Integrating liquid hydrogen infrastructure at airports: Conclusions from an ecosystem approach at Rotterdam The Hague Airport

Received (in revised form): 9th April, 2024

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Abstract

Aviation is a contributor to global warming. Hydrogen-powered aircraft are seen as an important option to decarbonise parts of commercial aviation. Airports have a pivotal role in facilitating the development of ground infrastructure. This paper provides a broader perspective on the supply and handling of liquid hydrogen, and necessary airport developments, to enable hydrogen-powered aviation. Hydrogen-related airport development projects at Rotterdam The Hague Airport (RTHA) are presented and discussed, and a detailed overview of the airport's liquid hydrogen (LH_2) storage facility is given. To link the ongoing developments to future needs, a LH_2 demand scenario for RTHA is determined for the years 2040 and 2050. Based on this demand, analysis of levelised cost of hydrogen for relevant value chains were conducted. This study exemplifies that the LH_2 value chain for an airport depends on individual characteristics of the airport and its surroundings. The hydrogen demand, the airport's proximity to larger hydrogen hubs (import and/or production hubs) and the availability of local renewable resources, which influence electricity price and hydrogen production and liquefaction costs, are key parameters and heavily influence the airport LH_2 value chain. Conceptualisation and future development of hydrogen infrastructure for airport supply should take into account the above factors. LH_2 demand *at RTHA in the year 2050 is predicted to range between 8–14kt. Under the given electricity price assumptions, local production and liquefaction of hydrogen at the airport is not seen as a viable option, as cost savings can be achieved by making use of the Port of Rotterdam's large hydrogen production and import cluster nearby. The work shows that trailer-based logistics for both the delivery of* LH_2 *to the airport and subsequent usage of these trailers in the storage and dispensing process at the airport seems the most viable for RTHA (and airports that show similarities). This further indicates that current small-scale* LH_2 *demonstration at airports provides important lessons for scaling up.*

Keywords

sustainable aviation, hydrogen, liquid hydrogen, LH_2*, value chains, hydrogen storage, airport development, airport operations, environmental management, sustainability*

INTRODUCTION

Decarbonising aviation: Hydrogen as one of the complementary methods

Aviation is one of the fastest-growing sources of greenhouse gas (GHG) emissions and affects global climate due to its CO_2 and non-CO_2 emissions. Direct emissions from aviation accounted for 3.8 per cent of total CO_2 emissions in the European Union (EU) in 2017,[1] thereby not taking into account non-CO_2 effects such as contrail formation, nitrogen oxides, water vapour, sulphate and soots. The European Green Deal[2] has set out the aim to reduce overall transport emissions by 90 per cent in 2050 compared to 1990. To achieve these reductions, a strong contribution from transport modalities is needed, including the aviation sector.

Making aviation more sustainable can be achieved through the development and implementation of multiple complementary methods. Destination 2050[3] presents a pathway to net zero CO_2 emissions in aviation; this includes methods such as improved air traffic management and operations, economic measures, the use of sustainable aviation fuels (SAF) and innovative aircraft and engine technologies such as hydrogen-powered aircraft and (hybrid-)electric aircraft. The study underlines the need to develop complementary methods, as there is no silver bullet. SAF, battery-electric aviation and hydrogen-powered aviation all have their own benefits and challenges but are all needed in order to decarbonise aviation.

Battery-electric aviation is traditionally not considered as a mainstream decarbonisation method given the current low energy density of (lithium-ion) batteries compared to kerosene and the corresponding low applicability in commercial aviation.[4,5] This is, however, challenged by recent studies[6,7] that show the potential of a 90-seater battery-electric regional aircraft, the E9X, by Elysian Aircraft. Short-term developments in the battery-electric domain focus on the electrification of general aviation, and specifically the flight trainer segment, such as the development of the electric model of the Daimond DA40, the eDA40.

Airports with a (large) general aviation segment can expect electrification in the upcoming years and need to adapt by introducing charging infrastructure at the airport. As reference, roughly one-third of the flight movements at Rotterdam The Hague Airport (RTHA) falls within the category 'flight lessons', which basically translates to most trainer flights up to an hour, a segment that is suitable to electrify in the near future. Decarbonising commercial aviation, however, requires more.

SAF and hydrogen are more widely considered as decarbonisation methods for current narrow- and wide-body operations. SAF has a main advantage as it can be used as a drop-in fuel in existing jet engines. It can therefore be used for existing fleets and has limited impact on airport infrastructure and fuel procedures, compared to the infrastructure and operational adjustments needed for battery-electric and hydrogen-powered aviation.[8] The new ReFuelEU Aviation regulation[9] obliges fuel suppliers at European airports to gradually increase the share of SAF in the form of biofuels and synthetic aviation fuels to 6 per cent in 2030 and 70 per cent in 2050. RTHA accelerates this effort by setting itself a minimum extra target of 8 per cent until 2030 to meet the more ambitious goal of the Dutch aviation sector of 14 per cent by 2030.[10]

Liquid hydrogen (LH_2), the state of hydrogen when cooled down to a cryogenic temperature of -253°C, as a fuel delivers around three times the energy per unit mass of conventional kerosene. To carry the same amount of total energy on board, however, the needed volume of LH_2 is around four times bigger than the needed volume of kerosene. This has an impact on the expected range and payload of hydrogen-powered aircraft and thereby the applicability of hydrogen as a fuel for aviation. Therefore, it is most likely that hydrogen-powered aircraft will play a role in decarbonising the current single-aisle narrow-body market. Intra-European aviation (flights within Europe between both EU and non-EU countries mostly carried out with single-aisle aircraft) emitted over 100Mt of CO_2 in 2019, which equate to 14 per cent of the total global passenger CO_2 emissions.[11] Regional and narrow-body aircraft, such as the Embraer 190 and Boeing 737-800 respectively, accounted for roughly 58 per cent of total global passenger CO_2 emissions.[12] By introducing greener alternatives for these aircraft classes, a potential reduction in climate impact for short and medium-haul flights could be achieved. Destination 2050[13] estimates that hydrogen-powered aircraft on intra-European routes can reduce up to 20 per cent net CO_2 of total European aviation emissions by 2050.

Aircraft manufacturer Airbus has plans to bring a short and medium-haul hydrogen-powered aircraft to market in 2035. The company has announced different configurations within its ZEROe project (see Figure 1). Among these are turboprop (<100 pax) and turbofan (<200 pax) hydrogen-powered aircraft with an expected range of 1000 and 2000nm respectively.[14] Other companies including ZeroAvia, H2FLY, Conscious Aerospace and Universal Hydrogen are currently developing fuel cell-based powertrains which will be used to retrofit existing turboprop aircraft such as the DHC Dash-8 and ATR 72. Hydrogen-powered aviation will evolve in the upcoming years and will play an important role in transforming aviation into a more sustainable mode of transport. Airports are necessary stakeholders to facilitate this transformation.

The role of airports in facilitating hydrogen-powered aviation

The aviation industry is currently kerosene-dominated, which is reflected by aspects like (kerosene) fuel storage and refuelling infrastructure, Joint Inspection Group (JIG) refuelling standards on airside and the organisational capabilities

Figure 1 Airbus ZEROe turboprop concept with visible refueller on the left side
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of airport operators. A recent study by Babuder *et al.*[15] shows a significant impact on airport infrastructure such as fuel depots, maintenance hangars and refuelling systems when hydrogen-powered aviation is introduced. A lower impact is expected on aprons and aircraft stands that might need modifications due to safety concerns and regulatory restrictions (which are still under development).

The introduction of hydrogen-powered aircraft requires airports to adapt and facilitate operations that are centred around hydrogen. Airport operators therefore need to start analysing how they would facilitate hydrogen-powered aircraft at their airports in the future. The new ReFuelEU Aviation regulation[16] even states that airports should

> undertake efforts to facilitate the access of aircraft operators to hydrogen or electricity used primarily for the propulsion of an aircraft and to provide the infrastructure and services necessary for the delivery, storage and uplifting of such hydrogen or electricity to refuel or recharge aircraft in line with national policy frameworks for deployment of alternative fuel infrastructure where relevant.

Hydrogen will be new for many airports. Airports therefore most likely need to start from scratch when setting up new value chains with stakeholders to allow the provision of hydrogen at their airports. The current lack of LH_2 value chains, regulations and frameworks for the development and deployment of infrastructure for LH_2 supply to and within airports (especially refuelling) are a main obstacle for the adoption of hydrogen-powered aviation. There is a significant amount of literature on hydrogen value chains for vehicle refuelling stations,[17,18] while literature on value chains for airports is still limited. On top of that, the adaptation of airport personnel — including airport operator personnel, ground handling personnel and airport rescue and firefighting — needs to be taken into account in order to introduce hydrogen at the airport in an efficient and safe manner.

Hydrogen value chains for airports

Incorporation of green hydrogen in the European energy system is one of the main enablers for decarbonisation in Europe.[19,20] There is a general lack of scaled hydrogen value chains, but their establishment is a strategic European priority. Transformation in this particular area will be particularly visible in the Rotterdam region in the coming decade. As from 2023, the potential for offshore wind production in the North Sea,[21] the initiation of a hydrogen transport pipeline network[22,23] and investments in electrolysis,[24,25] supplemented by hydrogen imports, may transform the Rotterdam region into a hydrogen hub for Europe.[26] RePowerEU[27] states ambitions for 10Mt (333TWh) hydrogen import and 10Mt produced in the EU by 2030. Given this total, Rotterdam has the ambition to import 4Mt and produce 0.6Mt locally.[28] Critical infrastructure includes production sites, (import) storage facilities, liquefaction plants and hydrogen pipelines for transport.

Value chain studies for hydrogen are often focusing on the delivery of gaseous hydrogen for vehicles or power production; however, hydrogen-powered aircraft are likely to require hydrogen in liquefied form onboard. This influences the evaluation drastically, as all hydrogen value chain pathways require a liquefaction step.

At a handful of airports, hydrogen has been used to a minor extent on airside for the demonstration of hydrogen-powered ground support equipment and/or for serving fuel cell electric vehicles. A hydrogen-powered ground power unit (GPU) and tow tractor are under demonstration at Amsterdam Airport Schiphol as part of the European TULIPS project. For the transformation to hydrogen-powered aviation, however, much larger volumes and corresponding delivery of (liquid) hydrogen are required at airports. Recent studies have considered the specific use case of hydrogen value chains for airports. Hoelzen *et al.*[29] conducted an economic study of hydrogen infrastructure within airports. The main findings of this study indicated a strong dependency between the scale of the system and the cost of hydrogen. Larger volume demand of LH_2 allowed for investment in larger, more efficient liquefaction plants. The hydrogen production and potential transport to the airport was outside the research scope. In all cases, hydrogen pipelines, local liquefaction and a constant electricity price was assumed. Given the identified scaling benefit and strong impact of the electricity price, other options are worthwhile to investigate.

Main future routes for hydrogen to airports according to Hoelzen are:

1. Offsite liquefaction with transport of LH_2 to the airport by lorry(lorries)/trailer or by rail or barge when suitable. Locally at the airport, LH_2 storage and refuelling infrastructure is required. The LH_2 trailers can in this case, if applicable at the airport, serve as mobile storage units as well.
2. Offsite hydrogen production (or

import) and transport of gaseous hydrogen though pipelines. Locally at the airport, on top of the required LH_2 storage and refuelling infrastructure, a hydrogen liquefaction facility is required to liquify the gaseous hydrogen.

3. Onsite hydrogen production, liquefaction and storage. This is the most local infrastructure-intensive route, with the need of a hydrogen production facility (including a source of renewables when considering green hydrogen and electrolysis), a hydrogen liquefaction facility, storage and refuelling infrastructure.

Hydrogen value chain developments around the Rotterdam region

The transition towards hydrogen-powered aviation requires infrastructure for hydrogen production, liquefaction and distribution. Rotterdam is one of the few European sites where such infrastructure exists or is being established. The Port of Rotterdam houses one of the few hydrogen liquefaction plants in Europe. The current production capacity is 5tpd of grey LH_2, with a plaNned capacity increase in 2025 that will double Europe's total current LH_2 capacity.[30] A local hydrogen pipeline is under construction and will be operative from 2025 in the port region.[31] An extension to the future European Hydrogen Backbone is planned in 2028–29. Investments in electrolysis for hydrogen production are emerging.

In the Port of Rotterdam there are currently multiple spots reserved for electrolysers to make use of a wind farm connection of, in total, 7.4GW (containing one 1.4GW and three 2GW wind farms). A 200MW electrolyser, the Holland Hydrogen 1 by Shell, is currently under development.[32] In combination with certificates of origin, green hydrogen can be guaranteed.

Even though the generation of renewable electricity in Europe is increasing, availability of low-carbon hydrogen is a limitation.[33] An intermediate solution would be the production of blue hydrogen. With a high degree of carbon capture and control of methane slip, blue hydrogen can compete with green hydrogen on cost in the coming decades, and thereby reduce the competition for electric power.[34] A blue hydrogen production plant is also planned in Rotterdam, operational from 2026.[35] In addition to these plans, the Port of Rotterdam estimates that the amount of imported green and/or low carbon hydrogen in 2050 could rise to 18 million tons, thereby relying on large amounts of imported hydrogen versus locally produced hydrogen in the future.

Developments in the field of hydrogen production (see Figure 2) and import are linked to the introduction of hydrogen at airports and one should take into account that local characteristics, such as the hydrogen demand and the proximity of hydrogen production, import and distribution clusters, play a significant role in establishing the hydrogen value chain for a specific airport. Combining the hydrogen demands of multiple (local) customers inside and outside the aviation domain can help in the development of the hydrogen value chain for airports. These developments influence the choice of partners to create the value chain with the formation of the hydrogen supply chain to the airport and the associated costs. RTHA can benefit from existing hydrogen value chains that originate in the Rotterdam region and those under development. Developments and learnings in this

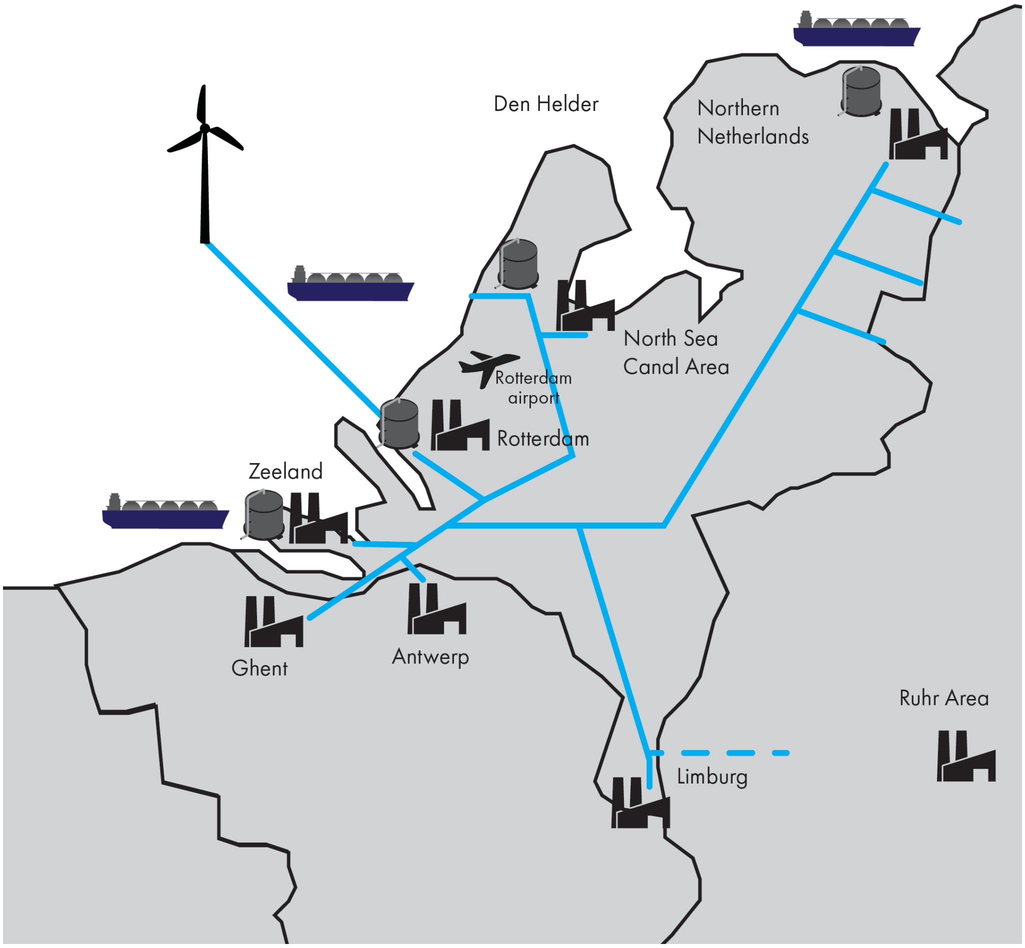

Figure 2 Hydrogen production and import hubs in The Netherlands including national pipeline connections and connections with the European Hydrogen Backbone

specific domain can be shared with fellow airport operators.

Scope of this paper

In this paper, we present insights into the different aspects of the hydrogen value chain that are necessary for the introduction of hydrogen at airports. Ongoing demonstration and implementation projects for hydrogen infrastructure and operations at RTHA — with emphasis on a small-scale LH_2 storage facility for refuelling — will be presented. Next to that, a hydrogen demand forecast for RTHA and a corresponding estimated levelised cost of LH_2 delivery for different value chain routes to the airport will be presented, after which the impact of the preferred value chain on airport infrastructure and operations will be evaluated.

HYDROGEN DEVELOPMENTS AT ROTTERDAM THE HAGUE AIRPORT

Rotterdam The Hague Airport (EHRD/RTM) is a regional airport located in The Netherlands and part of the Royal Schiphol Group. The airport facilitated around 56,000 aircraft movements and

2.2 million passengers in 2023 and handles commercial traffic, (recreational) general aviation and HEMS/police operations. Commercial activities at the airport, around 16,000 aircraft movements in 2023, are mostly carried out with narrow-body aircraft such as the Boeing 737, Airbus A319/320 and the Embraer 190. The airport serves destinations including London City, Malaga, Faro, Lisbon and Barcelona by main carriers Transavia, British Airways and TUI, among others.

The airport is ACA-level 5 accredited — the highest level in the Airport Carbon Accreditation programme and thereby committing to net zero in Scope 3 emissions by 2050 or sooner — and serves as an innovation platform within the Schiphol Group for the integration of hydrogen-powered aviation at airports. Characteristics of the airport are summarised in Table 1.

The destinations that are served by the airport, mostly short and medium-haul, are suitable to be replaced in the long term by hydrogen-powered aircraft such as the Airbus ZEROe turboprop or turbofan. Figure 3 gives an indication of the expected range of these Airbus ZEROe aircraft from RTHA and the currently served destinations from RTHA. The map does not indicate unserved destinations by the airport. The introduction of zero-emission aircraft might open up opportunities for the introduction of new routes.

The airport is situated in a relatively unique catchment with Europe's biggest seaport, the Port of Rotterdam, just around the corner. The port plays a vital role in the current arrival, production and distribution of energy streams in northwest Europe — currently dominated by fossil fuels, but gradually

Table 1 Characteristics of Rotterdam The Hague Airport

Characteristics of RTHA	
Airport type	Public (level 3 slot coordinated)
ICAO/IATA	EHRD/RTM
Airport capacity	RTHA is not limited by number of movements but by a yearly noise quota. The number of available slots therefore depends on assumptions for distribution over a 24 hour period and the types of aircraft used.
Runway details	06 — 2,199 metres 24 — 2,199 metres
Number of passengers (2023)	2.224.276 pax
Total amount of aircraft movements (2023)	56,480
– commercial aviation	16,530
– business aviation	6,310
– emergency services	5,780
– other aviation (among it recreational)	27,860
Main carriers	Transavia, TUI, British Airways, Pegasus
Aircraft stands for commercial aviation	There are 12 remote stands based on ICAO size C (max. wingspan 36 metres) which feature power-in power-out (PIPO) procedures. ICAO size D or E aircraft require special permission.
Fuelling	JET-A1 is provided by a single fuel supplier that uses a 'pendulum operation' which features the supply of mobile storage trailers from the production site in the Port of Rotterdam to the airport and distribution of the same trailers on airside by a dispensing vehicle.

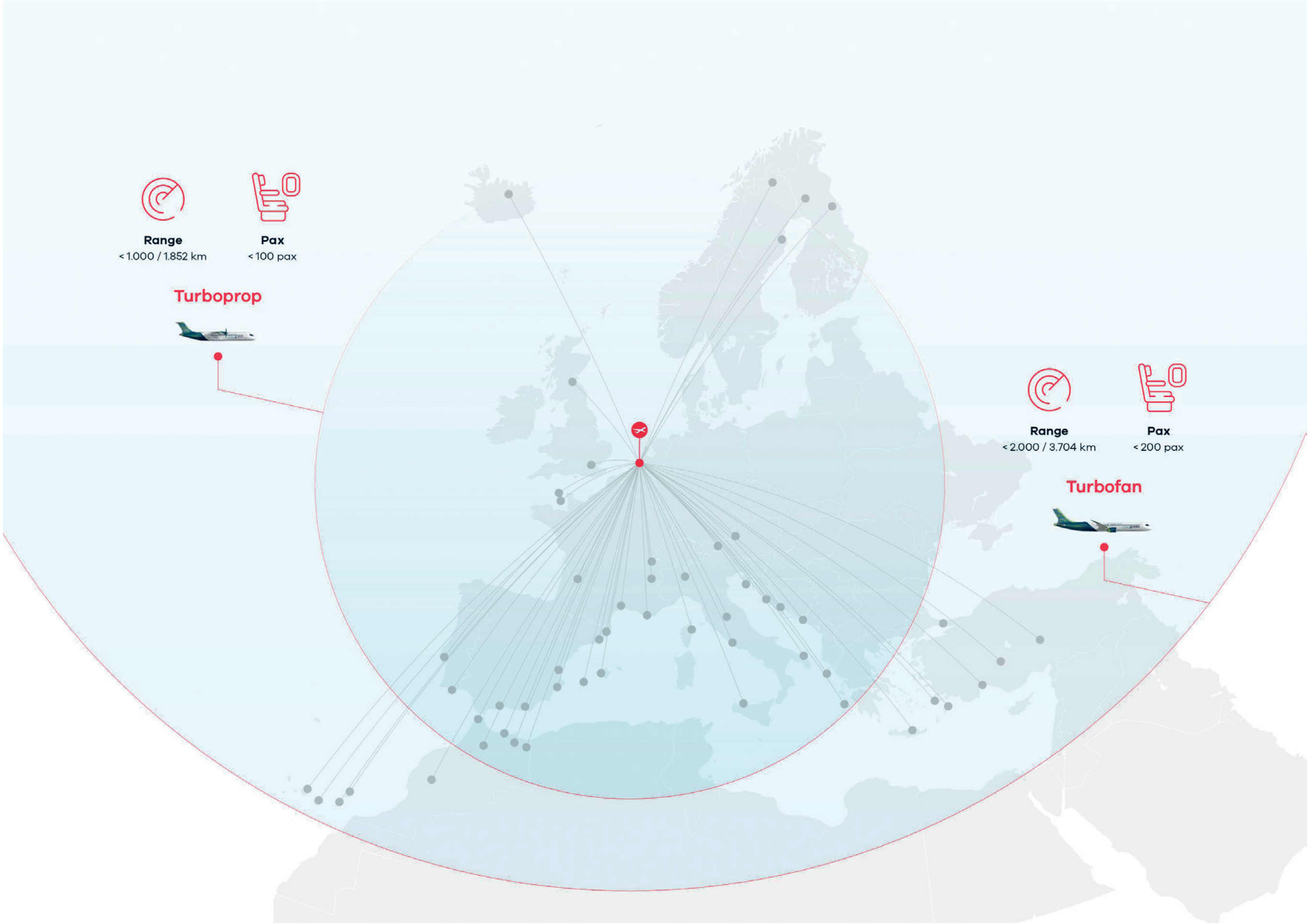

Figure 3 Expected Airbus ZEROe hydrogen-powered aircraft ranges and served destinations (grey dots) from RTHA in the year 2023

more focused on sustainable energy carriers. SAF and hydrogen, either locally produced or imported, will eventually become readily available just around the corner of the airport. The Delft University of Technology (TU Delft), including its Faculty of Aerospace Engineering which is focused on research and education in the field of sustainable aviation, is around the corner as well. The university's flight test operation base and hangar, which it shares with the Royal Netherlands Aerospace Centre (NLR), is also located at the airport. Both the TU Delft and NLR have the ambition to retrofit respectively a Cessna Skymaster and a Pipistrel Velis Electro with hydrogen propulsion systems. Knowledge and resources of (regional) industry parties and research institutes can be used for the further development of sustainable aviation, and especially hydrogen-powered aviation, at RTHA. The airport's ecosystem is visualised in Figure 4.

Hydrogen-related projects at RTHA

Multiple hydrogen-related projects, which range from research and

Figure 4 RTHA and its surrounding ecosystem including the Port of Rotterdam, Delft University of Technology and Amsterdam Airport Schiphol

development projects to infrastructure developments, take place at the airport and are presented in Table 2. The airport is geared towards the co-development of hydrogen-powered aviation and emphasises the need for integration of this new type of aviation at airports. The impact of hydrogen-powered aviation on airport operations, the supply of hydrogen to airports, hydrogen refuelling, (fire) safety and small-scale integration tests are focus areas of the airport's research and development team, among others.

Next to existing projects, the airport collaborates with the Port of Rotterdam on developing the hydrogen supply chain from the port to the airport and with Hamburg Airport. RTHA and Hamburg Airport joined forces on the realisation of a hydrogen corridor between the two port cities focusing on a demonstration flight in 2026. Both airports show similarities when it comes to nearby green energy clusters and their innovation ecosystem. Current work is done in the field of airport infrastructure and ground operations and commercialisation of a potential future route. The airport has also started the DutcH$_2$ Aviation Hub programme which aims to further develop hydrogen-powered aviation by creating a community around the entire hydrogen value chain.

Liquid hydrogen storage and dispensing facility at RTHA

RTHA is part of the European TULIPS project[36] and facilitates experiments to further develop hydrogen-powered aviation. TULIPS aims to demonstrate innovative solutions that enhance sustainability at airports. Within the project, the feasibility of LH$_2$ fuelling operations on an active airport are demonstrated by fuelling and flying a LH$_2$-powered drone, the HYDRA 2. The drone, owned by NLR, will be fuelled at a location

Table 2 Hydrogen projects at RTHA

Project	*Technology testing and demonstration*	*Expected TRL and scale*	*Timeframe*	*Involved partners*
TULIPS	Demonstration of a LH_2 refuelling and turnaround process executed with a drone. Procedures will be written as if a regular LH_2 will be active on the airport	TRL 6 | ~280g LH_2	2024	NLR, Air Products, Pipistrel
	Realization of a small-scale storage tank to store and dispense LH_2 at the airport	TRL 7 | ~9kg LH_2	2024	NLR, Air Products, RTHA, Cryoworld
H_2 leakage detection	Installation of (hydrogen) gas leakage sensors at the LH_2 storage facility. Controlled leakage and incident response by the ARFF will be demonstrated	TRL 7	2025	NLR, Veiligheidsregio Rotterdam and airport fire brigade
ALBATROS	Maintain a high level of safety in aviation in view of changes brought about by new fuel and energy systems (including hydrogen). Including a fully demonstrated emergency landing with a 'hydrogen aircraft' including incident response	Up to TRL 6	2023 – 2027	NLR, Pipistrel, Onera, Athens Airport, CIRA, DLR, Airbus, Aegean and others
Hydrogen refuelling station (HRS)	Realisation of a HRS for (heavy-duty) vehicles (350 and 700 bar) on landside including a potential pipeline link to and dispenser on airside	TRL 9	2024–	Fountain Fuel, Linde Gas
Conscious Aerospace (HAPPS)	Accommodating tier one system integrator Conscious Aerospace which develops a hydrogen fuel cell powertrain at a development centre (hangar) at the airport	TRL 3 – 4	2024–28	Conscious Aerospace, Zepp Solutions, Cryoworld, TU Delft, NLR and others
AeroDelft	GH_2 refuelling and LH_2 refuelling demonstration and ground tests (taxiing) with Sling 4 aircraft that will be retrofitted by TU Delft students	TRL 6 | ~2.1kg GH_2 and ~ 8kg LH_2	2024–26	AeroDelft, Air Products, NLR, TU Delft and other partners of AeroDelft
ZeroAvia	GH_2 refuelling and flight demonstration with Cessna Grand Caravan (outfitted with ZA600 powertrain)	TRL 7 | ~80kg GH_2	2025–26	ZeroAvia
GOLIAT	LH_2 refuelling demonstration via a ground refueller and trailer including a research project on future LH_2 operations at airports and infrastructure needs. Refuelling and ground (taxi) demonstrations will be performed with the HY4 aircraft	TRL 6 | ~3 ton LH_2	2024–28	Airbus, H2FLY, Chart Industries, TU Delft, Leibniz University Hannover, Stuttgart Airport, Lyon Airport, Royal Schiphol Group, VINCI Airports and Budapest Airport

ALBATROS is funded by the European Union under grant number 101077071
GOLIAT is funded by the European Union under grant number 101138379

designated for hydrogen operations at RTHA, after which it will fly a predetermined route at the airport. The drone can fly on hydrogen by using its onboard fuel cell technology. The hydrogen is supplied to the fuel cell from the internal LH_2 storage tank, suspended from the bottom of the drone (see Figure 5).

The LH_2 facility at the airport will be developed in order to facilitate the storage and dispensing of LH_2. Initially, the facility will be used to provide LH_2 to the HYDRA 2 drone. This particular operation will lead to learnings on the realisation of LH_2 infrastructure and operations at airports. The facility can be used in a later stage by retrofitted code letter A aircraft from, for instance, AeroDelft, NLR, TU Delft and others, as it is accessible for these types of aircraft.

The facility is located at Platform Lima, an operational part of the airport where handling of recreational general aviation takes place. Platform Lima at RTHA is dedicated to code letter A aircraft with a maximum wingspan of 13.5 metres and

Figure 5 The LH_2-powered HYDRA 2 drone

has several aircraft stands connected to the platform. One aircraft stand in this row will be used to develop the LH_2 storage facility (see Figures 6 and 7). The facility serves as a case to learn about the supply, storage, use and dispensing of LH_2 on an active EASA airport.

A quantitative risk assessment has been executed to assess potential external risks. These results have been used, together with, among others, an installation check and incident response plan, in the environmental permit application that will eventually allow the storage and use of LH_2 at the airport's premise.

The LH_2 facility, including the storage dewar — a storage tank with a vacuum used for storing liquefied gases — is stationary and will act as a location that will be used for aircraft-to-fuel operations (see Figure 8). The facility itself must be seen as a research and development facility. Future projects at the airport will focus on fuel-to-aircraft operations, seen as the preferred refuelling method in the future. The LH_2 facility consists of the following main elements (and subsystems):

1. LH_2 dewar and filling adapter;
2. Vent stack;
3. LH_2 trailer delivery platform.

Liquid hydrogen dewar and filling adapter

The LH_2 is supplied to the drone tank from a LH_2 dewar (see Figure 9). The storage capacity of the dewar is 125L, which equates to approximately 9kg of LH_2. This quantity of LH_2 will be enough to fuel the drone multiple times and is sufficient to fuel future retrofitted code letter A aircraft that can make use of the facility as well.

The dewar is a vacuum-insulated cryogen storage vessel that retains the hydrogen for extended periods of time. Boil-off losses due to the heat input of ambient environment are like any other LH_2 storage tank common. The tank is designed so that boil-off losses are kept to a minimum and are estimated by the

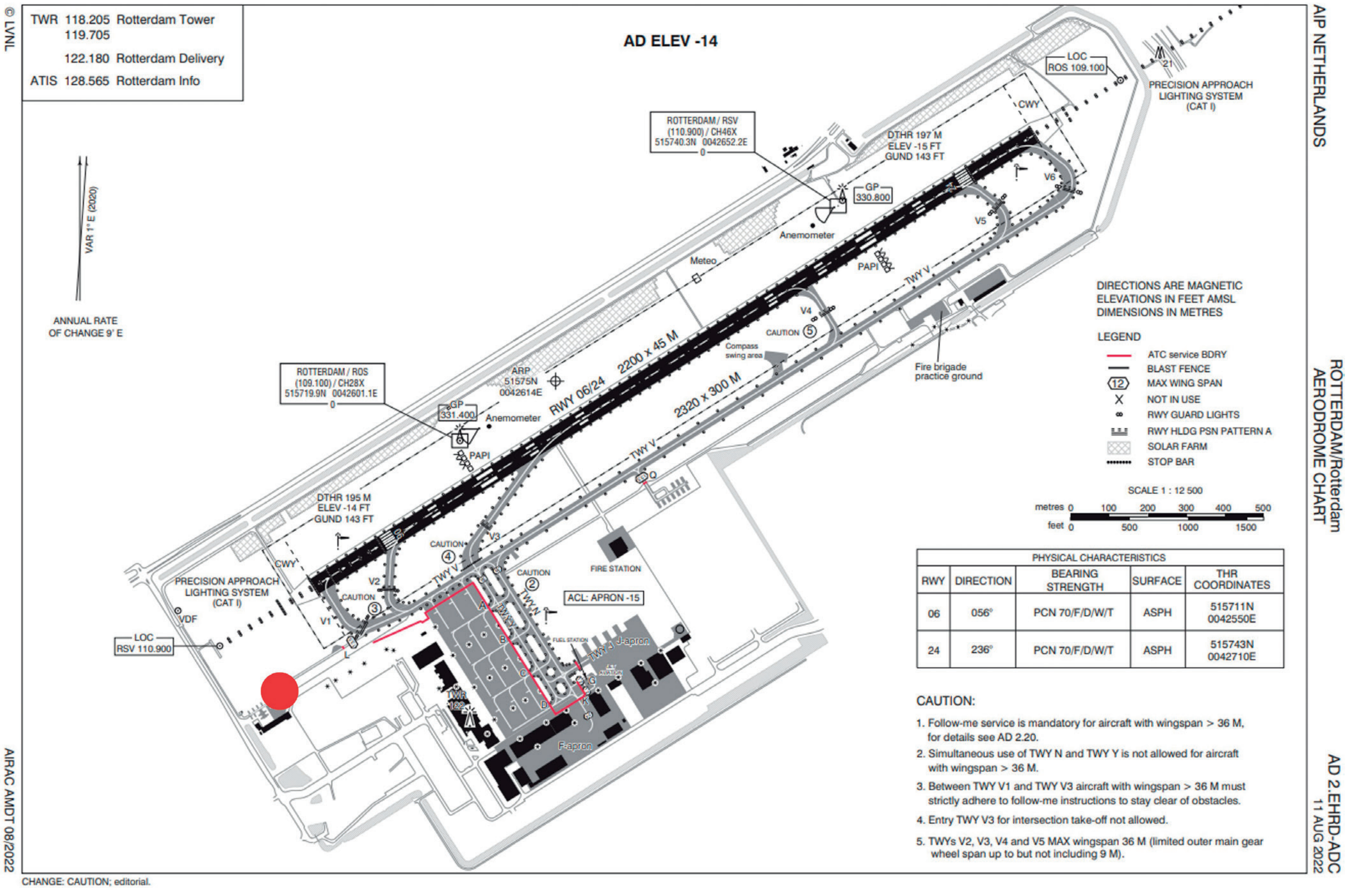

Figure 6 Location of the LH_2 facility at RTHA

manufacturer to be 1.5–2.0 per cent per day during normal operation.

A construction in the form of fences and a sloped roof protects the dewar against the elements and unauthorised persons. The construction allows the area around the dewar to be ventilated, to prevent the potential accumulation of hydrogen under the roof. An obstruction light is placed on the construction, including a solar panel and battery system for the supply of power. These specific assets need to be ATEX certified to ensure that they are compliant to be used in an explosive atmosphere. The installation has been checked according to the Dutch 'PGS-35' guidelines for hydrogen installations. These specific guidelines could not be used completely within the aviation domain as they are optimised for hydrogen refuelling stations and delivery of hydrogen to road vehicles.

The filling adapter (shown in Figure 9, bottom left) is used to make a connection between the LH_2 supply lorry and the dewar. The purpose of the filling adapter is to ensure the correct flow direction as well as act as a pressure relief valve.

Vent stack

The dewar is continuously connected to the vent stack to allow any boil-off to be released as to prevent excessive

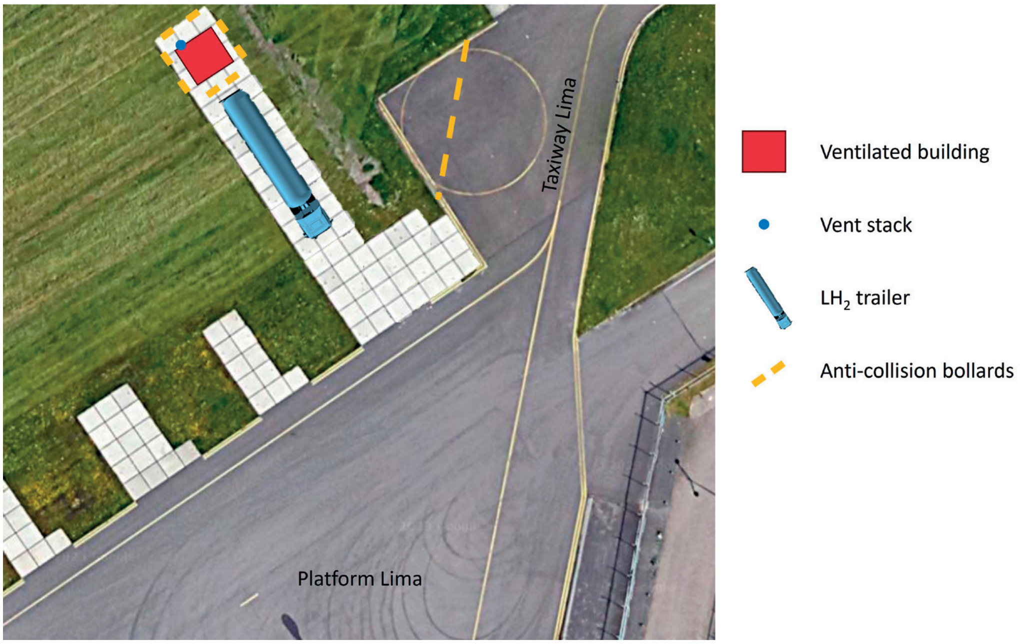

Figure 7 Panoramic view of the LH$_2$ facility

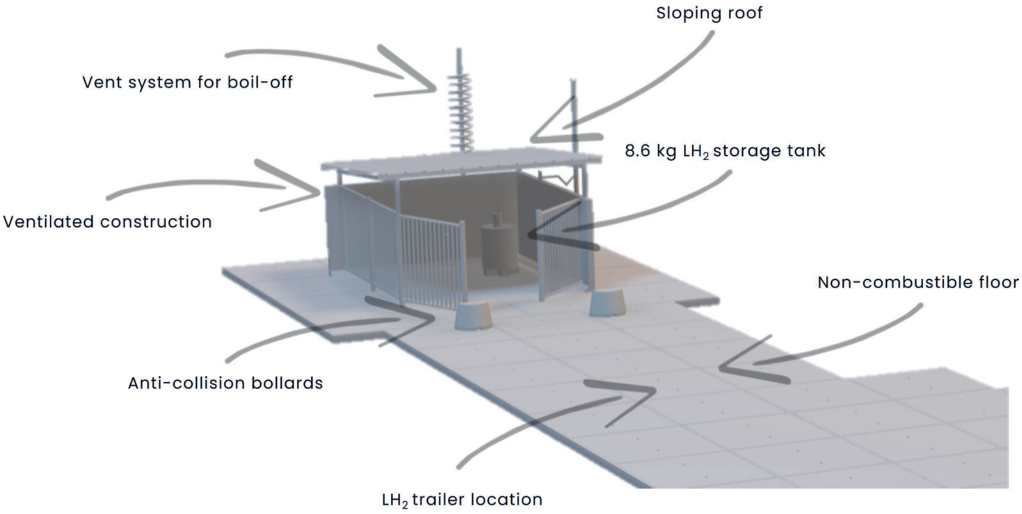

Figure 8 Overview of the subsystems of the LH$_2$ facility

pressure build up in the dewar. The dewar is connected to the vent stack with a flexible vent hose. The vent stack is 7 metres in height to provide additional heat exchange before the cold gas is released and to ensure a certain safety at ground level. This vent stack will allow any gas to be vented if needed and is attached to the facility itself. The boil-off will be vented to the atmosphere. It is likely that larger installations in the future will prevent this energy loss and environmental emissions by reusing or reliquefying the gaseous hydrogen.

Figure 9 The LH_2 facility with the dewar (storage tank) and filling adapter
Source: NLR

Liquid hydrogen trailer delivery platform

The area around the aircraft parking stand will be expanded to allow operations with a regular LH_2 trailer from Air Products (see Figure 10). The trailer has a carrying capacity of approximately 3–4 tons of LH_2 and is typically used for road transport of LH_2. The LH_2 will be brought from Air Products' production and liquefaction plant in the Port of Rotterdam, located 43km from the airport by road. This route could have been shorter, but LH_2 trailers are restricted from being transported through specific tunnels (specifically the Benelux tunnel with tunnel restriction code C). This extends the road distance between the facility and the airport. Overall, the road distance can still be seen as very short, which is advantageous to the airport.

The trailer features a pressurised vessel and a valve box in the rear that allows the operator to perform both filling and purging without any additional equipment required onsite. All fuelling operations will be carried out on a non-combustible surface for safety considerations and the delivery platform including the LH_2 facility are subject to a site survey and pre-check by the hydrogen supplier before giving approval to use the facility. Operators are trained to handle the LH_2 and any subcomponents, such as the dewar.

The shortest distance from the LH_2 filling point to potential ground operating vehicles and/or aircraft is 24 metres and a 12 metres clearance distance is taken into account between the front of the lorry and aircraft that taxi at Platform Lima, considering that other aircraft can

Figure 10 LH_2 trailer from Air Products
Source: Air Products

manoeuvre over the platform at the same time as LH_2 refuelling is taking place. The hydrogen supplier prescribes a safety distance of at least 15 metres (23 metres if the storage volume is bigger than 55,000 litres) from the filling point and a 'public way' and 8 metres from the filling point and 'plant roads'. Specific airport infrastructure and users are not listed (yet) in these overviews, as cryogenic installations at airports are fairly new and standards are still under development. The minimum distance of 24 metres at RTHA in this case is on the safe side and allows for potential expansion if needed.

Adaptation of airport personnel and airport rescue and firefighting (ARFF)

Hydrogen and its associated installations are not new, but integrating it on the airport is. As airport operators are eventually responsible for safety on airside, training and knowledge in the field of hydrogen at airports needs to be developed, not only in the domain of infrastructure development, (fire and external) safety and hydrogen operations, but also in the field of environmental permitting.

The development of the LH_2 facility at RTHA, although small, has led to the build-up of organisational knowledge and capabilities on hydrogen handling. For instance, the ARFF has received extra training on how to deal with hydrogen incidents and has prepared an incident response plan in case an incident at the LH_2 facility occurs, while operational personnel at the airport have received a briefing and a manual with contextual information on hydrogen and hydrogen handling sites at the airport. The gained knowledge can be used to further structure hydrogen developments at the airport and can be shared with industry peers through knowledge dissemination.

ROTTERDAM THE HAGUE AIRPORT AND ITS HYDROGEN VALUE CHAIN

Hydrogen demand forecast for RTHA

Initial developments at RTHA only require relatively small volumes, incidental supply of hydrogen and small storage infrastructure. As hydrogen-powered aircraft will become available in the future, the required volumes and corresponding storage and refuelling infrastructure will need to grow. The impact of this volume growth on airport infrastructure can be assessed by looking at certain LH_2 demand forecasts for RTHA in the years 2040 and 2050.

The scenarios are defined in accordance with a study of hydrogen-powered aviation at airports by Hoelzen *et al.*[37] *Low*, *medium* and *high* penetration rates of hydrogen-powered aircraft are defined for 2040 and 2050. Two aircraft types, which more or less correspond to the Airbus ZEROe concept aircraft and the aircraft currently operating at RTHA, are considered: a 100 PAX aircraft, operating flights up to 500 nm with a market entry ~2030–35, and a 200 PAX aircraft operating flights up to 2000 nm with a market entry ~2035–40. The resulting penetration rates are outlined in Table 3.

The projected LH_2 demand is based on historical flight data from RTHA in 2019. The aircraft model and destination are used to calculate the fuel consumption using the Base of Aircraft Data (BADA). First, the meridian arc between RTHA and the destination airport is calculated. This is the most efficient route, but in reality, flight distances are longer. The additional fuel consumption for routing is estimated by Single European Sky to be up to 12 per cent.[38] BADA calculates the total JET-A1 fuel consumption for each flight. To convert fuel consumption from today's commonly used JET-A1 fuel to LH_2, the respective heating values are used:

$$(LHV_{JET} = 42.80\frac{MJ}{kg}, LHV_{LH2} = 119.93\frac{MJ}{kg})$$

In addition, an extra 10 per cent LH_2 is added to account for potentially heavier fuel systems on board.[39] The penetration rates listed in Table 3 are used to estimate the fuel consumption in a *low, medium* and *high* scenario in 2040 and 2050. The demand throughout a year at RTHA in these scenarios is illustrated for 2040 in Figure 11 and for 2050 in Figure 12. The data is smoothened with a 30-day moving average. Table 4 shows annual demand, peak day demand, and daily average demand. Any potential growth over the upcoming years has not been taken into account in order to compare one-on-one replacement with current aircraft movements and operations at RTHA.

Table 3 Overview of scenarios with different penetration rates in 2040 and 2050

	2040	***2050***
Low	20% 100 PAX 0% 200 PAX 4% of total flights replaced	40% 100 PAX 20% 200 PAX 24% of total flights replaced
Medium	30% 100 PAX 15% 200 PAX 18% of total flights replaced	60% 100 PAX 50% 200 PAX 52% of total flights replaced
High	50% 100 PAX 40% 200 PAX 42% of total flights replaced	90% 100 PAX 90% 200 PAX 90% of total flights replaced

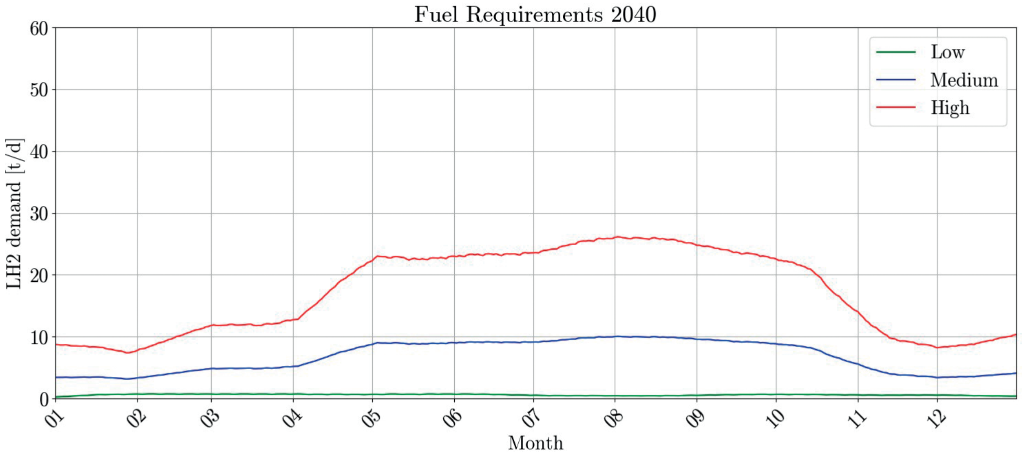

Figure 11 LH_2 demand throughout 2040 for low, medium and high penetration rates of LH_2-powered aircraft

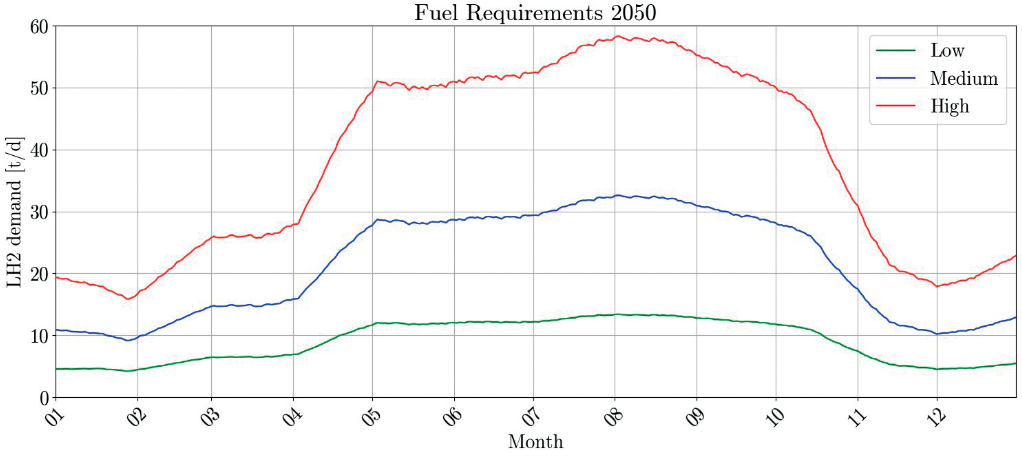

Figure 12 LH_2 demand throughout 2050 for low, medium and high penetration rates of LH_2-powered aircraft

Table 4 Annual and daily (average and peak) LH_2 demand

	2040	*2050*
Low	220t annual 1.2t daily peak 0.6t daily average	3,310t annual 15.1t daily peak 9.1t daily average
Medium	2,480t annual 11.4t daily peak 6.8t daily average	7,840t annual 36.7t daily peak 21.5t daily average
High	6,300t annual 29.4t daily peak 17.2t daily average	13,920t annual 65.5t daily peak 38.2t daily average

Hydrogen value chain scenarios for RTHA

Airports have a unique position and can play a key role in connecting airlines, fuel suppliers and operators and local partners. This position can be used to support the development of value chains for alternative fuels at the airport, being either SAF or LH_2. Potential value chains for the delivery of LH_2 to RTHA are examined in this part of the study.

Value chain routes description, method and assumptions

Three relevant routes for hydrogen to RTHA are considered, given the regional developments of hydrogen infrastructure and value chains in the Rotterdam region. The routes used in the calculations are outlined in Figure 13.

Route 1: LH_2 Import with LH_2 carriers to the Port of Rotterdam from regions with low electricity cost, and last-mile lorry distribution to the airport

Import of hydrogen via maritime corridors enables transport of low-cost low-carbon hydrogen from regions with abundant renewable energy to regions with limited (renewable) energy availability. The imported hydrogen can be produced in regions with lower electricity prices than in Europe. One example is Morocco where sufficient land is available with good, complementary solar and wind resources.[40] Using present costs and technology, the levelised cost of energy (LCOE) of utility-scale solar power in locations such as Morocco can be as low as €30MWh, compared to Europe where new energy is largely obtained from offshore wind, which has a LCOE of around €70–80MWh.[41,42] In 2040, the LCOE of utility scale solar and bottom-fixed offshore wind is projected to be as low as €13MWh and €41MWh respectively.[43] Inexpensive solar energy in North Africa is an attractive prospect for hydrogen production as the electricity costs account for approximately 70–90 per cent of the levelised cost of hydrogen

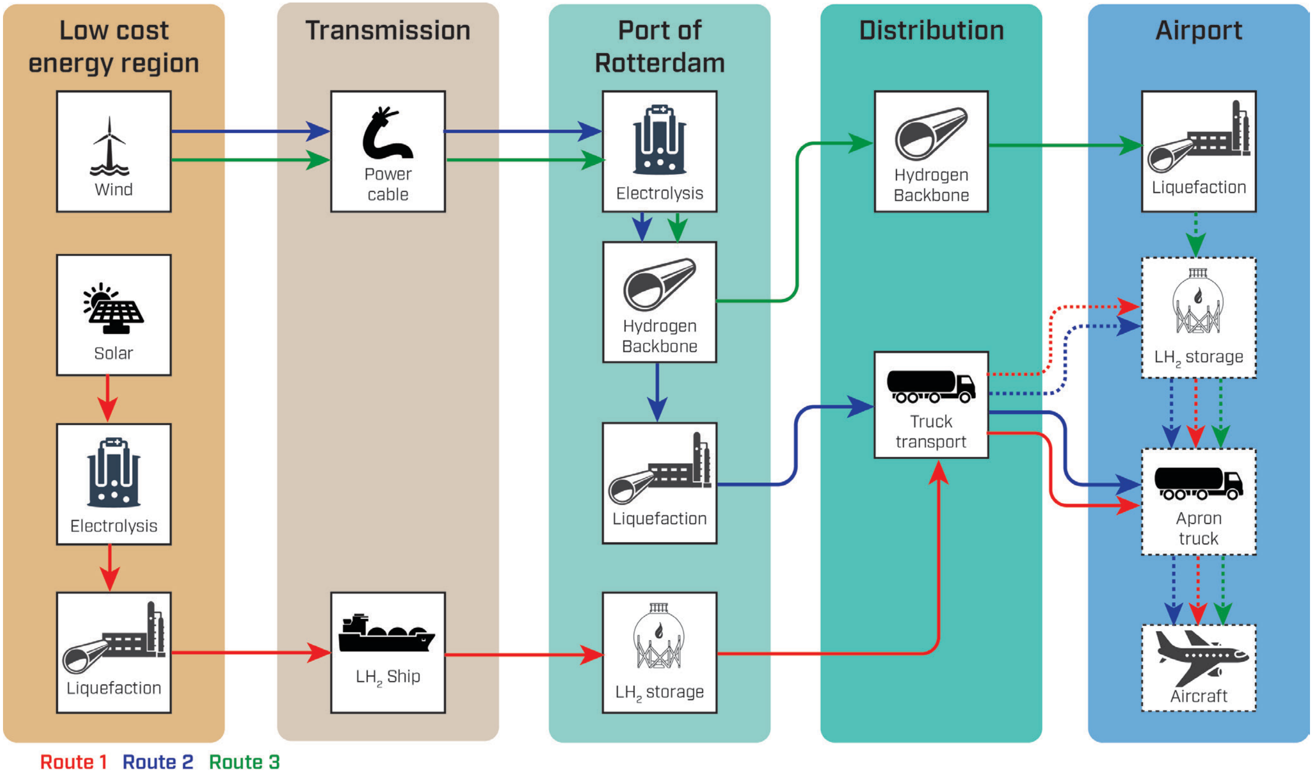

Figure 13 Potential hydrogen routes from renewables to the airport, including three relevant hydrogen routes to RTHA

(LCOH).[44] Both EHB[45] and McKinsey[46] present import value chains with lower cost for imported LH_2 than locally produced. The Port of Rotterdam may become a key reception point for (lower cost) imported hydrogen, and (end) users at the relatively nearby RTHA can benefit from this position. The Port of Rotterdam is familiar with the transshipment of hydrogen carriers and has experience with cold energy carriers such as LNG. Rotterdam is therefore a logical area for the further development of hydrogen import terminals.

Ammonia (NH_3) is seen as an important import vector due to the availability of scaled infrastructure and ammonia vessels by the year 2030.[47] Other energy carrier transport modes, such as LH_2 import, are also considered by industry but require further development. The specific deployed vessels for the transport of LH_2 have not been commercialised yet but are currently under demonstration between Japan and Australia.[48] Bigger vessels with larger storage capacities are planned in the future. Ishimoto *et al.*[49] analyse value chains for NH_3 and LH_2 import to Rotterdam from northern Norway, where the LH_2 vector has a more favourable cost of delivered gaseous hydrogen (also seen as 'pure hydrogen for end-use'). Other studies conclude that NH_3 carriers present a solution to the more favourable delivery option, as the method is more mature and as NH_3 carries more hydrogen by volume than LH_2.[50,51]

Imported hydrogen in the European Hydrogen Backbone is typically injected into the grid. NH_3 is simpler to store, but much energy is needed in the receiving terminal to extract hydrogen prior to injection to the grid. LH_2 has the advantage that it primarily consumes energy at the energy-abundant production and liquefaction site. Whenever the end user requires LH_2, a route via NH_3 would require significant extra energy input for both cracking and liquefaction at the import location. Direct import of LH_2 from regions with abundant renewable energy via LH_2 carriers and last-mile distribution via lorry is therefore considered in this work for route 1. The impact of this specific route on needed LH_2 airport infrastructure is relatively low and limited to infrastructure to receive and store the LH_2 trailers on the airport. Potential fixed peak of seasonal storage can be considered when operationally feasible.

Route 2: Liquefaction of hydrogen from the European Hydrogen Backbone at a centralised site in the Port of Rotterdam, and last-mile lorry distribution to the airport

Hydrogen at Air Products' liquefaction plant in Rotterdam is currently liquefied at a capacity of 5tpd.[52] This liquefaction plant is located 43km from the airport by road. From 2026, an increased capacity will be operational. Hydrogen can be supplied from the open access backbone. This can consist of different sources of gaseous hydrogen either imported (through, for instance, NH_3 or LOHC) and/or locally produced. Different industrial areas in the Port of Rotterdam will be connected via a hydrogen pipeline that is currently under construction and will be operational in 2025. A future extension to connect the port to the main backbone, including connections to neighbouring countries, is planned for 2030.

Route 2 is similar to today's operation and will be used to deliver the necessary LH_2 to carry out the LH_2-drone demonstration within the TULIPS programme.

LH_2 will be transported via lorry and the local storage at the airport will be filled via the trailer. LH_2 lorries have been operating for decades and are the main technology for distributing LH_2 today. It can be assumed that this centralised liquefaction site will serve more customers than the airport alone, such that a larger liquefier is established than would be the case in route 3, in which the local liquefaction plant would only serve the LH_2 demand of the airport and its users. Infrastructure impact on the airport is, just like in route 1, limited.

Route 3: Construction of a last-mile pipeline from the European Hydrogen Backbone to the airport, with local liquefaction to serve peak demand at the airport
Pipelines are more suitable than lorries to transport large amounts of gas. The backbone is planned for gigawatt-scale transport. From the backbone we estimate a distance of ~14km, on which an additional distribution pipeline could be established for last-mile delivery to the airport, where the hydrogen is liquefied locally. The liquefier at the local plant at the airport will be smaller than in route 2. As LH_2 is not particularly suited for seasonal storage, the liquefier may be dimensioned either for a summer schedule demand and run on low capacity through the winter, or an average demand with storage available onsite. In this study the first option is chosen, as seasonal storage of LH_2 can give aggregated evaporation of LH_2 around 12 per cent.[53]

Electricity price is a key driver in hydrogen production.[54] In hydrogen value chains, electricity price and scale are key parameters.[55–57] By comparing routes 2 and 3, we can study the significance of the scaling effect in the relevant hydrogen demand regime, and discuss centralised scaled production and distribution of LH_2 versus local liquefaction at the airport. This route will have a significant impact on the airport infrastructure as at least a connection to the hydrogen pipeline, a significant connection to the electricity grid and a liquefaction plant needs to be established on the airport. This does not take into account the potential need to establish renewables on the airport (in order to make the liquefaction process green) or onsite storage infrastructure to cope with demand fluctuations. This could be problematic for airports that have limited land availability, as is the case for RTHA. This particular infrastructure impact has not been taken into account in the cost model.

Methodology

In this work, we estimate the levelised cost of LH_2 delivery for the above value chain routes. The calculations are based on literature values and cost modelling.

Hydrogen and electricity price

The cost of hydrogen from North Africa is obtained from the latest EHB report on import corridors for hydrogen to EU[58] and the EHB report on future demand, supply and transport of hydrogen.[59] In 2040, the cost of hydrogen production in Morocco is estimated in the range of €1–1.4kg. Liquefaction in Morocco is assumed to cost around €0.8–1kg. In Rotterdam, the hydrogen is obtained from the North Sea through the Hydrogen Backbone at €1.8–2.9kg.[60] Liquefaction in Rotterdam represents a major electricity demand in an area with relatively high electricity prices that are assumed to be around €80MWh in a future European energy system with a strong hydrogen network.[61]

Liquefaction

To calculate the levelised cost of liquefaction, cost-scaling curves for liquefaction from Hoelzen *et al.*'s study were used.[62] Matching liquefaction capacity with average consumption requires seasonal storage of LH_2. Even with low daily boil-off, the accumulated seasonal evaporation is significant. Therefore, peak demand in 2050 was chosen for dimensioning the plant. The airport may operate at low capacity through the low season (with a capacity utilisation of 60 per cent) or assume external offtake to full capacity. For route 3, a small size liquefaction plant as presented in the Hoelzen *et al.* study[63] would be sufficient to produce the LH_2 volumes stated in the medium scenario. Figure 14 shows the liquefaction cost for different electricity prices, scales and capacity utilisation. The centralisation case (route 2) corresponds to a 100tpd medium-sized plant, which can be operated with higher efficiency. There are uncertainties related to these assumptions, particularity the larger liquefaction plants. The largest liquefaction plant existing today has a capacity of 30tpd. Theoretical studies demonstrate pathways for significant cost savings for liquefaction plants with capacities up to 100tpd.

Distribution pipeline

Costs for establishing pipelines depend on the specific land factors, material cost fluctuations, pipeline optimisation and capacity utilisation. A proposed general rule of thumb is that a demand of 1–1.2 ton H_2/day/km is needed to drive economic viability (~ca €0.34kg)

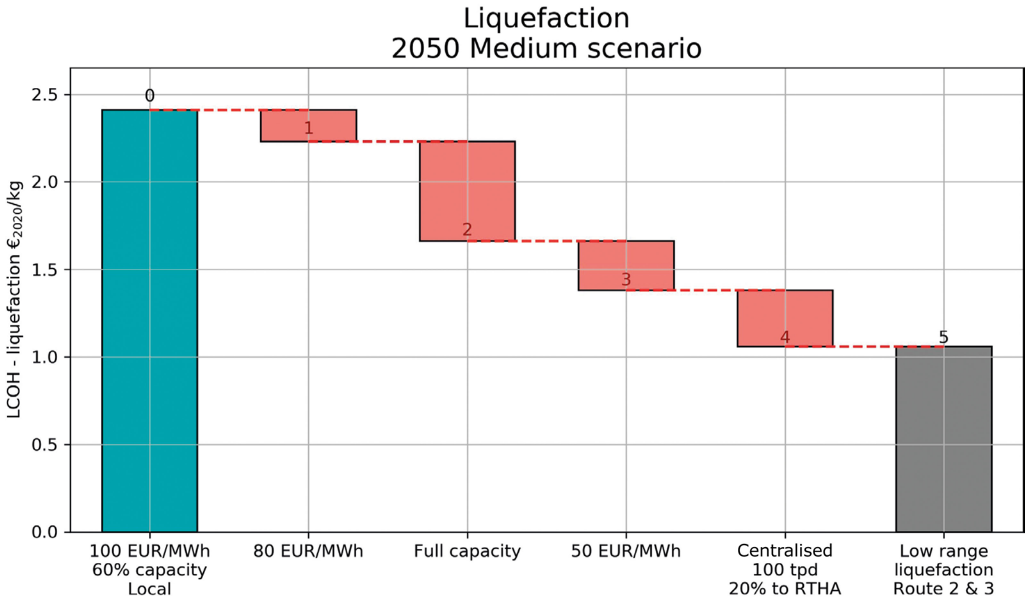

Figure 14 Levelised cost of hydrogen liquefaction and dependency on electricity price (€50–100 m/MWh), capacity utilisation and scale of production. 0–1:35tpd capacity (route 3) at 60 per cent and effect of reducing electricity price from €100 to 80MWh; 1–2 effect of increasing capacity utilisation from 60 per cent to 100 per cent; 2–3 effect of reducing electricity price from €80–50MWh; 3–4 effect of increasing capacity to 100tpd (route 2)

for short-distance pipelines without the need for compressors.[64] The potential distribution pipeline from backbone to RTHA is one such pipeline. This means that the pipeline in route 3 in general is relevant for 2050 medium and high scenarios. The method for estimation of pipeline costs was adapted from Kahn *et al.*,[65] with an assumed inlet pressure of 80 bar from the backbone and exit pressure of 20 bar without additional compressors. The pipeline was dimensioned for 35tpd (2.3 in). The low scenario assumes 100 per cent liquefaction capacity utilisation (external offtake in low season), and the high scenario assumes an average liquefaction capacity utilisation of 60 per cent (only airport offtake).

Lorry transport

The delivery cost via LH_2 lorry was calculated using the Hydrogen Delivery Scenario Analysis Model.[66] The Danish Energy Agency[67] reports even lower levelised costs of delivery. The shortest drive between the port and airport was used. Current transfer of LH_2 takes several hours, which is much longer than the drive from the liquefaction plant to the airport. An accelerated transfer time should be expected in the future, either through technological advancements or through the implementation of mobile LH_2 storage operations at the airport. Important drivers for cost are personnel wages, particularly during transfer operations, and capacity utilisation. These factors add uncertainty to the costs. As shown in the work of Hoelzen *et al.*,[68] the storage cost is constant for different systems scale and has little influence on the comparison. Potential infrastructure and operational cost savings can be gained by limiting the amount of LH_2 transfers at the airport.

Insight from cost modelling

Figure 15 presents estimates for LCOH via routes 1–3, also testing sensitivity to some input parameters. The main cost driver for LH_2 is the electricity price, as both production through electrolysis and liquefaction are energy-intensive processes. Based on the reported costs, import of LH_2 from regions with

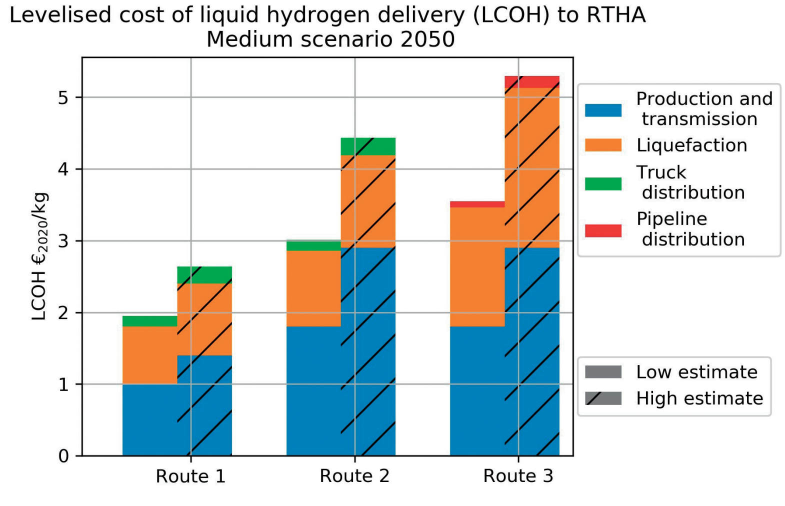

Figure 15 Estimated levelised cost of LH_2 delivery for the three candidate routes, at a 2050 medium scenario for LH_2 demand. The high and low estimates show the effect of varying electricity prices and capacity utilisation

large-scale production and very low cost of renewable energy (route 1) can lead to lower cost than domestically liquefied hydrogen. LH_2 production in North Africa based on electricity from solar power is an attractive prospect, as solar power is the technology that provides the lowest LCOE combined with high capacity factors in the region of up to 30 per cent. The long distance to the end users in Europe is less of an issue when the end user requires LH_2 instead of gaseous hydrogen. Energy used for liquefaction is not lost in reconversion compared to hydrogen from other supplies. LH_2 is lost due to evaporation at a rate of around 0.001 per cent/km under the transport,[69] which result in a total loss of around 2.8 per cent when transported from Morocco to Rotterdam.

Routes 2 and 3 investigate purchasing gaseous hydrogen from the future European Hydrogen Backbone. For an airport with relatively low LH_2 demand, such as RTHA, there is a potential cost saving by sourcing LH_2 from a larger centralised liquefaction plant nearby (route 2) compared to local liquefaction at the airport (route 3). In the presented example, the cost saving from the scale of the liquefaction plant in route 2 is larger than the added costs for lorry distribution compared to pipeline distribution in route 3. This holds even if 5 per cent boil-off is assumed for lorry delivery (not shown). The saving depends on the relative size of the airport's LH_2 demand and the nearby centralised capacity.

Distribution costs are a small share of the total cost, and the difference depends on input assumptions. For airports with larger LH_2 demand than RTHA, pipelines are an increasingly relevant distribution option due to the better cost scaling of this distribution method compared to lorry distribution costs.

Route 1 gives the LCOH for RTHA, but depends heavily on the scalability and large-scale deployment of LH_2 carriers and on the realisation of LH_2 corridors from production regions with low energy costs to Rotterdam. The H2Sines.RDAM project aims to develop such a corridor from Portugal to Rotterdam.[70] Route 2 gives higher LCOH but is less dependent on the further development of LH_2 carriers. This route can benefit from the (more mature) developments in the field of NH_3 carriers, liquid organic hydrogen carriers (LOHC) and the realisation of the Hydrogen Backbone. A more detailed process design and business model is needed as the basis for future infrastructure planning, especially in the case of high LH_2 demand scenarios. The associated extra costs when implementing local production facilities at the airport, such as safety measures and use of land, have not been taken into account in route 3 and are presumed to have a negative impact on associated costs.

Impact on RTHA, its value chain and the required LH_2 infrastructure

The close proximity of RTHA to the Port of Rotterdam benefits the airport's position in the LH_2 ecosystem. The airport can gain from the development of nearby LH_2, NH_3 and LOHC import hubs, large-scale liquefaction plants and the relatively easy lorry distribution to the airport. Development of mobile storage for LH_2 on airports, which allows LH_2 tank trailers to be used to supply, store and dispense LH_2, could be an effective operational method to reduce distribution and local storage costs for the low and medium demand scenarios at RTHA. In Europe, these cryogenic trailers have a capacity of up to 3.2 ton of LH_2. Given the medium scenario in 2050, this would translate to roughly seven daily trailer deliveries on average, with up to 12 daily trailer deliveries during peak days (see Figure 16 for a size comparison between the current JET-A1 mobile storage facility and the required LH_2 storage facility). Further studies on the assurance of LH_2 delivery or the necessity for back-up storage are needed, as a just-in-time delivery is assumed in this specific case.

This trailer-based logistics method is most likely to be adopted by many airports when hydrogen-powered aircraft will enter into service. This operational method will save time and lower risks as it reduces the number of LH_2 transfers. It also limits boil-off and personnel costs due to fewer handlings and has the advantage that infrastructure investments are relatively low compared to installing fixed storage tanks, pipeline systems and/or liquefaction plants onsite. RTHA's airport master planning currently takes into account a future location to receive, park and operate a number of LH_2 trailers.

Guidelines for this specific airport infrastructure and corresponding operation, including the development of high-performance LH_2 refuelling technologies, are still under development and will be part of the European Horizon project GOLIAT. This study will assess the impact that hydrogen operations using LH_2 lorries and trailers have on airport infrastructure. Detailed descriptions on the needed infrastructure, such as layouts and installations, to receive, park and operate LH_2 trailers at airports will be developed in this study, as well as the scalability and 'tipping-points' of this specific lorry-based operation. The work will be complemented with a real-life LH_2 refuelling demonstration at RTHA,

Figure 16 Current JET-A1 mobile storage facility at RTHA and a size comparison for a LH_2 mobile storage facility that accommodates 12 trailers (the exact location and details of the infrastructure are subject to the outcomes of the GOLIAT project and future developments in the specific domain of airport hydrogen infrastructure)

Stuttgart Airport and Lyon Airport. The demonstration includes the transfer of LH_2 between an industrially available LH_2 trailer and the HY4 hydrogen-powered aircraft of H2FLY and ground operation tests.

CONCLUSION

The most optimal LH_2 value chain for an airport depends on individual characteristics of the airport and its users. The hydrogen demand, the airport's proximity to larger hydrogen hubs (import and/or production hubs) and the availability of local renewable resources, which influence electricity price and hydrogen production and liquefaction costs, are key parameters and have a major impact on the airport LH_2 value chain. Conceptualisation and future development of hydrogen infrastructure for airport supply should include consideration of neighbouring hydrogen users (in different industries) for more efficient use of distribution (pipeline) networks and increased capacity utilisation of (large-scale) liquefaction plants.

The introduction and initial facilitation of hydrogen-powered aviation at airports can be realised by making use of existing trailer-based logistics for LH_2. These highly insulated vessels are commonly used in other industries, from which the aviation industry could learn. Airport infrastructure for this specific operation is less extensive than fixed storage tanks or liquefaction plants and associated operations but are limited in terms of total storage volume at the airport. This specific supply, storage and dispensing method, therefore, might only be feasible for regional airports with lower demand and at hub airports during the introduction period of hydrogen-powered aircraft. A comparable study for a hub airport such as Amsterdam Airport Schiphol would lead to different insights.

Airports play a pivotal role in the adoption and development of hydrogen-powered aviation. It is inevitable that airports will need to invest in developing a robust and cost-effective LH_2 value chain including airport hydrogen infrastructure. Airport operators, as central organisations within their own airport ecosystems, can act as a connecting body towards relevant partners such as infrastructure developers, fuel (hydrogen) suppliers, handlers, airlines and aircraft manufacturers.

Airports can also further stimulate developments by acting as an innovation platform for organisations that develop hydrogen-powered aircraft, as is the case for RTHA. Gaining knowledge and experience as an airport operator on this specific topic can be achieved by seeking involvement in regional hydrogen development projects and programmes, even though sometimes these are not specifically targeted to aviation, and by implementing (small-scale) hydrogen projects within the airport. The airport's presence within the local hydrogen ecosystem and the gained knowledge on this — for airport operators — new domain will eventually benefit the LH_2 value chain development at the airport and the enhancement of more sustainable air travel. Early-stage involvement as an airport operator within the field of hydrogen is crucial to further develop hydrogen-powered aviation and to reduce carbon emissions as an industry.

About TULIPS

This project has received funding from European Union's Horizon 2020 research and innovation programme under grant agreement No. 101036996

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