the introduction of hydrogen, these protocols might differ, depending on the specific safety requirements for gaseous or LH2, though the extent of these differences remains uncertain at this stage.

Additionally, airport engineering and maintenance departments will need to expand their expertise to include the maintenance of hydrogen infrastructure. This includes fueling stations, pipelines, storage facilities, and any associated monitoring and detection systems. Staff must be capable of inspecting and maintaining hydrogen-specific equipment, such as cryogenic storage tanks and high-pressure lines, and ensuring compliance with evolving safety standards.

Finally, all relevant staff require ongoing education and training to stay informed about best practices, technological advancements, and updates to regulations concerning hydrogen. These programs should be tailored to the specific needs of different departments and roles, ensuring that every team member involved in hydrogen operations is adequately prepared.

11 | Conclusion and Recommendations

This report provides an evaluation of the potential for hydrogen-powered aviation at Groningen Airport Eelde (GAE), focusing on the operational, infrastructural, and economic considerations necessary for its successful adoption. The report highlights the strategic opportunities and challenges in integrating hydrogen into GAE's operations through analyses of hydrogen production, delivery, and utilization.

Hydrogen-powered aircraft are expected to play a considerable role in reshaping GAE's flight network. Short- to mid-range routes will likely transition to hydrogen-powered operations, supported initially by GH2 and later expanding with LH2 to cover longer distances and higher capacities. The adoption of hydrogen-based aviation offers a pathway to reduce greenhouse gas emissions, aligning GAE with broader European and global sustainability goals. However, the successful integration of hydrogen technology will depend on advances in aircraft design, such as extended ranges and CASK, to ensure commercial viability.

Stakeholder perspectives reveal a cautious optimism about the transition to hydrogen aviation, driven by sustainability goals but tempered by uncertainties around adoption rates, infrastructure costs, and hydrogen availability. While a clear vision for hydrogen-based traffic growth is established, business aviation remains a variable factor and is therefore excluded from the current hydrogen consumption estimates. A more detailed study into this aviation segment may unveil additional opportunities to boost hydrogen flight.

A stable hydrogen supply chain will be a critical factor in enabling this transition, which introduces trade-offs between on-site production and regional supply. On-site production offers localized control and reduced transportation dependencies, while regional production leverages economies of scale but requires robust delivery systems. The feasibility of these approaches depends on future demand, cost-efficiency, and advancements in liquefaction and storage technologies. With the provided vision of hydrogen aviation at GAE, the most likely roadmap for introducing hydrogen aviation is local production in Tier 1, switching to regional production in Tier 2, with the transition point determined by demand.

11.1 Discussion

The findings in this report underscore the importance of scalable hydrogen infrastructure, adaptable safety regulations, and evolving technological advancements in determining the feasibility of hydrogen-powered aviation. The report also emphasizes the importance of integrating hydrogen operations within the broader airport ecosystem. Safety considerations, such as storage distances, refueling procedures, and compliance with evolving regulations, will require ongoing attention to ensure seamless and secure operations.

The results of this report are based on the expertise of the consortium and an extensive literature study. While detailed analyses are not included, the approach provides a solid foundation for understanding the opportunities and challenges of hydrogen-powered aviation at GAE. This methodology combines existing sector knowledge with up-to-date insights from literature, resulting in a valuable guide for research and demonstrations.

The information presented in this report is concrete enough to inform strategic priorities and decision-making but should be seen as a starting point. Specific aspects, such as infrastructure requirements, safety protocols, and operational integration, have been outlined at a high level, and further refinement will be necessary with the use of demonstration and real-world applications. The findings provide a realistic view of what is achievable within the current and anticipated context.

The overall perspective presented in the report is optimistic, highlighting the significant potential of hydrogen aviation to contribute to the sustainability of the aviation sector. However, the challenges are not underestimated. Key obstacles, such as the development of cost-effective infrastructure, the availability of high-purity hydrogen, and the need for coherent regulatory frameworks, require attention and collaboration. The report underscores that the transition to hydrogen aviation demands a multidimensional approach, bringing together technological advancements, economic feasibility, and policy support to ensure successful implementation.

In closing, it is important to underscore that the hydrogen market remains fluid, with significant potential for shifts in technology, policy, and economic factors. The data and insights presented in this study were collected progressively throughout the course of 2024, with a final validation and review conducted as of May 1st, 2025. While this report reflects the most accurate and current information available at that time, the fluid nature of the hydrogen sector means that market conditions, technologies, and policy frameworks may continue to evolve.

11.2 Recommendations

The feasibility study identified several key areas requiring further exploration and development to ensure the successful implementation of hydrogen aviation at GAE. The next steps should focus on expanding the implementation strategy for Tier 1 infrastructure with corresponding strategic reservations for Tier 2 and subsequent phases. Additionally, the proposed operational concepts and safety strategies must undergo consultation with relevant stakeholders and government organizations to validate their practicality and applicability and make necessary adjustments.

Regarding demand, the traffic vision requires ongoing verification and validation, particularly with general and business aviation inclusion. Incorporating simulation models and data-driven analyses of city pair demands will improve the reliability of projections for hydrogen developments at GAE. These efforts will strengthen the justification for future investment decisions by better understanding potential market opportunities.

Beyond the airport's immediate operations, the regional hydrogen ecosystem in the Northern Netherlands also needs further definition and support. From production and processing (e.g., liquefaction) to distribution, it is crucial to secure strong commitments from government entities, industry partners, and other hydrogen clients. Establishing a clear and stable regulatory framework will be essential to fostering these developments. GAE and its consortium are encouraged to actively participate in shaping these regulations to ensure alignment with the airport's strategic goals.

GAE and its partners are aware of the numerous hydrogen-related initiatives currently underway across the Netherlands and the European Union. Strengthening connections with these initiatives presents an opportunity to accelerate the development of a hydrogen aviation ecosystem. The unique strengths of the Northern Netherlands region in hydrogen production and innovation can be emphasized to highlight the added value of GAE's partnerships and initiatives. By fostering collaboration and leveraging regional assets, GAE can contribute to and benefit from the broader transition to hydrogen-powered aviation.

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Appendix A: Aircraft Specifications

Table 11: Fokker NextGen Aircraft Characteristics.

Specification	**Description**	**Detail**
Company Name	*Name of the company developing the aircraft*	Fokker Next Gen
Aircraft type	*Type of the aircraft*	Bifuel (SAF+Hydrogen) combustion single aisle regional airliner
Service entry		2035
Weights		
MTOW	*[kg]*	54000
MZFW	*[kg]*	49000
OEW	*[kg]*	36000
Performance		
Max fuel capacity	*[kg]*	2300 kg LH2; 5000 kg SAF
Payload [pax]	*Number of passengers (full economy setup)*	120
Payload [weight]	*[kg], pax and/or cargo*	12600
Range [max payload]	*[km], fuel filled to MTOW*	2600 km on LH2 with SAF reserves 4000 km on LH2+SAF with SAF reserves
Range [max fuel]	*[km], payload filled to MTOW*	2600 km on LH2 with SAF reserves 4000 km on LH2+SAF with SAF reserves
Propulsion system		
Propulsion system type	*Fuel cell/ combustion engine*	Combustion engine
Propellant type	*LH2/GH2*	LH2
Aircraft dimensions		
Wingspan	*[m]*	36
Overall length	*[m]*	40
Engine placement configuration	*Generic description*	On high wing
Operations		
Compatibility with existing GSE	*Any remarks concerning compatibility with GSE*	Same as conventional a/c for non-hydrogen related GSE
Airport refueling considerations	*Safety considerations airports could make regarding refueling procedure*	The ground part of the fueling system should be able to receive gaseous hydrogen, liquid hydrogen and for instance gaseous helium (used to cool the tank).

Table 12: Characteristics for Cranfield Aerospace hydrogen fuel cell powertrain fitted to Islander BN2B-26 Aircraft

Specification	**Description**	**Detail**
Company Name	*Name of the company developing the design*	Cranfield Aerospace Solutions
Aircraft type	*Type of the aircraft*	Britten-Norman Islander BN2B-26
Service entry		2027
Weights		
MTOW	*[kg]*	2994kg-3176kg
MZFW	*[kg]*	2957-3139kg
OEW	*[kg]*	2257-3102kg
Additional weight remarks	*Generic description*	An existing modification exists on the BN2B-26 Islander to take the MTOW from 2994kg to 3176kg. The above figures under this section reflect both the 2994kg MTOW and 3176kg MTOW aircraft
Performance		
Max fuel capacity	*[kg]*	37-60kg GH_2
Payload [pax]	*Number of passengers (full economy setup)*	6-8
Payload [weight]	*[kg], pax and/or cargo*	700-900kg (pax & baggage, excluding pilot)
Range [max payload]	*[km], fuel filled to MTOW*	200-400km, plus 45 mins' reserve
Range [max fuel]	*[km], payload filled to MTOW*	As above, covers MTOW
Additional performance remarks	*Generic description*	Range data given covers all proposed MTOW variants of the hydrogen powered Islander, as noted under the 'Weights' section
Propulsion system		
Propulsion system type	*Fuel cell/ combustion engine*	Hydrogen Fuel Cell
Propellant type	*LH2/GH2*	GH_2
Propellant state at refueling	*State, temperature, pressure*	Gaseous 350bar. Temperature dependent on refueller and regulation.
Propellant quality requirement	%	ISO 14687 Grade D for demonstrator, product TBC.
Refueling system	*Generic description*	Currently looking at automotive standards J2600 for nozzle, J2601 (2010) for refuelling and SAE J2799 for H_2 comms and non comms refuelling. TBC.
Additional propulsion system remarks	*Generic description*	Between 18-21 kg per block hour.
Aircraft dimensions		
Wingspan	*[m]*	14.9
Height	*[m]*	4.4
Overall length	*[m]*	10.9
Ground clearance	*[m]*	0.41
Landing gear wheelbase	*[m]*	4
Engine placement configuration	*Generic description*	Twin engine, one on each wing

Table 13: Airbus Aircraft Characteristics. Preliminary parameters: These do not necessarily reflect the aircraft under development.

Specification	Description	Detail
Company Name	*Name of the company developing the aircraft*	Airbus
Aircraft type	*Type of the aircraft*	ZEROe
Service entry		TBA, after 2035
Weights		
MTOW	*[kg]*	-
MZFW	*[kg]*	-
OEW	*[kg]*	-
Performance		
Max fuel capacity	*[kg]*	-
Payload [pax]	*Number of passengers (full economy setup)*	100
Payload weight	*[kg]*	-
Range	*[km]*	1850
Propulsion system		
Propulsion system type	*Fuel cell/ combustion engine*	Fuel cell
Propellant type	*LH2/GH2*	LH2
Aircraft dimensions		
Wingspan	*[m]*	-
Height	*[m]*	-
Overall length	*[m]*	-
Engine placement configuration	*Generic description*	Four engines, two under each wing

Table 14: BYA-I Characteristics

Specification	**Description**	**Detail**
Company Name	*Name of the company developing the aircraft*	Beyond Aero
Aircraft type	*Type of the aircraft*	Light jet
Service entry		2030
Weights		
MTOW	*[kg]*	8600
MZFW	*[kg]*	8350
OEW	*[kg]*	7700
Performance		
Max fuel capacity	*[kg]*	250 kg GH2 at 700 bar
Payload [pax]	*Number of passengers (full economy setup)*	8
Payload [weight]	*[kg], pax and/or cargo*	760
Range [max payload]	*[km], fuel filled to MTOW*	1500
Range [max fuel]	*[km], payload filled to MTOW*	1500
Propulsion system		
Propulsion system type	*Fuel cell/ combustion engine*	Fuel cell
Propellant type	*LH2/GH2*	GH2
Aircraft dimensions		
Wingspan	*[m]*	17
Overall length	*[m]*	18.59
Engine placement configuration	*Generic description*	Rear mounted
Operations		
Compatibility with existing GSE	*Any remarks concerning compatibility with GSE*	
Airport refueling considerations	*Safety considerations airports could make regarding refueling procedure*	

Appendix B: Traffic Scenario examples GAE

Table 15: H2 Scenario example GAE 2030

2030						
Passengers scheduled (Traditional kerosene/SAF mixture)	CAP	SLF	Freq/wk	Season	flights	pax
London, ATR72	72	70%	4	Year-round	400	20.160
Copenhagen, ATR72	72	70%	4	Year-round	400	20.160
Total scheduled-passengers (in+out)					800	40.320
Passengers leisure (Charter & LCC) (Traditional kerosene/SAF mixture)	CAP	SLF	Freq/wk	Season	flights	pax
Antalya	189	90%	3	Summer	180	30.618
Barcelona	189	90%	2	Summer	120	20.412
Burgas	189	90%	2	Summer	120	20.412
Faro	189	90%	2	Summer	120	20.412
Ibiza	189	90%	2	Summer	120	20.412
Innsbruck	189	70%	2	Winter	80	10.584
Kos	189	90%	2	Summer	120	20.412
Heraklion	189	90%	3	Summer	180	30.618
Las Palmas	189	90%	2	Year-round	200	34.020
Malaga	189	90%	3	Year-round	300	51.030
Mallorca	189	90%	3	Summer	180	30.618
Rhodes	189	90%	2	Summer	120	20.412
Scandinavian Mountains	189	70%	2	Winter	80	10.584
Tenerife	189	90%	2	Year-round	200	34.020
Total leisure-passengers (in+out)						354.564
Passengers battery-electric (9-30 seaters)	CAP	SLF	Freq/wk	Season	flights	pax
Amsterdam	9	70%	14	Year-round	1.400	8.820
Brussels	9	70%	7	Year-round	700	4.410
Eindhoven	9	70%	10	Year-round	1.000	6.300
Esbjerg	9	70%	3	Year-round	300	1.890
Maastricht	9	70%	10	Year-round	1.000	6.300
Total battery-electric-passengers (in+out)						27.720
Passengers GH2 (9-30 seaters)	CAP	SLF	Freq/wk	Season	flights	pax
Hamburg	9	70%	5	Year-round	500	3.150
Rotterdam	9	70%	14	Year-round	1.400	8.820
Total GH2 passengers (in+out)						11.970
Passengers LH-2 (50-80 seaters)	CAP	SLF	Freq/wk	Season	flights	pax
Total LH2-hydrogen-passengers (in+out)						0
Total scheduled-passagies (in+out)						40.320
Total leisure-passengers (in+out)						354.564
Total battery-electric-passengers (in+out)						27.720
Total GH2-hydrogen-passengers (in+uit)						11.970
Total LH2-hydrogen-passengers (in+uit)						0
Total commercial passengers (in+out)						434.574

Table 16: H2 Scenario example GAE 2035.

2035						
Passengers scheduled (Traditional kerosene/SAF mixture)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
Total scheduled-passengers (in+out)					-	0
Passengers leisure (Charter & LCC) (Traditional kerosene/SAF mixture)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
Antalya	189	90%	3	Summer	180	30.618
Barcelona	189	90%	3	Year-round	300	51.030
Burgas	189	90%	2	Summer	120	20.412
Faro	232	90%	2	Summer	120	25.056
Ibiza	189	90%	2	Summer	120	20.412
Innsbruck	189	70%	2	Winter	80	10.584
Kos	189	90%	2	Summer	120	20.412
Heraklion	189	90%	3	Summer	180	30.618
Las Palmas	189	90%	2	Year-round	200	34.020
Malaga	232	90%	3	Year-round	300	62.640
Mallorca	189	90%	3	Summer	180	30.618
Rhodos	189	90%	2	Summer	120	20.412
Scandinavian Mountains	189	70%	2	Winter	80	10.584
Tenerife	189	90%	2	Year-round	200	34.020
Total leisure-passengers (in+out)						401.436
Passengers battery-electric (9-30 seaters)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
Amsterdam	19	70%	21	Year-round	2.100	27.930
Berlin	19	70%	7	Year-round	700	9.310
Brussels	19	70%	7	Year-round	700	9.310
Eindhoven	9	70%	14	Year-round	1.400	8.820
Esbjerg	9	70%	5	Year-round	500	3.150
Maastricht	19	70%	14	Year-round	1.400	18.620
Munich	19	70%	7	Year-round	700	9.310
Paris	19	70%	7	Year-round	700	9.310
Total battery-electric-passengers (in+out)						95.760
Passengers GH2 (9-30 seaters)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
Hamburg	19	70%	5	Year-round	500	6.650
Rotterdam	9	70%	21	Year-round	2.100	13.230
Total GH2 passengers (in+out)						19.880
Passengers LH-2 (50-80 seaters)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
London	50	70%	14	Year-round	1.400	49.000
Copenhagen	50	70%	14	Year-round	1.400	49.000
Total LH2-hydrogen-passengers (in+out)						98.000
Total scheduled-passagies (in+out)						0
Total leisure-passengers (in+out)						401.436
Total battery-electric-passengers (in+out)						95.760
Total GH2-hydrogen-passengers (in+uit)						19.880
Total LH2-hydrogen-passengers (in+uit)						98.000
Total commercial passengers (in+out)						615.076

Table 17: H2 Scenario example GAE 2040.

2040						
Passengers scheduled (Traditional kerosene/SAF mixture)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
Total scheduled-passengers (in+out)					-	0
Passengers leisure (Charter & LCC) (Traditional kerosene/SAF mixture)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
Antalya	189	90%	3	Summer	180	30.618
Barcelona	232	90%	3	Year-round	300	62.640
Burgas	189	90%	2	Summer	120	20.412
Faro	232	90%	2	Summer	120	25.056
Ibiza	189	90%	2	Summer	120	20.412
Innsbruck	189	70%	2	Winter	80	10.584
Kos	189	90%	2	Summer	120	20.412
Heraklion	189	90%	3	Summer	180	30.618
Las Palmas	232	90%	2	Year-round	200	41.760
Malaga	232	90%	3	Year-round	300	62.640
Mallorca	232	90%	3	Summer	180	37.584
Rhodes	189	90%	2	Summer	120	20.412
Scandinavian Mountains	189	70%	2	Winter	80	10.584
Tenerife	232	90%	2	Year-round	200	41.760
Total leisure-passengers (in+out)						435.492
Passengers battery-electric (9-30 seaters)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
Amsterdam	19	70%	21	Year-round	2.100	27.930
Berlin	19	70%	14	Year-round	1.400	18.620
Brussels	19	70%	10	Year-round	1.000	13.300
Eindhoven	19	70%	14	Year-round	1.400	18.620
Esbjerg	9	70%	5	Year-round	500	3.150
Frankfurt	19	70%	10	Year-round	1.000	13.300
Maastricht	19	70%	14	Year-round	1.400	18.620
Manchester	19	70%	7	Year-round	700	9.310
Munichen	19	70%	10	Year-round	1.000	13.300
Paris	19	70%	14	Year-round	1.400	18.620
Prague	19	70%	7	Year-round	700	9.310
Zurich	19	70%	10	Year-round	1.000	13.300
Total battery-electric-passengers (in+out)						177.380
Passengers GH2 (9-30 seaters)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
Hamburg	19	70%	7	Year-round	700	9.310
Rotterdam	19	70%	21	Year-round	2.100	27.930
Total GH2 passengers (in+out)						37.240
Passengers LH-2 (50-80 seaters)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
Copenhagen	50	70%	14	Year-round	1.400	49.000
Innsbruck	120	70%	4	Winter	160	13.440
London	80	70%	14	Year-round	1.400	78.400
Manchester	80	70%	10	Year-round	1.000	56.000
Milan	50	70%	14	Year-round	1.400	49.000
Prague	50	70%	10	Year-round	1.000	35.000
Scandinavian Mountains	120	70%	3	Winter	120	10.080
Vienna	50	70%	10	Year-round	1.000	35.000
Total LH2-hydrogen-passengers (in+out)						325.920
Total scheduled-passagies (in+out)						0
Total leisure-passengers (in+out)						435.492
Total battery-electric-passengers (in+out)						177.380
Total GH2-hydrogen-passengers (in+uit)						37.240
Total LH2-hydrogen-passengers (in+uit)						325.920
Total commercial passengers (in+out)						976.032

Table 18: H2 Scenario example GAE 2045.

2045						
Passengers scheduled (Traditional kerosene/SAF mixture)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
Total scheduled-passengers (in+out)						0
Passengers leisure (Charter & LCC) (Traditional kerosene/SAF mixture)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
Antalya	189	90%	3	Summer	180	30.618
Barcelona	232	90%	3	Year-round	300	62.640
Burgas	189	90%	2	Summer	120	20.412
Faro	232	90%	2	Summer	120	25.056
Ibiza	189	90%	2	Summer	120	20.412
Kos	189	90%	2	Summer	120	20.412
Heraklion	189	90%	3	Summer	180	30.618
Las Palmas	232	90%	2	Year-round	200	41.760
Malaga	232	90%	3	Year-round	300	62.640
Mallorca	232	90%	3	Summer	180	37.584
Rhodes	189	90%	2	Summer	120	20.412
Tenerife	232	90%	2	Year-round	200	41.760
Total leisure-passengers (in+out)						414.324
Passengers battery-electric (9-30 seaters)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
Amsterdam	30	70%	21	Year-round	2100	44.100
Berlin	30	70%	14	Year-round	1400	29.400
Brussels	30	70%	10	Year-round	1000	21.000
Dublin	30	70%	5	Year-round	500	10.500
Eindhoven	30	70%	14	Year-round	1400	29.400
Frankfurt	30	70%	10	Year-round	1000	21.000
Gothenburg	30	70%	5	Year-round	500	10.500
Maastricht	30	70%	14	Year-round	1400	29.400
Munich	30	70%	10	Year-round	1000	21.000
Nice	30	70%	5	Summer	300	6.300
Oslo	30	70%	5	Year-round	500	10.500
Paris	30	70%	14	Year-round	1400	29.400
Zurich	30	70%	10	Year-round	1000	21.000
Total battery-electric-passengers (in+out)						283.500
Passengers GH2 (9-30 seaters)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
Hamburg	30	70%	7	Year-round	700	14.700
Rotterdam	30	70%	21	Year-round	2100	44.100
Total GH2 passengers (in+out)						58.800
Passengers LH-2 (50-120 seaters)	**CAP**	**SLF**	**Freq/wk**	**Season**	**flights**	**pax**
Copenhagen	50	70%	14	Year-round	1400	49.000
Innsbruck	120	70%	4	Winter	160	13.440
London	80	70%	14	Year-round	1400	78.400
Manchester	80	70%	10	Year-round	1000	56.000
Milan	50	70%	14	Year-round	1400	49.000
Prague	50	70%	10	Year-round	1000	35.000
Scandinavian Mountains	120	70%	3	Winter	120	10.080
Stockholm	50	70%	3	Year-round	300	10.500
Berlin	50	70%	7	Year-round	700	24.500
Vienna	120	70%	4	Year-round	400	33.600
Zurich	50	70%	5	Year-round	500	17.500
Total LH2-hydrogen-passengers (in+out)						377.020
Total scheduled-passagies (in+out)						0
Total leisure-passengers (in+out)						414.324
Total battery-electric-passengers (in+out)						283.500
Total GH2-hydrogen-passengers (in+uit)						58.800
Total LH2-hydrogen-passengers (in+uit)						377.020
Total commercial passengers (in+out)						1.133.644

Table 19: H2 Scenario example GAE 2050

2050						
Passengers scheduled (Traditional kerosene/SAF mixture)	CAP	SLF	Freq/wk	Season	flights	pax
Total scheduled-passengers (in+out)					-	0
Passengers leisure (Charter & LCC) (Traditional kerosene/SAF mixture)	CAP	SLF	Freq/wk	Season	flights	pax
Burgas	189	90%	2	Summer	120	20.412
Las Palmas	232	90%	2	Year-round	200	41.760
Tenerife	232	90%	2	Year-round	200	41.760
Total leisure-passengers (in+out)						103.932
Passengers battery-electric (9-30 seaters)	CAP	SLF	Freq/wk	Season	flights	pax
Brussels	30	70%	10	Year-round	1000	21.000
Dublin	30	70%	5	Year-round	500	10.500
Eindhoven	30	70%	21	Year-round	2100	44.100
Frankfurt	30	70%	10	Year-round	1000	21.000
Gothenburg	30	70%	5	Year-round	500	10.500
Maastricht	30	70%	21	Year-round	2100	44.100
Nice	30	70%	5	Summer	300	6.300
Oslo	30	70%	7	Year-round	700	14.700
Total battery-electric-passengers (in+out)						172.200
Passengers GH2 (9-30 seaters)	CAP	SLF	Freq/wk	Season	flights	pax
Hamburg	30	70%	7	Year-round	700	14.700
Rotterdam	30	70%	21	Year-round	2100	44.100
Total GH2 passengers (in+out)						58.800
Passengers LH-2 (50-150 seaters)	CAP	SLF	Freq/wk	Season	flights	pax
Antalya	120	90%	5	Summer	300	32.400
Amsterdam	50	70%	21	Year-round	2100	73.500
Barcelona	120	90%	7	Year-round	700	75.600
Copenhagen	80	70%	14	Year-round	1400	78.400
Faro	120	90%	5	Summer	300	32.400
Ibiza	150	90%	7	Summer	420	56.700
Berlin	50	70%	14	Year-round	1400	49.000
Kos	80	90%	7	Summer	420	30.240
Innsbruck	120	70%	4	Winter	160	13.440
Heraklion	80	90%	8	Summer	480	34.560
Lisbon	80	70%	5	Year-round	500	28.000
London	80	70%	14	Year-round	1400	78.400
Malaga	80	90%	10	Year-round	1000	72.000
Mallorca	120	90%	7	Summer	420	45.360
Manchester	50	70%	7	Year-round	700	24.500
Milan	50	70%	7	Year-round	700	24.500
Munich	50	70%	10	Year-round	1000	35.000
Paris	50	70%	14	Year-round	1400	49.000
Prague	120	70%	5	Year-round	500	42.000
Rhodes	80	90%	5	Summer	300	21.600
Rome	150	70%	3	Year-round	300	31.500
Scandinavian Mountains	120	70%	3	Winter	120	10.080
Stockholm	50	70%	5	Year-round	500	17.500
Vienna	120	70%	4	Year-round	400	33.600
Zurich	50	70%	10	Year-round	1000	35.000
Total LH2-hydrogen-passengers (in+out)						1.024.280
Total scheduled-passagies (in+out)						0
Total leisure-passengers (in+out)						103.932
Total battery-electric-passengers (in+out)						172.200
Total GH2-hydrogen-passengers (in+uit)						58.800
Total LH2-hydrogen-passengers (in+uit)						1.024.280
Total commercial passengers (in+out)						1.359.212

Appendix C: Cost Estimations Hydrogen Production

Table 20: Hydrogen production cost estimations

Study	Type of costs	Today (2019/2020)	Short and medium-term (2030/2035/2040)	Long-term (2050)
McKinsey & Company et al. (2020)	Unit costs green hydrogen		Europe: 2.6–3.5 USD/kgH_2 Imports: 2.4 USD/kgH_2	
IEA (2021)	Production costs green hydrogen	3.5–7.5 USD/kgH_2	1.5–3.5 USD/kgH_2	1.0–2.5 USD/kgH_2
NLR and SEO (2021)	Production costs green hydrogen			Europe: 2.2 EUR/kgH_2
NLR (2020)	Production costs green hydrogen	Europe: 8.0 EUR/kgH_2	Europe: 3.0 EUR/kgH_2	Europe: 2.2 EUR/kgH_2
ATAG (2021)	Production costs green hydrogen (=IEA's estimates)	3.5–7.5 USD/kgH_2		1–2.5 USD/kgH_2
ATAG (2021)	Distribution, liquefaction, storage, refueling	+1.2 USD/kgH_2 = 4.7–8.7 USD/kgH_2		+1.2 USD/kgH_2 = 2.2–3.7 USD/kgH_2
Steer and DLR (2023)	Unit costs green hydrogen	Europe: 6.33 EUR/kgH_2	Europe: 5.00 EUR/kgH_2	Europe: 4.00 EUR/kgH_2
Steer (2023)	Unit costs green hydrogen		Europe: 3.90 EUR/kgH_2	Europe: 3.45 EUR/kgH_2
Steer (2024) Gronau et al. (2023)	Unit costs + infrastructure			+0.52 EUR/kgH_2 = 3.97 EUR/kgH_2
	Unit costs + infrastructure + aircraft development			+0.71 EUR/kgH_2 = 4.16 EUR/kgH_2
	Unit costs green hydrogen + infrastructure			Europe: 2.71 EUR/kgH_2

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AirportCreators

airportcreators.com
hello@airportcreators.com

+31 (0) 20 899 0000

Tupolevlaan 93
1119 PA Schiphol-Rijk
The Netherlands