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Demonstrating lower polluting solutions for sustainable airports across Europe

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Abstract

This report considers scale-up of LH_2 infrastructure for airports. We conduct a literature review and propose a method to estimate the LH_2 demand and H_2 demand for ground support equipment (GSE) in 2050 for the TULIPS airports. Based on the estimated demand for Schiphol airport in 2050 and the literature review, we propose a refuelling infrastructure where LH_2 is transported in pipes. A dynamic process model is used to estimate the amount of boil-off for a day of operation, and it is found that the boil-off corresponds well with the H_2 demand for GSE, meaning a “loss free” infrastructure concept may be feasible. A safety analysis is conducted for the infrastructure concept, and a set of risk-reducing measures identified.

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Acronym	Meaning
AMS	AMsterdam airport Schiphol
BADA	Base of aircraft data
barA	Bar absolute
barg	Bar, gauge
BLEVE	Boiling liquid expanding vapor explosion
BOG	Boil-off gas
BOMS	Boil off management system
BOR	Boil-off rate
CGH2	Compressed GH2
EHB	European hydrogen backbone
FTA	Fault tree analysis
GCOL	Ground collision
GH_2	Gaseous hydrogen
GHE	Ground handling equipment
GSE	Ground support equipment
HAZID	Hazard identification
LCA	Larnaca International Airport
LH_2	Liquid hydrogen (H_2)
MIE	Minimum ignition energy
NFPA	National fire protection agency
OSL	Oslo Gardermoen Airport
PEM	Proton exchange membrane (electrolyzer)
QRA	Quantitative risk assessment
RRM	Risk reducing measure
RTHA	Rotterdam The Hague Airport
SMR	Small and medium range

ST	Total sensitivity index
TRN	Turin Airport
VLE	Vapor-liquid equilibrium

1 Executive Summary

Air travel contributes to a significant share of climate gas emissions. An important potential alternative to fossil fuels, is the use of hydrogen-powered aircraft and corresponding ground infrastructure for fuel supply and handling. Liquid hydrogen (LH_2) is considered as a potential fuel to power regional and short-middle range (SMR) aircraft. In addition to challenging technology development, a major bottleneck is the availability of LH_2 at airports and refuelling of aircraft. The challenges are multiple, as hydrogen and LH_2 is not produced and distributed at enough quantity and with sufficiently low carbon footprint.

LH2 has been used for decades in the space industry. Technology for LH2 refuelling of road vehicles is a recent development to decarbonize the transport sector. A review of openly available information on available technology elements (production, liquefaction, storage, transport, distribution and refuelling) was conducted to enable a first evaluation of how these technologies potentially can be applied for scaling up LH2 infrastructure at airports.

As a basis to conduct a comparison of available capacities for these technologies, scenarios for LH_2 needs with intra-day resolution were developed for the partner airports in this project. The low level of maturity for onboard technology and aircraft design makes these estimates uncertain. However, preliminary scenarios are needed to initiate necessary R&D efforts for ground infrastructure. Based on BADA (aircraft performance database) and actual flight schedules, assumptions related to e.g. the market penetration of LH_2 aircraft, LH_2 needs scenario are suggested for the TULIPS lighthouse and fellow airports Amsterdam Schiphol (AMS), Oslo Gardermoen (OSL), Turin (TRN) and Larnaca (LCA).

The airports in TULIPS have different sizes and air travel profiles. This influences the LH_2 needs and share of fuel that is LH_2. At AMS the low, medium and high scenario for 2050 suggests a daily LH_2 consumption of 178, 360 and 609 tonnes, respectively. There is also an internal variation from 0 in the night, to a peak demand at 53 tonnes/hour. TRN has the smallest LH_2 needs, 30 tonnes per day. These scenarios are strongly sensitive to the assumptions related to market penetration of LH_2 aircraft.

When these LH_2 needs are compared to current available capacities for renewable hydrogen production, liquefaction and storage, it is clear that the LH_2 system scales for the larger airports (AMS, OSL) will be unprecedented. If produced according to the directive for renewable hydrogen, the needed electrolyser capacity is reaching towards GW-scale (currently not built) and new liquefaction technologies is required. Only a few storage tanks of the largest operative size are needed, but it is unclear whether filling/draining of these tanks can be done quickly enough. If not, an array of smaller tanks is more likely. With local liquefaction at the airport, the holding times of current tanks may be sufficient for the normal 3 days storage. The smaller airport, TRN, have a LH_2 scale that is already demonstrated in industrial environment.

This report presents a concept for large scale LH_2 infrastructure at airports. The system is based on LH_2-pipeline distribution; from liquefaction to the airport fuel farm, and from the fuel farm to the aircraft stands. The pipelines are insulated with commercially available systems, and a conceptual pump is used to ensure the required mass flow to aircraft. To minimize evaporation, the system is kept continuously cold by always (re)cycling a certain amount of LH_2. The proposed system incorporates relevant elements from both the space industry (system scale) and the automotive industry (use-pattern of refuelling).

A dynamic process model was developed to analyse the system concept for the medium 2050 scenario for AMS. The simulation suggest that it is technically possible to supply LH2 to the airport's fuel farm from a liquefier 4 km away (i.e. near the European Hydrogen Backbone) using commercially available insulation for the pipeline. If the liquefier is 25 km away (port region), a significant additional amount of insulation is needed.

The modelling and simulation of the refuelling system suggest that a small recirculation flow of LH_2 is required at night to keep the pipes sufficiently cold. The recycled LH_2 is returned to the LH_2 fuel farm as a liquid and can be re-used. The recycle flow is significantly smaller than the flow when refuelling aircraft. Therefore, the system will warm up to some extent during the night, leading to the amount of boil-off gas (BOG) is highest when refuelling aircraft in the morning. Adjusting the nightly recirculation rate affects the BOG amount when refuelling the "first plane in the morning": a low recirculation rate yielded 98 kg BOG, while a slightly higher rate reduced it to 74 kg. In the evening, the system is cold, and no BOG is generated during refuelling. If the aircraft is filled in the evening and used the next morning, 77 kg BOG is generated due to heat ingress to the aircraft tank. These values are strongly sensitive to the aircraft tank design.

The preliminary estimates of LH_2 evaporation during refuelling and overnight indicate that there is a reasonable mass balance of boil-off and CGH_2 needs for ground support equipment, such that could potentially be integrated with other end use. However, their values are specific for the applied system parameters and will change as specifications are updated.

The presented system concept is aimed at LH2 scenario for 2050, towards which any development will be step-wise and also synchronized with regulatory development for sustainable hydrogen value chains. In aviation, this is seen as a major bottleneck to fast implementation of hydrogen technologies, and there is a strong focus is on safety aspects. LH_2 safety management differs from both CGH_2 and kerosene safety management. This is evident both from the physical properties of LH_2 and evaporated cold gas (temperature, density, flammability and buoyancy) and new risk phenomena related to low temperature (overpressure, hazards of low temperatures). The safety strategy for hydrogen in aviation shall prioritize i) prevention of LH_2 release, ii) prevention of ignition and iii) minimization of consequences. Safety analysis of LH_2 systems is improving, but the establishment of standards takes time. Experience from historical incidents with LH_2 and hydrogen guide the focus to both technical, external and organizational factors, with emphasis on the refuelling operation. Based on reviews of reported LH_2 incidents, as well as a HAZard IDentificaiton session of the conceptual refuelling operations followed by Fault Tree Analysis for identified risk scenarios, a set of risk reducing measures can be proposed, as follows:

- **Procedures**: Clear, systematic and comprehensive procedures and operator training that covers normal operation, maintenance operations, comprehensive non-nominal operations and establishment of safety zones. The human and organizational factor is also an important element that limits influence of human error.
- **Handling of BOG:** Monitoring of temperatures within the LH_2 system, and control of operation to avoid and handle excessive evaporation. BOG handling system with sufficient capacity to handle situations with excessive evaporation.
- **Material integrity and cryo-hazards:** Selection of materials with sufficient compatibility with hydrogen and low temperatures. Monitoring of material health and control of thermal stress.
- **Vent/flare:** The concepts investigated is based on conserving all BOG, but for situations where venting is necessary the vent/flare stacks should be designed for safe venting in terms of vent temperature, ignition control and thermal radiation from flares.
- **External factors:** Establishment of ignition control zones, focus on effect of weather, avoidance of ground collisions, and barriers towards external fires.

The review and analysis presented in this report shed a light important future challenge related to the scaling up of LH_2 infrastructure for aviation. There are many uncertainties, as the large scale concepts and technology bricks are somewhere between a conceptual low- to mid-TRL stage, and not at a high TRL or commercially available stage. Analytically demonstrated processes that are not based on experimentally validated models also have uncertainties.

A future focus should include experimental data acquisition for model validation, such that systems for handling and utilization of boil-off gas, system control and safety procedures can be developed.

2 Motivation and background

2.1 Climate impact of aviation

Air travel is responsible for more than 2 % of the global CO_2 emissions (2022)[1], and potentially 50 % higher than the reported emissions[2]. While the industry projects a future increase in travel demand of a round 3% annually[3], the emissions are likely to increase further unless action is taken to reduce the carbon intensity of air travel. In addition to the emitted CO_2, a range of non-CO_2 effect also contribute to global warming. Of particular concern are contrail, soot and NOx. Estimates consider the non-CO_2 emissions to be responsible for 2/3rd of the impact on global warming from aviation[4]. In line with the increasing emission reduction ambitions elsewhere, the industry has increased their ambition level from "carbon neutral growth though offsetting" to climate neutral aviation by 2050, or net-zero carbon emissions by 2050[5].

2.2 Pathways for climate neutrality

Several potential solutions and their pathway for emission reduction from air travel have been proposed and analysed [6,7]. The main policy is to scale up production of sustainable aviation fuel (SAF), as mandated through RefuelEU Aviation, where EU has set a target for blend-in of certified hydrocarbon fuels with lower carbon intensity. Both synthetic and bio-derived certified SAFs can be used, but there are limitations to resource availability (biomass, renewable energy and CO_2), production capacity and emission reduction potential for different fuel production pathways[8].

An additional emission reduction mean is though energy efficiency. ICAO has an aspirational target of an annual improvement of fuel efficiency of 2 % [9]. This can be enabled by fleet turnover to new and more efficient aircraft, and to some extent air traffic management. IATA estimates that progressive replacement of aircraft with best-in-class next-generation aircraft will provide 7 % reduced fuel burn (and equivalent emission reduction), compared to the baseline[10]. The baseline emissions include the expected increased travel demand, and therefore total emissions will rise significantly from the current level – despite utilizing the best-in-class aircraft. New fuels are *therefore needed both to cut* emissions and reach net zero climate impact from aviation.

The role of SAF and zero-emission fuel in decarbonizing aviation have to some extent been studied. Due to the non-CO_2 emission effect and upstream emission from the production chain of alternative hydrocarbon fuels, direct air capture is needed to reach net zero when biofuels and synthetic fuels are used [11]. The net zero scenario by IEA and others state there is also a need of reducing air travel demand, i.e. modal shift to less polluting transport modes[12].

As a disruptive alternative to the above pathway, development of hydrogen-powered aircraft has started. Some scenarios consider hydrogen used directly as a fuel [11,13]. A feasibility study concluded that hydrogen powered aviation can be feasible and contribute to 40 % emission reduction by 2050[14]. More moderate replacement rates indicate a possible reduction of emissions by 125 Mt in 2050[10].

2.3 Aviation powered by liquid hydrogen

LH_2 powered aircraft have had recurring interesting for many decades. Today, development of core technology for hydrogen powered aircraft is a strategic research and innovation activity in Europe, and there is also significant development activity in the US. Flight testing of hydrogen fuel cell and electric engines is ongoing at different scales. Most testing is using compressed hydrogen as energy storage, but there is an increasing shift towards storage as liquid hydrogen onboard. Table 1 highlights some examples on aircraft development programmes, and their targeted entry into service.

Table 1: Some examples of development programmes for hydrogen-powered aircraft.

	Range (nm)	PAX	EIS	Market potential / type
Airbus ZeroE	1.000	<100	2035	Turbo-prop LH_2 Narrowbody
	2.000	<200	2035	Turbo-fan LH_2 Narrowbody
Cranfield Island hopper		9	2026	Sub-regional
Zero Avia		9-19	2025	Sub-regional
		40-80	2027	Regional
Universal hydrogen		40	2025	Regional

IATA have published a roadmap for aircraft technology for net zero[10], which summarizes the main technology testing and demonstrations to on the way to hydrogen-powered aviation.

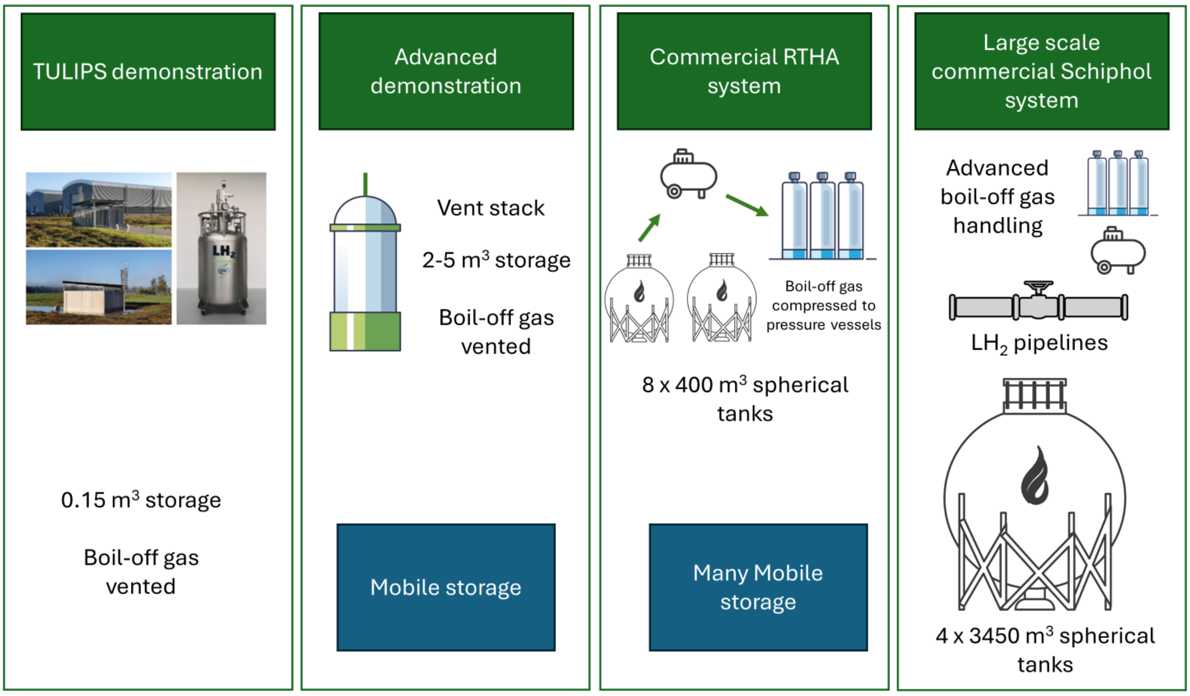
In addition to significant remaining technology development onboard, there is a parallel need to develop value chains and ground systems for fuel supply, handling and refuelling. These systems will have a significantly different physical behaviour and risk management requirements. Development of procedures and regulations are also seen as a major factor that can delay implementation of hydrogen powered aviation.

2.4 Focus of this report

The TULIPS project has contributed to identifying and removing barriers for introduction of liquid hydrogen to airports, by facilitating a demonstration of a Liquid hydrogen drone flight. In addition, the project has studied possible concepts and barriers for LH_2 infrastructures at larger scales.

In total, four different system sizes are considered

- The demonstration system itself, consisting of commercially available 150 L storage refuelled by a truck. For this system, a quantitative risk assessment (QRA) was performed, technical planning and approvals acquired. The execution of the demo is planned in 2024. The QRA and facility is described in Chapter 4.
- A system designed to support an advanced demonstration phase at RTHA with 2-5 m^3 storage capacity. In this phase, the airport will host LH_2-faciltiies to support experimental development of small scale aircraft and potentially larger scale aircraft. A preliminary QRA of the facility was performed. The QRA and facility is described in Chapter 4.
- A commercial scale system for RTHA was outlined. In this phase, a commercial scale hydrogen-powered activity is facilitated at the airport. The QRA and facility is described in Chapter 4.
- A large scale system concept for future large scale Hydrogen-powered aviation is proposed and analysed though modelling. The system dimensions were set based on scenario for LH_2-needs (Chapter 5), for Schiphol, Oslo, Turin and Larnaca airports. A dynamic model was developed to analyse the level of boil-off and study the conditions needed to refuel the aircraft tanks (Chapter 6). Hazard Identification (HAZID) and fault tree analysis (FTA) was performed to provide a preliminary safety analysis (Chapter 7). Based on the identified risk reducing measures, necessary procedures towards large scale systems were identified.



3 Introduction to infrastructure for LH_2

3.1 System description

Access to liquid hydrogen is today a major limitation for research and development within technologies and fundamental research related to LH_2. Access to LH_2 is also a major challenge for implementation of hydrogen-powered aviation. The main infrastructure elements needed are shown in Figure 1. Hydrogen production is via reforming of natural gas with CCS and electrolysis powered by renewable electricity. Liquefaction can be one on the production site, or in reach of a hydrogen gas pipeline transmission/distribution system. When liquefied at the production site, LH_2 is transport with ships, trucks or by rail to a local storage at the airport or airport forecourt. The various pathways for hydrogen supply are discussed in other publications from the TULIPS project[15].

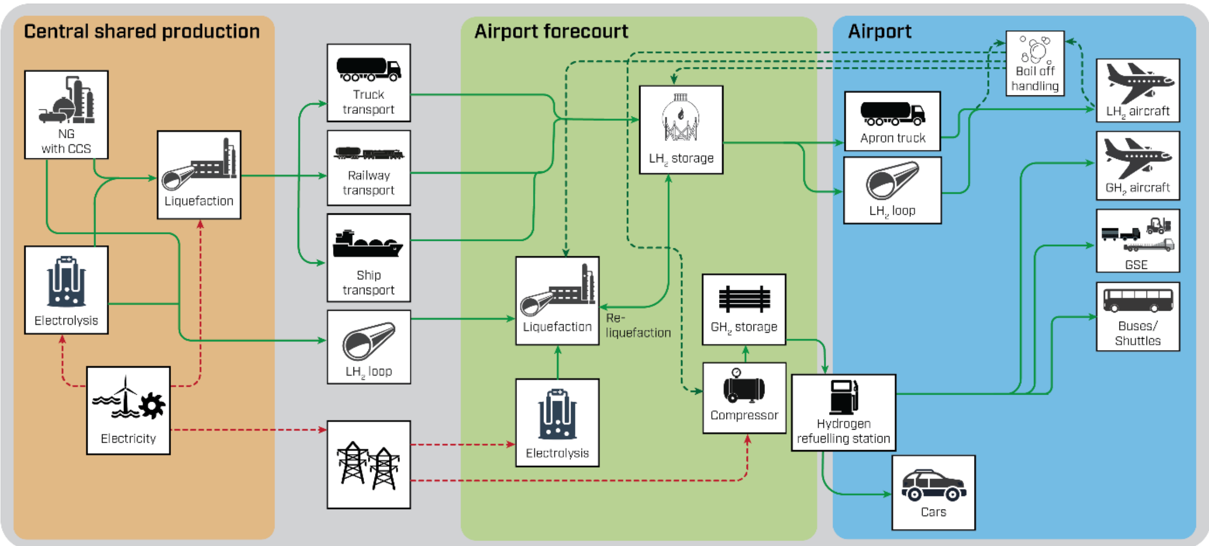


Figure 1: Main infrastructure elements in hydrogen powered-aviation.

At the airport, and potentially the airport forecourt, several systems for LH_2 handling may be needed. Some locations may have local production and liquefaction. All locations will have a form of LH_2-storage, and truck and/or pipeline distribution technology for refuelling of aircraft. To fill the aircraft receiving tank, LH_2 is transferred by pump and differential pressure refuelling. Tank swap is also proposed. Inevitably, some LH_2 will evaporate during handling and storage. In the long term, this cold gaseous hydrogen must be handled by other means than venting (boil-off gas management). Re-liquefaction to LH_2, compression into high-pressure vessels for refilling of hydrogen-powered ground activities are potential zero-hydrogen-loss uses. Last, but not least, safety system requirements will require different components, systems and barriers to be in place.

3.2 Safety, guidelines and standards

Current knowledge and gaps related to the safety of liquid hydrogen (LH_2) is reviewed by many. Guidelines, standards, recommendations and handbooks for hydrogen safety have been published by NASA[16], and from different European initiatives[17–19]. The potential hazards of LH_2 are extensively reviewed in such publications – including knowledge status and limitations on the phenomenological side.

For aviation, the development of a regulatory and certification framework for hydrogen technologies is deemed as a barrier for introducing hydrogen-powered aircraft. In addition to the regulations, codes and standards screened by PRESHLY-project, there are recent aviation-relevant or aviation-specific efforts to develop standards, regulations and certification requirements. AZEA, the alliance for zero emission aviation, is working on a GAP analysis for industry standards and certification requirements for entry into service of hydrogen aircraft. This analysis will result in roadmaps for development of certification requirements and industry standards. An overview of relevant standardization committees is found in an AZEA status report, including SAE and EUROCAE work groups[20]. Two of these are identified as of special relevance for aircraft refuelling, as follows:

- EUROCAE / WG80 – for the refuelling of aircraft; and
- ISP/TC 197 WG 34 – for the refuelling of LH2-powered trucks.

While being currently at a drafting level, the proposed standards and procedures are not available to the general public.

Current fuelling safety zones for Jet-A1 are 3 meters in *all directions* from vent points, tanking points, fuel hydrants, fuel hoses and fuel vehicles[21]. These will increase with the introduction of hydrogen. A preliminary study from ATI suggests fuelling safety zones for LH_2 today will be in range 20-60 meters, and that these can be decreased over time to 20 meters during connection/disconnection and 8 meters during refuelling[22]. It is important to note that these separation distances are related to the refuelling operation at the aircraft, and not for the storage facility which will contain much more LH_2 and have a larger consequence radius.

The abovementioned ATI-reported separation distance is linked to recommended separation distances from EIGA[23], which are, in metres, roughly in line with the standard safety distances from the National Fire Protection Agency (NFPA). However, the methodology for deriving the distance is different between EIGA, and the two relevant NFPA's. European regulations typically require a risk-based criteria for risk assessment (as in EIGA), that also reflects low frequency high consequence scenario and differentiates risk acceptance for different populations. NFPA-55 is developed for general cryogenics and are based on "worst credible events" for standardized systems. NFPA-2 is developed for hydrogen systems and are risk-informed[24]. ATI does not report whether the methodology follows NFPA-2 or -55, and it is therefore challenging to compare the parameters and criteria used for deriving these separation distances. Recent analysis by Hecht et al utilizing the risk-informed framework from NFPA-2 on LH_2 indicates that the updated distances "(…) could enable smaller footprints for infrastructure that includes bulk liquid hydrogen storage tanks, especially when using firewalls to mitigate Group 3 hazards and exposure distances." [25]. All in all, there is an ongoing evolution in the calculation of separation distances from LH2 systems as better data on release frequencies and release behavior emerges.

Furthermore, the potential amounts of LH_2 stored on site at the airport or in the forecourt may quickly reach (and exceed) the lower limits of the Directive 2012/18/EU on the control of major-accident hazards involving dangerous substances (Seveso-III directive)[26]. It is therefore likely that future development and acceptance processes for LH_2-storage and refuelling at airports will require updated quantitative risk assessment for the specific systems involved.

3.2.1 Registered accidents related to LH_2 storage and handling

Incidents with hydrogen can be registered in databases such as HIAD 2.1 to allow for learning and statistical analysis of risk factors. As gaseous hydrogen is more common in use, most registered incidents are with gaseous hydrogen. Nevertheless, key learnings are relevant for LH_2 systems. For all databases, important weaknesses are underreporting as well as the quality of information provided.

Recent reviews of the HIAD 2.0 database shows that 79 % of the events lead to ignition of hydrogen, and 48% also to explosion[27]. 75 % of the events were initiated by the hydrogen systems, and the remaining 25 % by non-hydrogen system events. Another database analysis[28] indicates that most events have mechanical causes (material failure, design – 23 %), operational causes (installation, inspection and maintenance – 19 %), human error (9.4%), organizational errors (safety management systems, improper guidelines – 9 %) and environmental and external causes (1.6 %). Although lower in frequency, environmental and external causes as well as organizational factors have had larger consequences in terms of injuries – and should therefore not be underestimated.

Less information is available for LH_2 systems. A report form Loughborough University and Shell prepared in the IDEALHY project[29,30] summarizes LH_2-incidents occurring in road transport, liquefaction and storage. The basis of the review was NASA and US databases, as the HIAD database at the time did not have useful information on LH_2.

Table 2: Summary of incident classification as reviewed by Lowesmith et al [30].

** Multiple causes for the incident.*

Cause	**Road transport**	**Liquefaction and storage**
Design/Construction failure / Inadequate Hazard Assessment	0	12
Equipment Failure	6	8
Incorrect operation/procedural deficiency/poor maintenance	8	18

Impact or RTA	3	0
Contamination	0	1
Natural causes / terrorism	1	5
Escalation	0	2
Total	18	46*
Consequences		
No release	2	5
Accumulation/Dispersion	12	14
Fire	4	9
Explosion	1	13
BLEVE	0	1
Injury to personnel (cold burns)	3 (2)	3
Property and equipment damage	7	23

18 incidents were identified in the road transportation of LH_2. Loading/offloading had the highest incident occurrence (72%), compared to transit (28%). Transport typically has personnel closer to the operations, compared to liquefaction and storage. This can have resulted in a higher personnel injury rate as observed. The summary states that incidents are dominated by cases where human involvement is important – and operational and procedural aspects are the most frequent cause of an incident.

The review identifies several critical phases and subsystems in the use of LH_2: System commissioning and decommissioning, purging phases, ignition in venting systems, procedural deficiency in offloading operations (valve and pressure control, ad hoc solutions), and higher rate of injury with personnel are close to the systems.

Equipment failures observed were related to burst disk failure, loss of vacuum, loose connections, inappropriate material selection, system sizing, leaking seals/packings.

Finally, an appropriate understanding of dispersion of cold H2 – and how it is different for ambient temperature H2 is critical in developing safety systems. Inadequate firefighting procedures have led to escalation. Other important external factors were cold weather and lightning.

In order to describe hazards related to LH_2-systems, a review of registered incidents with LH_2 (from H2tools) is provided below. The incidents may overlap with incidents covered by the above review.

Source H2tools, accessed 2022	**Description**	**Identified Safety Barrier failure**
2x850 m^3, 3.5 barg, 2007 Physical damage to the storage tanks, bellows, pressurization line, vent line	**Ignition** in burn stack and flame propagation to air-H_2 mix in the system after long term storage where	Check valves and the vent valve in the system could not arrest a hydrogen flame as it

Source H2tools, accessed 2022	**Description**	**Identified Safety Barrier failure**
and instrumentation, heat build-up	subsystems had been opened and air let in.	travelled in the vent system towards the tanks.
50 m^3, 2006	**Leak** of cold hydrogen which could not be switched off. Variable winds caused in uncertainty of safe zones, hampering repair. Lack of appropriate leak and dispersion models for cold hydrogen.	Toppled vent line due to high winds, restricting H_2 flow and creating back pressure in vessel relief system. Mounting was in an inadequate state for the load (wind) and exposure (material degradation of brackets by sun).
1969, transfer from tank trailer to receiving vessel.	**Frost bite** on the feet of personnel not wearing correct shoes upon operating a shutoff-valve, as a response of a leaky bayonet fitting. The **leak** produced a LH_2 spray enveloping the hand-operated shutoff valve.	Primary barrier failure (leaky bayonet from loose flange and thermal shrink of O-ring), and failure of using appropriate shoes. Shut-off valve was placed in the leak envelope, non-safe zone.
2009, 34 m^3 Lower-than-normal consumption from storage tank	**Leak** (of cold gas) from LH_2 storage tank observed as a vapor plume (condensed air). Caused by excessive venting (lower than normal consumption) and cold weather, placing thermal stresses on gland nut.	Thermal stresses causing loosening of gland nut. Leak stopped by thawing ice on gland nut and tightening.
2008, 34 m^3	**Burst disk relief** and **loud bang**.	Back pressure causing burst disk to pop. Risk was reduced as it was possible to replace the disk due to redundancy by a diverter to another safety relief valve.

Source H2tools, accessed 2022	**Description**	**Identified Safety Barrier failure**
2009, filling of a gaseous tube delivery trailer	**Leaking LH_2** pump shaft caused **explosions** and **fire**. Likely ignition source: static electricity and friction from pump shaft.	Leak at cold end packing.
2004, delivery from trailer	**Leak** from LH_2 offloading valve, which **ignited** causing flash and loud concussion.	Human error
1974, 75 m^3	**Rupture disk blew**. Remaining LH_2 removed, except a residual. Cooling with water to stabilize the tank. Vacuum lost. Water was directed to the fire on the vent stack, channelled into it – freezing and sealing the stack, disabling exit of residual cold hydrogen gas. Over time the gas was heated, causing over-pressure and rupture of the tank leading to BLEVE.	Error in procedure and lack of backup vent systems.
2005, lab	**Rupture disk failure,** loud venting of entire gas content and condensing air on top of the stack. Liquid air formed.	Redundancy in vent systems. Need to avoid air liquefaction.
1969, delivery	**LH_2** leak when disconnecting a fill line with valve partially open.	Barrier clothing not sufficient to protect from burns. Valve not shut upon disconnection.
2022, gas combustion unit	**Brief fire propagating from gas combustion unit** during operation of the unit for handling LH_2 boil-off after loading.	Solenoid valve for operating a air fan used to supply GCU with air for dilution and cooling failed. The valve was of incorrect specification, leading to premature failure. Causing

Source H2tools, accessed 2022	Description	Identified Safety Barrier failure
		high temperature alarm of the GCU and incomplete combustion inside.

The following hazardous scenario summarizes the above review:

- Leaks with subsequent ignition causing fire and /or explosion;
- Leak causing frost-bites;
- Leak causing evacuation; and
- Leak causing loud sounds.

The leak causes identified in the events reported in the database can be summarized as follows:

i) leaks from components due to thermal stresses caused by higher-than-normal (colder-than-normal) venting;
ii) materials with insufficient resistance to exposure;
iii) vent errors.

A set of identified risk reducing measures are:

i) redundancy in vent-systems:
ii) safety procedures that can be performed from safe zones; and
iii) trained emergency personnel and fire brigade.

With respect to sound hazards, rupture disks in pressure relief systems are sensitive to back pressure, which may cause un-necessary failures with loud sounds and H_2 venting. Escalation of events are seen when multiple barriers and risk reducing measures fail.

In summary, historical events with hydrogen in both gaseous and liquid form shows that the development and implementation of technology for handling these substances must consider:

- Proper design of safety systems;
- Development of a deep understanding of material degradation and selection;
- Development of appropriate procedures for normal operation, installation, inspection and maintenance; and
- Development of organizational factors, safety management systems and training.

The above review highlights that a critical gap for advancing safety engineering is lack of failure frequency data for quantitative risk assessments. What is clear is that barriers and reliable systems are needed to reach acceptable risk levels for LH2 systems. Leak minimization by reducing the frequency and amount released is a key strategy.

3.3 Hydrogen production

Increased production and import of hydrogen are a cornerstone ambition in RePowerEU, aiming at 10 Mt own production and 10 Mt import by 2030[31]. Beyond 2030, climate targets require a further increase in hydrogen production and use. Scenarios are many and highly scattered. An overview by the European Hydrogen Observatory[1] shows a scatter in hydrogen demand scenario for 2040 between 12-45 Mt and 2050 6-145 Mt, most between 10-80 Mt. The European parliament has adopted regulations for the definition of renewable hydrogen (Regulation 2023/1184 [32]) and is developing regulations for low-carbon hydrogen based on CCS-pathways and nuclear power[33].

The definitions of renewable hydrogen require that the use of the renewably produced hydrogen shall give greenhouse gas emissions savings of at least 70 % (Directive 2018/2001 [34]). Thus, the electricity used for electrolysis must have a low carbon footprint (18 gCO_2e/MJ). This leads to an implementation challenge as clean electricity today is in deficit and require substantial investments for capacity ramping both to meet the current clean electricity targets and keep up with an increasing demand for electric power. To avoid the unwanted effect of increased indirect emissions as renewable hydrogen is scaled up, from e.g. displacing other electrification targets and leading to increased fossil electricity production, the legislation is based on principles of i) additionality, and ii) temporal correlation and iii) spatial correlation (see Regulation 2023/1184). This means that there are now clear rules on how and where electrolysers can be powered to produce renewable hydrogen.

There are four main types of electrolysers. Alkaline, PEM, AEM (anion exchange membrane) and SOEC (Solid oxide). The technologies have different cost profiles, efficiencies and capability for flexible operations. In addition, the operating pressure is different, which can have influence on value chain evaluations. No type of technology is best on all aspects. The most mature technologies are alkaline and PEM electrolysers.

As the electrolyser capacity shall increase rapidly in the years to come, there is a long list of electrolysis plant developments and construction projects. Operating PEM electrolysers today are in the range some 10's of MW. Linde is building PEM-electrolyser facilities for production of renewable LH_2 in USA and Germany (35 and 24 MW respectively)[35]. Larger electrolyser plants are in development. Some examples are REFHYNE 2 (targeting an increase from 10 to 100 MW for PEM and 15000 tonnes H_2/year), Air Liquide Normand'Hy (targets 200 MW, will be the largest PEM ever built, from deliver from 2026)[36]. The largest green hydrogen production facility in the world is found in China, a 260 MW alkaline facility powered by solar power[37,38]. This facility is in operation, but not at full planned capacity (20 000 tonnes/year).

The European Hydrogen Observatory offers an open platform for data and information on the European Hydrogen sector, such as cost[39] and production volumes[40]. There is a large body of

[1] https://observatory.clean-hydrogen.europa.eu/tools-reports/scenarios-future-hydrogen-demand , accessed 2024

literature on the emission reduction potential and cost for hydrogen produced through electrolysis and from natural gas with CCS [41–43]. As blue hydrogen can contribute to the accelerated energy transition at reduced system cost, there is an increasing focus on low-emission hydrogen, for which regulations are in development. In advent of similar regulations related to emission reduction potential (70%), plans have been announced in Rotterdam. In USA, Exxon Mobile plans for a facility for blue hydrogen production with a capacity of 2 400 000 tonnes/year[44].

3.4 Hydrogen liquefaction

The global production capacity of LH2 amounts to around 380 tons/day45, of which around 25 tpd of the capacity is located in Europe (Germany, Netherlands and France). The current largest liquefaction plant in operation has a capacity of 30 tonnes/day. There are several alternative processes for liquefaction. Historically, a priority has been to reduce the investment costs, as operating costs are subordinate at small production volumes. Operating expenses are dominated by the energy consumption for liquefaction, and therefore power price. Upon increasing capacity, there is a drive for decreasing the liquefaction energy consumption. As seen in Figure 2, the best efficiency in operational plants is 10 kWh/kg$_{H2}$. Commercial plants in the larger capacity range typically uses a pre-cooled Claude Cycle for operation[46].

The potential need for LH_2 at airports are ultimately up to several hundred or 1000 tonnes/day. This means that there is a need for developing liquefaction technologies for much larger capacities and higher efficiencies than currently operating. Several conceptual processes for the range 50-864 tonnes/day have been reviewed by Ghafri et al[46]. These concepts show a reduced power consumption for liquefaction. Ghafri et al states that a specific power requirement between 6 and 8 kwh/kg is plausible without need for novel technologies – but with more advanced and integrated process designs, for example mixed refrigerants. However, there are remaining challenges and gaps. Particularly, the authors emphasize the difficulty in establishing investment cost data for conceptual designs. Work by Cardella et al[47] on cost and energy-optimized processes for large scale (up to 150 tpd) demonstrate the possibility of reaching low liquefaction energy procceses with costs cut to 1/3 of conventional processes which considers capacities of 5 tpd. Thus, potential significant improvements to current conventional efficiencies and investment cost are likely for large-scale plants. The current liquefaction cost is estimated between 2.5 and 3 USD/kg, but industry as well as past research indicate that a cost around or less than 1 USD/kg is achievable. Power price is also an uncertain variable that influences the overall liquefaction cost.

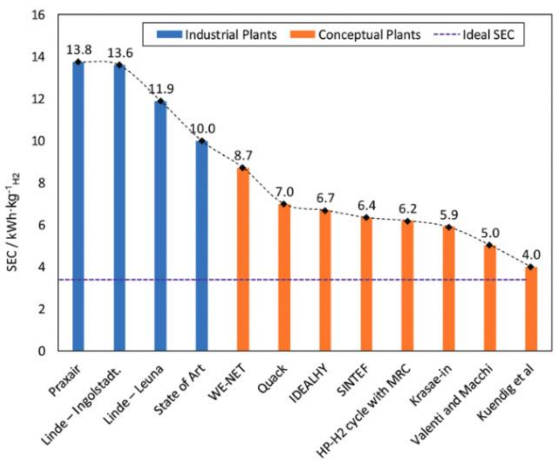


Figure 2: Liquefaction process efficiencies, from Ghafri

3.5 Liquid hydrogen storage

For aircraft to be able to operate on LH_2 fuel, there need to be LH_2 storage tanks stationed at or near the airport. Several storage tanks concepts and sizes exist, and an overview is shown in Table 3.

In general, LH_2 tanks are insulated double wall steel tanks. The insulation layer normally consists of vacuum - and often an additional insulation material, such as perlite or multilayer insulation (MLI). Novel concepts are in development[48]. The inner tank shell is supported by for example suspension through steel rods. Designs for larger ship tanks involve suspension by a skirt. The suspension material must tolerate temperature gradients from below 20K to ambient temperature. The tanks are often operated at near ambient pressure, but with a higher design pressure to allow for pressure-driven transfer from the storage for smaller tanks. Due to heat ingress, the ullage pressure is increasing over time. The pressure is relieved through controlled venting, or pressure relief systems. In conventional systems, the vented hydrogen is either consumed by a flare stack or similar, and even vented to the atmosphere. The targeted boil-off rate for a design, depends highly on the expected use pattern, and is subject to cost optimization as well as safety considerations. For instance, NASA reports that over 30 years of service the normal evaporation loss from the stationary storage was 12 %[49], as much of the LH2 storge was for longer periods of time. In this case, NASA has concluded that investing in more expensive and better insulation systems is economically worth it[48]. For other, high-utilization systems, a higher boil-off rate can be accepted.

Table 3 Overview of LH_2 storage tanks, based on information from different references.

**Measured and reported values for boil-off rate. **Tank under construction from 2018-2022. ***Theoretical boil-off rate with integrated refrigeration on. Information on Linde tanks from [50], NASA tank information from [48,49,51,52] Kawasaki [53,54,55]. When needed, conversion between volume and mass is done using the density 0.07085 g/cm³ and ignoring ullage as it is not always stated if ullage is included in the volume data.*

Vendor	Volume [m3]	Design / Max pressure [barg]	Storage capacity [kg]	Ullage	Insulation	Max BOR	Applications	Shape
Linde	71	12	4600	5 %	vacuum-perlite	0.95 %	High demand	Cylinder
Linde	11.5	6	900	5 %	vacuum-MLI	0.60 %	Fuelling stations	Cylinder
Linde	6	12	400	5 %	vacuum-special	0.50 %	Fuelling stations low demand	Cylinder
Linde	300	3.5	19300	10 %		0.30 %	Bulk storage	Cylinder
Linde	1100	2.6	70200	10 %		0.10 %	Bulk storage	Sphere
Linde	2300	2.6	145000	10 %		0.10 %	Bulk storage	Sphere
Linde	42	12	3000	5 %			Road transport	Portable tank 40 ft
Linde	56	12	4000	5 %			Road transport	Portable trailer tank 13.7 m
NASA	190		13462		vacuum-perlite	0.18 %	Bulk storage	Sphere
NASA	190		13462		vacuum-glass bubble	0.11 %	Bulk storage	Sphere

Kawasaki	540		38259		vacuum-perlite	0.18 %	Bulk storage	Sphere
Kawasaki	1250		88563				Ship transport	Cylinder dome
Kawasaki	2250		159413	10 %	vacuum-perlite	0.10 %	Bulk storage	Sphere
NASA	3218	6.2	227995	7 %	vacuum-perlite	0.08 %	Bulk storage	Sphere
NASA	3218	6.2	227995	7 %	vacuum-perlite	0.04 %	Bulk storage	Sphere
NASA	4732	6.6	335262	11 %	vacuum-glass bubble-IRAS	"0 %" – integrated refrigeration	Bulk storage	Sphere

With regards to safety, the insulation must be sufficient to minimize condensation and freezing on the external surfaces, but also to sufficiently withstand external heat loads from fires. Schmidtchen et al states that cylindrical tanks are easier to construct than spherical tanks, but does not reflect on the effect of tank size on this statement[56].

3.6 Transport, distribution and refuelling of hydrogen

If it is infeasible or economically not competitive to locate the production and/or liquefaction of hydrogen close to or at the airport, LH_2 must be transported to the airport's LH_2 storage in a cost-effective manner.

3.6.1 Hydrogen transmission

Hydrogen transport over large distances enable supply of hydrogen from regions with abundant resources for clean hydrogen production to end users in areas with restricted access to these resources. Examples are the planned European hydrogen backbone (EHB) that will enable transmission of gaseous hydrogen through key corridors[13]. Distribution pipelines for gaseous hydrogen exist, for example in industrial areas. Both types of pipelines make it necessary to liquefy hydrogen at or near the airport.

LH_2 carrier ships connects continents end enable global import and export. Shell, Kawasaki and partners are demonstrating a pilot[2] for an international value cain for liquid hydrogen, where brown coal is gasified to hydrogen, liquefied and shipped from Australia to Japan. The aim is to develop a full scale value chain current LNG size ship transport (e.g. 160 000 m^3) from Australia to Japan. The pilot-ship, Susio Frontier, has a 1250 m^3 vacuum-insulated tank for LH_2. The pilot testing is ongoing and has transported at least 55 t LH_2 (~770 m^3) from Australia to Japan. A marine loading arm for LH_2 bunkering has also been demonstrated in this project.

[2] HySTRA - https://www.hystra.or.jp/en/project/

3.6.2 LH_2 distribution by trucks and pipelines to the airport forecourt

Hydrogen distribution over shorter distances enable local distribution of hydrogen from a production/storage site in the region. Both liquid and compressed hydrogen can be distributed by truck.

Truck transport of LH_2 is commercially available today as a service. In Europe, these trailers have a capacity of ~4000 kg. Several techno-economic studies compare distribution of hydrogen on the road by LH_2 trailers with gaseous pipeline distribution[57,58]. Studies comparing LH_2-trailers with LH_2-pipelines are scarce, but relevant for airports facilitating hydrogen powered aviation, as the end use is LH_2. Brewer et al (1977)[59] conducted cost assessments for both truck and pipeline refueling systems, where the net LH_2 requirement for the aircraft fleet was 731.4 tons/day and the liquefier was placed maximum 161 km (100 miles) from the airport. Using commercially available MLI-insulated vacuum-jacketed pipelines as a starting point (8, 10 and 12 " diameter), Brewer et al found that for this (very high) consumption LH_2 pipelines was the preferred economic option if the airport is located less than 64 km (40 miles) from the liquefication plant while truck transport was more favourable for longer distances.

Importantly, Brewer et al's analysis i) considered that the actual LH_2 quantity to be transported from the liquefier to the airport is significantly higher than 731,4 tons/day due to various losses (i.e. conversion from LH_2 to GH_2) depending on the transportation mode, and ii) assumed that the "lost" LH_2 is nonrecoverable in their economic analysis. The assumption in ii) is questionable, as GH_2 may be used to power ground support equipment. However, the estimated quantity of "lost" LH_2 by Brewer is significant which means that the liquefier must produce far more than aircraft demand of 731.4 tons/day. In Brewer's analysis, the losses related to fueling the aircraft fleet (from the airport's storage tank) was estimated to be 15.7% implying that the airport must receive 846.5 tons/day LH_2, irrespectively of the transportation mode from the liquefier to the airport. Losses during truck transport are dominated by vehicle operations and approximately independent of distance, and the required LH_2 capacity of the liquefaction plant is 951.7 tons/day. For LH_2 pipeline transport, losses are heavily influenced by the distance; for 8 km (5 miles) the production requirement of the liquefier is 858.7 tons/day while for 80 km (50 miles) it is 934.7 tons/day.

The choice between truck or pipelines has other considerations than cost. Pipelines avoid increasing the traffic on the roads, which is a desired side-effect especially relevant for airports located close to urban areas. Schmidtchen (1997) claims that pipeline distribution can be superior to truck distribution due to safety reasons, as each transfer for LH_2 is associate with loss[56], and risk.

While relatively short LH_2 pipelines (< 1 km) exist for e.g. refueling space launchers, the authors are not aware of longer LH_2 pipelines in operation today. To investigate the behavior of long LH_2 pipelines, we must reside to simulations of pipeline models. Jones [60] developed in 1983 a LH_2 pipeline model for longer distances (6 km in Jones' case study), where design engineers can study the sensitivity of important parameters such as length, insulation thickness etc. However, a variety of more general pipeline models exists which uses physical properties of any fluid (e.g. LH_2) to calculate the properties of our interest. Unfortunately, selecting the “best” model for an application is not straightforward (or even possible), since there is a lack of open experimental data which can be used to check the validity of the various pipeline models.

3.6.3 Airport logistics and refuelling

LH_2 must be transported from the fuel farm’s storage tanks at the airport to each aircraft. Three options are typically considered, namely, i) the airport operates several LH_2 trucks, which transports the LH_2 from the fuel farm and to the aircraft, ii) a pipeline with hydrant system, similar to today’s filling of kerosene at larger airports, or iii) the (empty) fuel tank in the aircraft is swapped with a pre-filled tank at a designated place in the airport.

3.6.3.1 Direct refuelling from truck

Refuelling aircrafts by using a fleet of trucks is seen as a flexible option, as i) the only “fixed” point in the supply-infrastructure is the location of the fuel farm’s storage tanks and ii) increasing the refuelling capacity is done by acquiring more trucks. In a techno-economic analysis, Hoelzen[61] found that refuelling from a truck is more cost-effective than the pipeline refuelling for a LH_2 consumption less than 125 000 tons/year (342 tons/day). The investment cost of one truck is limited, which makes this option attractive for smaller airports and in initial stages of implementation.

Hoelzen mentions that the major drawbacks with truck-refuelling are i) increased traffic at the airport, which is a safety concern, and ii) the truck-fleet needs space to park/drive.

Road transport trucks are typically defueled with differential pressure, and the resulting rate is slower than the expected fuelling rate for LH_2-aircraft[50,62]. Thus, some adaptions of the technology is needed to realize direct refuelling.

3.6.3.2 Direct refuelling from a pipeline

For large LH_2 demands, the mentioned study by Hoelzen found that it is most cost-effective to have a pipeline from the fuel farm’s storage tank going to each aircraft stand. From each aircraft stand, a hydrant system connects the main supply pipe to each aircraft through a flexible hose; see 3.6.3.4 for a discussion regarding flexible hoses for LH_2. This system resembles the fuelling system for kerosene at airports today, and it avoids congestion. Furthermore, refuelling from a pipeline system potentially gives faster refuelling times. The drawback is the large investment cost of the system, and that the dimensioning is not as flexible.

The mentioned publication by Schmidtchen (1997) highlights hat pipeline distribution can be superior to truck distribution due to safety reasons, as each transfer for LH_2 is associate with loss[56], and risk.

In the pipeline distribution approach, a pipe goes from the fuel farm's storage tanks to each aircraft stand. The pipeline is routed back to the fuel farm's storage tanks, and a small flow of LH_2 is constantly being circulated to keep the pipes cold. Since the required flowrate for keeping the system cold is relatively small, we may have a smaller pipe diameter in the "return" pipe compared to the large "supply" pipe from the fuel farm's storage tanks to the aircraft stand, with the intention to save cost/CAPEX.

To transfer LH_2, we must either i) use a pump or ii) pressurize the fuel farm's storage tank with GH_2 or Helium and depressurize the tank when it should be filled. Both options were considered by Brewer[59], which concluded that the pump system is the only adequate option for this application.

In more recent studies, Mangold et al develops a model for LH_2 aircraft refuelling and assesses the implication on turnaround times[62]. Based on their review of LH_2 transfer, they argue for the feasibility of transferring LH_2 with at least as high energy flow rates as Jet-A1 (2100 MJ/s). A challenge is the pump. Smaller LH_2 pumps used to refuel trucks are, however, existing[63]. There is also some documentation that the onboard turbopump for the space shuttle may have sufficient capacity as discussed by Mangold[62]. Linde is currently developing a cryo-pump suitable for LH_2[64].

3.6.3.3 Tank swap

Tank swap concepts are often considered as an alternative to refuel maritime vessels with compressed hydrogen. This is motivated by the relative low rate of refuelling compressed gas. Aviation tank swap concepts are under development, notably by Universal Hydrogen. In practice, the TULIPS demo is a tank swap demonstration, as the tank is filled prior to the mounting of the drone.

3.6.3.4 Connections

When an aircraft is refueled, a flexible hose connects the fuel tank of the aircraft to the pipeline (the hydrant system at the airport) or truck. Cryogenic flexible hoses exist today[65], and are used in a robot-driven filling station with LH_2 for motor vehicles located in Munich[66]. Typically, hoses are manually connected but the robot-driven filling station in Munich demonstrates that connecting the hose may be done automatically.

When connecting such a hose to the consumer, the type of coupling is important since the hose is subjected to moist air. To prevent moist air from freezing and blocking the hose when cryogenic LH_2 flows through it, the hose is typically purged with either i) N_2 (to remove moisture) and GH_2 (to remove N_2), or ii) helium (which has a lower freezing point than H_2). However, such purging processes add a penalty to the turn-around time and there is a need to find solutions that are self-sealing and prevent air ingress into the hose and connection system.

Mangold et al simulated the refueling process to validate the potential for achieving acceptable refilling times for aircraft. Different couplings such as Johnston-couplings and clean-break-disconnect were discussed[62]. Turn-around time analysis showed that particularly for short range aircraft, it was important to avoid the need for purging to enable competitive turn-around times with Jet-A1. This favored the self-sealing clean break disconnect. A particular feature with these connections is the need for slight overpressure (0.2 barg) to prevent penetration of air – and also the release of small quantities of hydrogen.

3.7 Onboard LH_2 tank

As of today, aviation LH_2-tanks and their pathway to certification are both under development and it is not yet known how such a tank will be in its final design. However, the tank capacity, operating pressure, holding time and thermal ingress (insulation level) will influence ground operations. To evaluate the refueling infrastructure, parameters for the tank capacity, ullage, operating pressure window and thermal ingress are needed.

A major challenge in the design of the onboard tank is the delicate interplay between tank holding time, necessary insulation, operating pressure, and weight. These factors also depend on the onboard fuel extraction rate in flight, and pressure build-up allowance. The tank must be significantly more lightweight than what existing LH_2 tanks are. Therefore, new materials are under consideration for use in the construction of the tank. Still, these materials must tolerate hydrogen, cryogenic conditions and aircraft vibration loads.

Some studies on tank design and optimization are available in the open literature. A NASA review from 2006 state that double-wall constructions with vacuum and Multilayer insulation (MLI)-insulation systems show promise for long duration and distance applications[67]. Short-duration flights can possibly accept shorter hold times, and single-wall tank designs may suffice for short-duration flights. Mills et al. (2012) reports on an LH_2 tank for a prototype high altitude long endurance demonstration aircraft built by the Boeing Company Phantom Works[68]. The aircraft is currently expected to be capable of a 4-day flight and is equipped with two spherical tanks that weigh 705 pounds (320 kg) empty. The tanks can be operated at a maximum pressure of 95 psig (5.2 barg) and are made of aluminum insulated with 4.6 inches (11.7 cm) of spray on foam insulation.

A heat transfer model for predicting heat ingress to a cylindrical tank with external foam insulation is described in the paper by Rompokos et al. (2021)[69]. In this work, an optimal tank design was proposed. The tank concept consisted of aluminum 2219 with polyvinylchloride closed-cell foam insulation. The effect of having a venting system or allowing for increased pressure-buildup was explored. In the cases where no gaseous hydrogen was vented, the optimal insulation thickness was 0.124 m giving an external volume of 99.8 m^3 and a total dry tank mass of 2242 kg, which resulted in a gravimetric efficiency of 68 %. In the cases where gaseous hydrogen was vented, the optimal insulation thickness was less at 0.063 m giving an external volume of 92.3 m^3 and a total dry tank mass of 1488 kg, which resulted in a gravimetric efficiency of 74 %. These storage densities are superior to commercial systems today. The amount of LH_2 stored is 5313 kg when there is no venting and is 5484 kg with venting setup. These masses define the internal volume through the density of the fluids.

Gomez et al.[70] considered fuel tanks for conventional mid-range commercial airplane. The fuel mass was 17 700 kg LH_2, shared by two tanks located at the forward and aft of the airplane. The heat ingress for the tanks were estimated to 1.5 kW and 1.4 kW for the forward and aft, respectively. Both tanks are equipped with a venting valve, keeping maximum 1.7 barA in the tanks to avoid overpressure. Selecting the venting pressure is a critical factor, since a high venting pressure means thicker tank walls are required, while a low venting pressure requires i) thick insulation or ii) venting large(r) quantities of GH_2. Note that some of the vented GH_2 may be used by auxiliary engines and are not vented into the atmosphere, depending on how the fuel conditioning and boil-off handling systems are designed. Gomez reserved 5.2% of the tank volume for ullage, while Rompokos reserved 3%.

Different studies focus on different mission profiles. Mills et al. (2012)[68], mentioned above, reported on an aircraft that is intended for a 4-day flight in the first phase, and a 10-day flight in a later phase. On the other hand, Rompokos et al. (2021)[69], also mentioned above, considers a 18 hours flight time. Winnefeld et al developed a model for tank design, and applied it to a specific flight profile[71]. For a fuel cell powered aircraft on a sub-3 hours (short haul) mission, the total consumed hydrogen was 1912 kg, and a storage density of 0.64. The tank and fuel mass would be 1/3 of the corresponding kerosene tank (9187 kg) but take up 3.34 times more space.

Short-medium range aircraft are typically defined based on flight times up to 6 or 8 hours, and the studies and passenger aircraft above therefore tend to fit for a long range or ultra long rage flight time, which is beyond the target for the technology development agenda for Clean Aviation Joint Undertaking. Therefore, tanks fit for SMR aircraft may be smaller than the presented review. Many tank parameters remain to be fully explored, for instance the effect of allowable pressure and hold time. A higher allowable pressure increases weight but allows for potentially simpler refueling and longer hold times. Other aspects are related to crashworthiness, cost and material properties. All in all, there is still significant development work remaining for bringing forth certifiable tanks and fully understanding what the nominal capacity, weight and insulation performance will be.

3.8 Boil-off management systems

The amount of hydrogen boil-off from a future large-scale LH_2 system at an airport may scale to significant dimensions. This gaseous, potentially cold, H_2 must be handled. Although venting or flaring is common today, this will not be accepted for future large-scale needs. For liquid natural gas (LNG), the conventional Boil Off Management System (BOMS) is either based on use for generation of heat, power or reliquefication. Hence, the gas is not lost through venting, but the energy for initial liquefaction is lost.

For H_2, there is a limited number of studies on BOMS. Studies on BOMS onboard a LH_2 carrier either explore use of boil-off as fuel[72], flaring, or reliquefication[73]. The strategy of combining reliquefication and use as fuel on a LH_2 carrier has been studied and found energetically favourable for such carriers[74,75]. The studies show that including utilization of the cold energy in the boil-off in the reliquefication process, reduces the energy consumption of the BOMS. A study on a LH_2 pathway including LH_2 transfer for filling of a LH_2 trailer, also uses reliquefication as the BOMS[76]. However, reliquefication of hydrogen come at a higher cost than for LNG and is more complex due to challenges thermal integration and the lower temperatures required.

Other options are the potential use of the cold gas as a shield gas in double-walled liquid pipelines, or integration of the residual cold for precooling in high pressure H2 refuelling stations. The potential for energy saving is high, but there is a lack of studies on finding the optimal handling for airport-relevant systems. To progress on this issue, a better understanding of the amount of boil-off is needed – such that the match with potential CGH_2-end use can be assessed.

4 LH_2 infrastructure for RTHA

4.1 Introduction

Rotterdam The Hague Airport (further RTHA) is a regional airport specialized in scheduled traffic towards European destinations as well as facilitating private business traffic, holiday flights, recreational general aviation and HEMS operations. Around two million passengers utilize the airports facilities each year. The airport is part of the Royal Schiphol Group.

With an objective to become a leading airport in the transition to sustainable aviation, RTHA has adopted the ambitious goal of being one of the first hydrogen compatible airports. For that purpose, RTHA adopted a so-called 'Hydrogen Roadmap' which elaborates on the steps to move from a demonstration phase towards commercial flight, that will allow RTHA to be a hub for the first regional roots serviced by sustainable hydrogen fuelled flights. To guide this process RTHA has adopted a hydrogen road map (Figure 3).

Figure 3: RTHA Hydrogen roadmap.

The first step on the route to achieving such an ambitious goal is to gain the necessary know how, licenses, and certifications through implementing a small-scale project. With that in mind, RTHA established a partnership with NLR through the TULIPS project that aims to fly a vertical takeoff and landing (VTOL) drone fuelled with liquid hydrogen on site in 2024. This project is referred to as the **Initial Demonstrator**.

With the knowledge gained from the Initial Demonstration phase, hydrogen fuel operations can be expanded through the **Advanced Demonstrator** phase. In this phase RTHA will accommodate multiple hydrogen fuelled aircrafts that are currently in development, like a Sling-4 and Cessna Skymaster. For this purpose, a larger volume of hydrogen will be necessary and more frequent refuelling procedures will be carried out throughout the year.

The gained operational know-how gained from both demonstration phases will allow RTHA a high level of preparedness for when hydrogen fuelled aircraft will be ready for **commercial flights**. Such preparedness and in-house knowledge will be necessary to serve the increasing demand on hydrogen fuel when aircraft operators start transitioning to hydrogen fuel use.

Because of the intended introduction of flammable hydrogen on the RTHA site, studies must be performed to evaluate its safe usage. One important question to be answered is which location(s) on RTHA is/are suitable for positioning the hydrogen containing equipment.

4.1.1 Scope

The objective is to address the safety concerns related to the positioning of hydrogen facilities on the airport premise. This report covers the conceptual design & safety analysis for the Initial Demonstrator, Advanced Demonstrator, and Commercial phases. The level of detail considered is limited to the main requirements of the necessary facilities, such as volume of storage vessels, and the general assumptions on operation. Table 14 presents the cases which are investigated in this safety assessment.

Scenario	LH_2 Storage Size [L]
Initial Demonstration	125
Advanced Demonstration	5,000
Commercial Use	3,000,000

Table 4: Overview of cases studied in this Safety Assessment

Please note that this study is not intended as a QRA of the entire RTHA site but is limited to the above-mentioned installations and the selected locations.

4.2 Quantitative risk assessment

A Quantitative Risk Assessment (QRA), which provides insight into the safety risks of persons being present at a location outside of an (hazardous) site (so-called ‘external safety risk’). The basic concepts of a QRA includes the specific requirements and the legal framework are summarized below.

Disclaimer: Please note the text in the following sections involve English translation and interpretation of Dutch national legislation. Please always refer to the original Dutch legislation as can be found on the government website for legal matters. No rights may be derived from the texts in the following sections.

A QRA provides insight into the safety risks of persons being present at a location outside of an (hazardous) site (so-called ‘external safety risk’). When assessing the external safety risk three criteria are evaluated, namely the ‘Location-specific individual risk’ (LSIR); the ‘societal (or group) risk’ (SR) and the Areas of interest (Dutch: “Aandachtsgebieden”):

- The LSIR is a measure of the likelihood that an individual who is continuously present at a particular location, without any protective means, becomes a fatality as a direct result of an unusual incident involving a hazardous substance (continuously in this sense meaning a whole year). The LSIR contour of 10^{-6} per year may not intersect locations where (highly) vulnerable buildings are present or are permitted to be developed according to the local zoning plans. The concept of a vulnerable building refers to it's intended use such as hospitals, elderly homes, schools, restaurants.
- The SR is a measure of the likelihood that a group of people becoming fatalities as a direct result of an unusual occurrence occurring at a nearby installation, transport route or pipeline, involving a release of a hazardous substance. The societal risk is graphically represented by a so-called FN-curve. This curve provides the logarithmic relationship between the number of fatalities (N) and the cumulative likelihood (f) of the possible accidents involving a release of hazardous substances (and leading to fatalities). The potential number of fatalities is dependent on the population (density) outside the site boundary.
- Areas of interest (Dutch: "Aandachtsgebieden") refer to the area impacted upon occurrence of specific failure modes. This measure does not represent the likelihood of failure, but the effective area impacted by a failure. The intersection of the area of interest with zoning plans will inform requirements for additional investigations or mitigation measures. The local government may prescribe additional measures to the construction of buildings to mitigate the risk to local population to acceptable levels.

For determining the risk profile of an installation, the risks related to the various (hazardous) activities are summated to a total LSIR and SR. The LSIR is independent of the actual presence of individuals, while the SR does consider the presence of individuals.

4.3 Discussion and summary

We refer to Appendix B for the full results and detailed discussion. Here, we provide a brief summary.

Initial demonstrator phase

The local specific risk 10-6/year contour is well within the airport boundary at RTHA. Due to the limited sizing of the process equipment, the LSIR contours relevant for the societal risk do not extend outside the airport boundary for a large distance. In fact, there is no societal risk according to the criteria as the potential number of fatalities is below 10 which is the threshold for the societal risk. No justification of the societal risk is therefore required. The aandachtsgebieden are outside the airport boundary. They do not intersect with existing vulnurable objects or areas within the zoning plan where vulnurable objects are allowed to be developed. It is however recommended to consult with local gouverment on their position on the aandachtsgebieden.

Advanced demonstrator phase

The local specific risk 10-6/year contour extents to outside the airport boundary for approximately 50 meters, thereby intersecting with adjacent communal gardens. These communal gardens are not designated as vulnerable objects and as such the intersection is permittable. Due to the limited sizing of the process equipment, the LSIR contours relevant for the societal risk do not extend outside the airport boundary for a large distance. A (small) societal risk is applicable, though well below the orientation value. It is expected that justification of this societal risk by local government poses no problem. The aandachtsgebieden are outside the airport boundary. They do not intersect with existing vulnurable objects or areas within the zoning plan where vulnurable objects are allowed to be developed. It is however recommended to consult with local gouverment on their position on the aandachtsgebieden.

Commercial phase

The local specific risk 10-6/year contour extents to outside the airport boundary. With the current layout it intersects with an vulnurable object (maternity care) and is very close to an hotel which is also an vulnurable object. This is not permittable according to the criteria setout in Dutch national legislation with respect to vulnurable objects. The societal risk is below but very close to the orientation value and requires justification by local gouvernment. The aandachtsgebieden are outside the airport boundary and intersect with vulnurable objects. Because of the intersection with vulnurable objects, the aandachtsgebieden (or part of) will therefore be designated as 'voorschriftengebieden' requiring additional measures to be taken at the vulnurable objects to mitigate the risk.

Determing of the riskprofile of the commercial phase was performed to give high level insight in the extent of the risk profile which is to be expected from such an installation. Further detailing of the installation will provide a more accurate risk profile. It is however recommended to carefully consider the desired location of the commercial installation in order to minimize the risk profile to external population, at least to acceptable levels. In addition it is recommend to consult with the local gouvernent on the (potentialy) desired future hydrogen facilities and discuss possible locations with respect to local zoning plans. Specifically it should be addressed where, with respect to the zoning plan, aandachtgebied (or voorschriftengebieden) are allowed to intersect with the surrounding, and conditions to do so. And how to ensure potential (vulnurable) developments in the vecinity of the airport, prior to obtaining a permit for the hydrogen facilities, do not complicate the hydrogen development or even prohibit the development.

In addition to the above it was noted that passengers present on the airport side are technically not 'external population' (and therefore not included in the societal risk), but it is recommended to discuss if the passengers should be considered as external population anyhow. This seems to be inline with Schiphol group internal regulations. In addition, the passengers cannot be expected to be self-reliant to the same extend as might be expected from personnel on the airport, as the latter receive more dedicated training and information on how to act upon potential hazards/treats related to their job.

5 Large scale LH_2 needs for zero emission aviation

5.1 Introduction

Four airports are partners in the TULIPS project. These have different size and travel patterns. Inter-day and seasonal differences occur, and the number of long-distance vs short- and regional distance vary between the airports. This means that the potential future LH_2 needs for refuelling aircraft will strongly differ between the airports. The scale of LH_2 needs, and type of receiving aircraft, also influence what is the suitable supply, storage and distribution technology[15].

The considered airports are listed below, ranging from the 3rd busiest airport in Europe to a relatively small airport. Further information regarding the airports are in Appendix H.

- Amsterdam Airport Schipol (AMS): 72 million passengers in 2019.
- Oslo Gardermoen Airport (OSL): 29 million passengers in 2019.
- Larnaca International Airport (LCA): 8 million passengers in 2023.
- Turin Airport (TRN): 4 million passengers in 2022.

5.2 Method for estimating future large scale LH_2 needs at TULIPS airports

5.2.1 Hydrogen demand for aircraft

Estimates for future large scale LH_2 needs for fuelling aircrafts at airports are needed for the evaluation of system and value chain dimensions. It is important to know not only the total demand, but also the peak loads. Thus, a time-resolved analysis of future LH_2 needs under different scenario have been conducted. For this a flight plan for a given airport was used and the distance to each destination is calculated. The meridian arc between the examined airport 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%[84]. The fuel consumption for a given distance is then calculated using the Base of Aircraft Data (BADA). BADA is a set of ASCII files containing performance and operating procedure coefficients for 1822 different aircraft types. The coefficients include those used to calculate thrust, drag and fuel flow and those used to specify nominal cruise, climb and descent speeds. Flight profiles for every departure in the flight plan are calculated with the BADA model and the corresponding fuel needs are estimated for the given aircraft model.

BADA calculates the total Jet-A1 fuel consumption for each flight. To convert fuel consumption from today commonly used Jet-A1 fuel to LH_2, the respective heating values are used ($LHV_{JET} = 42.80 \frac{MJ}{kg}, LHV_{LH2} = 119.93 \frac{MJ}{kg}$).

Early phase studies of concepts for hydrogen-powered aircraft indicates an increased onboard energy consumption of 10-20%[85], but there are significant uncertainties and variations. A feasibility study[14] differentiates aircraft types and finds a reduced energy consumption for commuter (-10 %), regional (-8 %) and short range aircraft (-4 %), and increased energy consumption for medium-range (+22 %) and long-range (+42 %). Our scenario address flights up to 2000 nm as eligible for LH2, i.e. long-range are not considered relevant for LH_2 at this point. As a simplification we add +10% energy consumption for the conversion of an aircraft to LH_2-propulsion, account for potentially heavier airframes and fuel systems[14]. The method was validated by comparing the calculated Jet-A1 fuel demand throughout 2019 for departures from Rotterdam airport (RTM) with reported consumption. This analysis showed a good agreement, with only a 6% error between the calculated and reported data[15].

There are large uncertainties related to the market penetration rate of LH_2-aiviation. To account for this, we chose a scenario-based approach. The scenarios were defined in accordance with a study on hydrogen-powered aviation at airports by Hoelzen et. al.[61] *Low*, *Medium* and *High* penetration rates of hydrogen-powered aircraft were defined for 2040 and 2050. Two aircraft types were considered; a 100 PAX aircraft, operating flights up to 500 nm with a market entry ~2030 and a 200 PAX aircraft operating flight up to 2000 nm with a market entry ~2035. The resulting market penetration rates are outlined in Table 5.

Table 5: Overview of scenarios with different penetration rates in 2040 and 2050.

	2040	**2050**
Low	20% 100 PAX 0% 200 PAX	40% 100 PAX 20% 200 PAX
Medium	30% 100 PAX 15% 200 PAX	60% 100 PAX 50% 200 PAX
High	50% 100 PAX 40% 200 PAX	90% 100 PAX 90% 200 PAX

Departure time	Destination	Airline	Aircraft	Aircraft type
01:40:00	Krakow (KRK)	Wizz Air	A21N (HA-LGB)	A21N
06:00:00	Stockholm (ARN)	SAS	A20N (SE-ROO)	A20N
06:00:00	Copenhagen (CPH)	SAS	A321 (OY-KBB)	A321
06:00:00	Roros (RRS)	Wideroe	DH8C (LN-WFP)	DH8C
06:00:00	Stavanger (SVG)	Airwing AS	BE20 (LN-AVA)	BE20
06:00:00	Trondheim (TRD)	SAS	B738 (LN-RRH)	B738
06:05:00	Bergen (BGO)	Wideroe	DH8C (LN-WFO)	DH8C
06:25:00	Paris (CDG)	Air France	A320 (F-HZFM)	A320

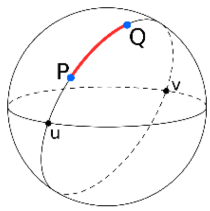


Figure 4 Distance calculated based on light schedule (here from OSL).

The main data source are flight schedules of a single average day (Monday 24.10.2022) for the airports AMS, OSL, TRN and LCA to compare the variations between the airports. In addition, for OSL historic flight data for the full year 2023 was used. To illustrate the methodology Figure 20 and Figure 6 show flight profiles generated in BADA for a given flight schedule at OSL and AMS. In addition, also the distribution of fuel use between the different flight phases is illustrated. This shows, that for the comparably shorter flights from OSL, a large share of the fuel is used in the climb phase, whereas flights from AMS use most fuel in cruise.

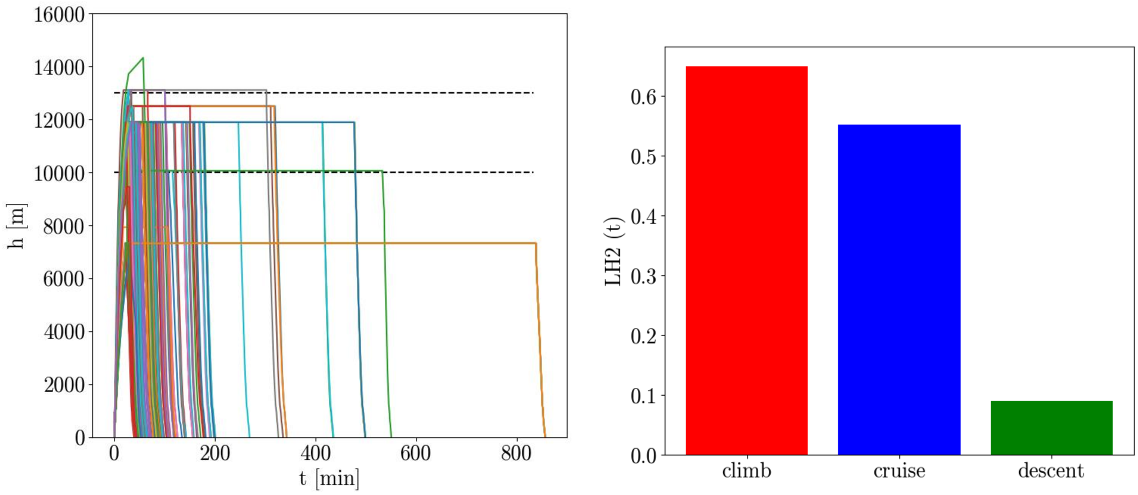


Figure 5 Flight profiles and LH2 consumption in different flight phases

in scenario 2050 medium for departures from OSL.

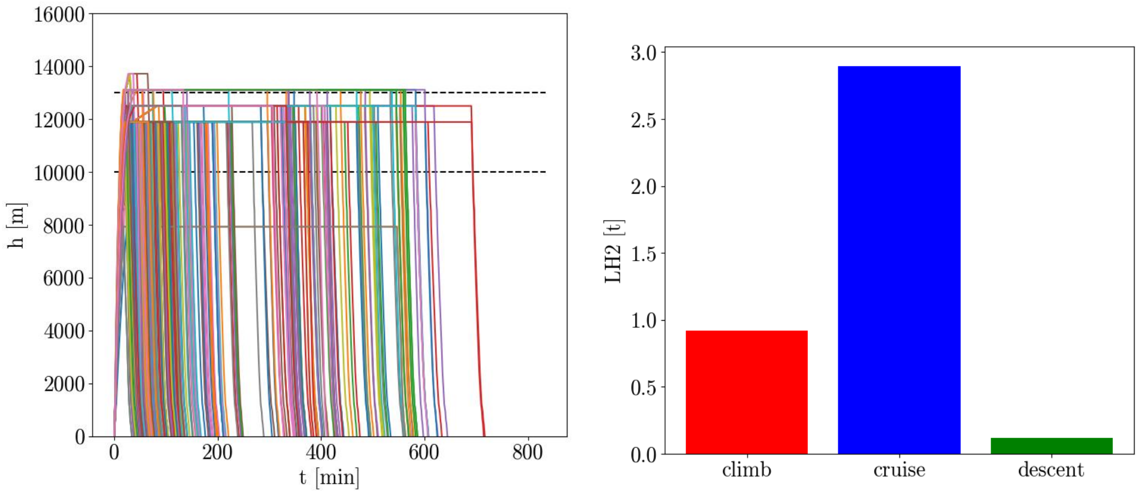


Figure 6 Flight profiles and LH_2 consumption in different flight phases

in scenario 2050 medium for departures from AMS.

5.2.2 Hydrogen demand for fuelling Ground Support Equipment (GSE)

Hydrogen and fuel cell technologies are also discussed as potential energy sources for Ground Support Equipment (GSE) to reduce emissions at airports[86]. Thus, also hydrogen demand for GSE operations is estimated in this study. Testa et. al[86] gives an estimate of the H_2 demand for every ground handling operation, dependent on the aircraft class. This is used as a basis to calculate the H_2 demand throughout a day at the TULIPS airports for two different scenarios:

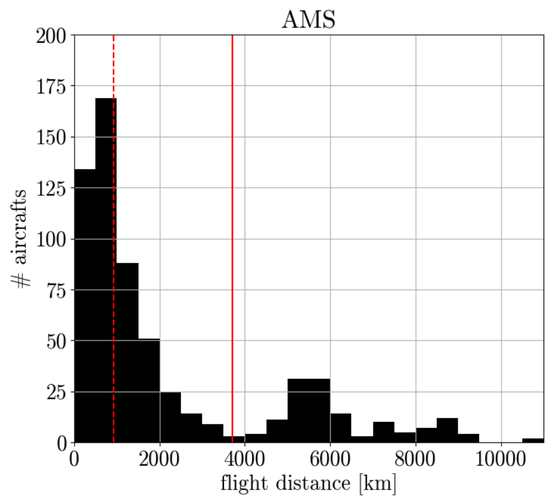
1) **Low**: The first operations to run on hydrogen based on information provided by *KLM Equipment Services during the TULIPS project*, i.e.:
    - Baggage tractors
    - Container loader
    - Pushback
    - Ground power unit (GPU)
2) **High**: All ground handling operations

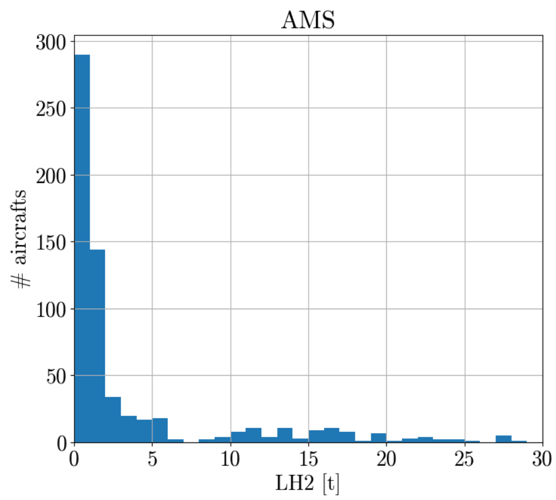
The aircraft class for every flight is identified based on BADA and the GSE H_2 demand for every flight is calculated throughout a day for the different airports.

Other land transport and industrial end use are not a part of the scope of this method. However, these user groups are important for the capacity utilization of the infrastructure for hydrogen.

5.3 Results and discussion

To illustrate the differences between the examined airports the flight statistics for departures from AMS and OSL are shown in Figure 7. Flight distances of 500 nm and 2000 nm are marked in the figure, as these correspond to the different aircraft types considered in the analysis. It is apparent that for both airports a large share of the flights are below 500 nm, with 42% from AMS and 61% from OSL. However, at AMS a significant number also exceeds 500 nm and 2000 nm (22%), whereas there are only very few flights (6%) with distances bigger than 2000 nm from OSL. This signifies that solutions at different airports will be dependent on the local flight pattern. This also reflects in the LH_2 demand per flight where 96% of all flights from OSL would require less than 5 t of LH_2 and 88% would require less than 2 t of LH_2, whereas from AMS only 81% and 69% would be covered with less than 5 t and 2 t of LH_2 respectively.





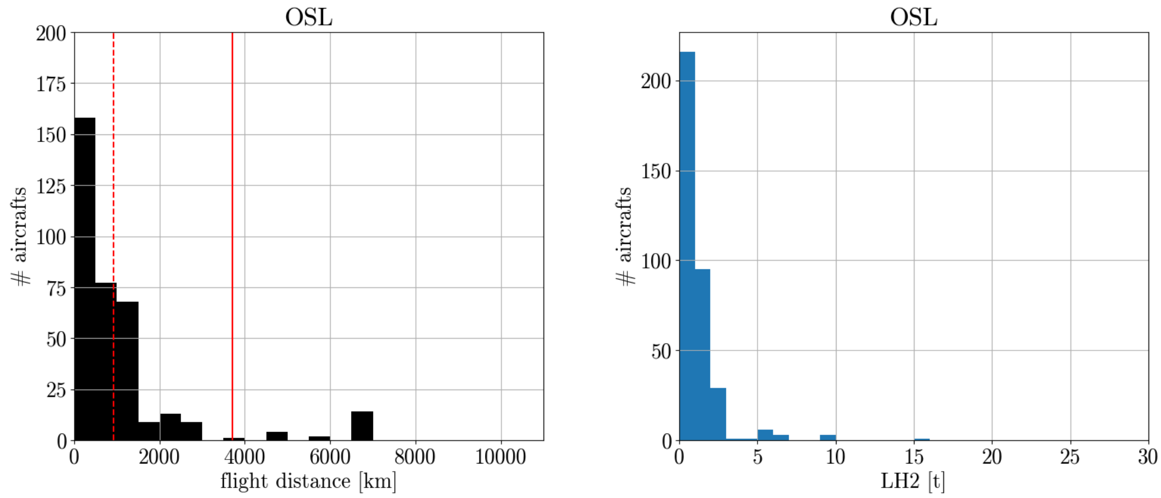


Figure 7 Histograms of flight distances and LH2 demand for departures from AMS and OSL.

In Figure 8 the LH_2 demand for the in 5.2.1 defined scenarios of *low*, *medium* and *high* penetration rate of hydrogen powered aircraft in 2040 and 2050 is shown for the TULIPS airports AMS, OSL, LCA and TRN. Three quantities are illustrated, daily energy demand, daily LH_2 demand, and peak LH_2 demand per hour. This shows that significant variations exist, dependent on the scenario and assessed quantity. While LCA has generally higher energy and LH_2 demand than TRN, in a *low* scenario in 2040 without any flights above 500 nm operated with LH_2, TRN requires more energy and LH_2 than LCA. The peak demand per hour in 2040 *low* on the other hand scales in the same way as for the other scenarios and years. It is apparent that LCA is generally closer to OSL in peak demand, than in daily demand, suggesting that the demand at OSL is more distributed throughout a day. Generally the spread for the different scenarios is large, showing that airports have to prepare for a wide range of demand scenarios in the near to midterm future. The results can be compared to D2.1 in TULIPS, a feasibility study on airports delivering energy supply for future aircraft. While the approaches to estimate future hydrogen demand have been quite different, the results are nevertheless comparable. For the here presented *medium* scenario in 2050 a similar number of departures of hydrogen-powered aircraft as in D2.1 is projected for AMS. Also the energy demand is estimated similarly with 385 t of LH_2 in this study, compared to 360 t in D2.1. Considering that all these estimates come with significant uncertainty when projecting this far into the future, the deviation between the different approaches is small.

The energy and LH_2 demand are calculated individually for every flight as described in 5.2.1. Figure 9 displays the LH_2 demand throughout a day at AMS with an hourly resolution for the *low*, *medium* and *high* scenario in 2040 and 2050. This shows, that from 0:00 to 5:00 there are only very few departures and thus also very little LH2 demand. A first demand peak occurs at 7:00, which corresponds to the peak demand per hour for the *high* scenario at AMS. Other peaks are at 11:00, 14:00 and 21:00.

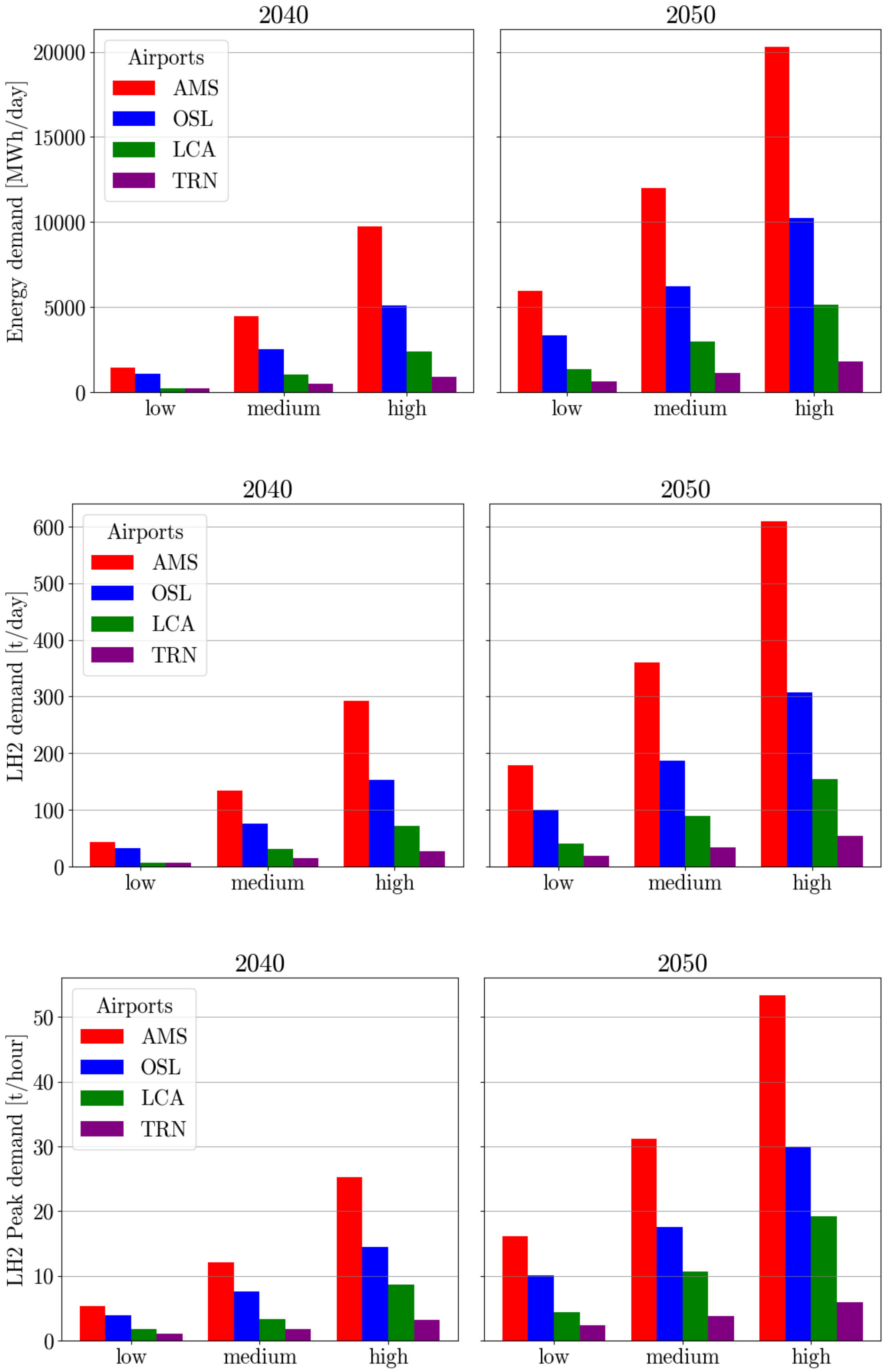


Figure 8 LH2 demand at AMS, OSL, LCA and TRN.

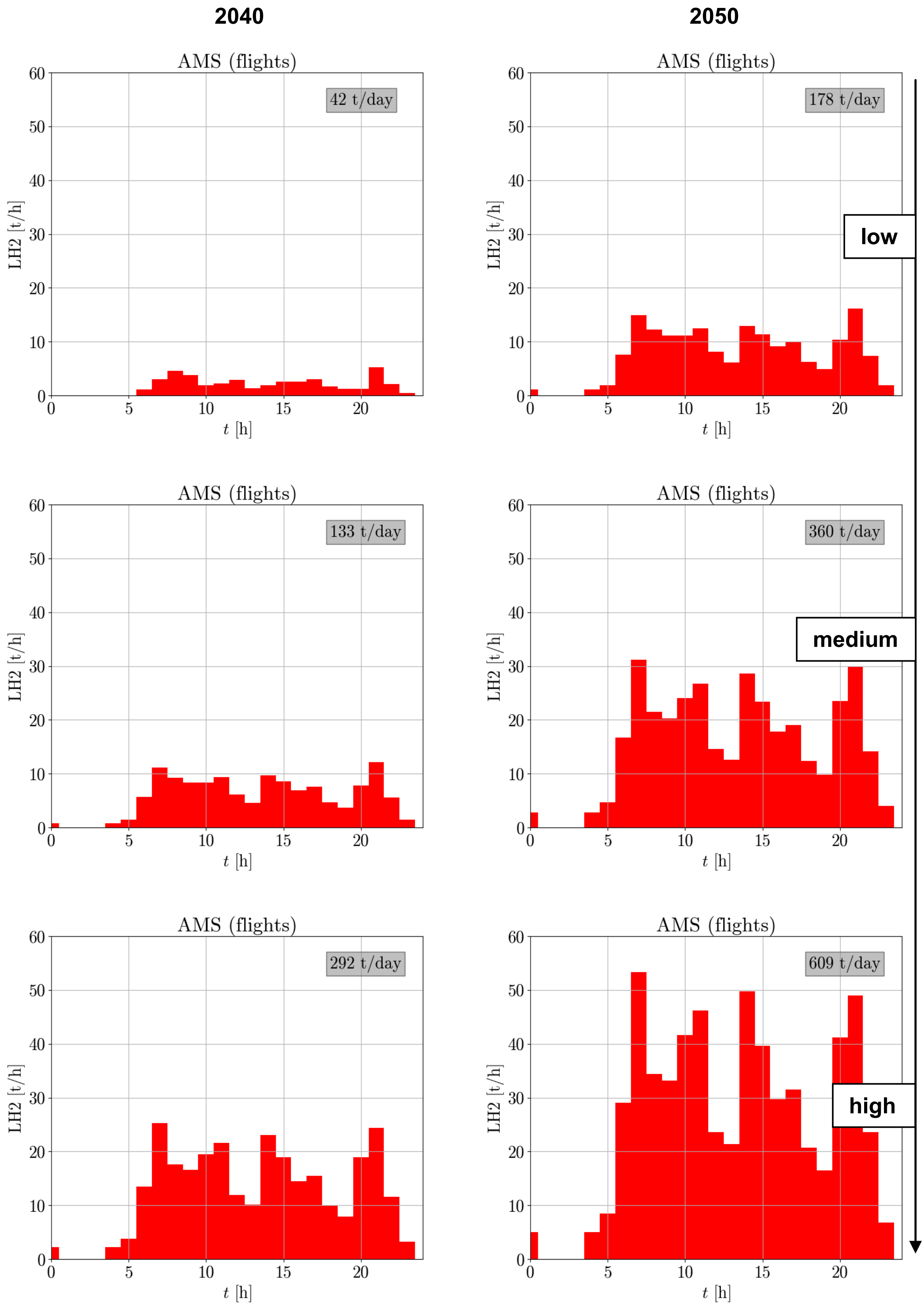


Figure 9 LH_2 demand throughout a day at AMS for the low, medium and high scenario in 2040 and 2050 with hourly resolution.

LH_2 demand throughout a full year based on all departures from OSL in 2023 is displayed in Figure 10. This shows that the energy demand does not only fluctuate throughout a day, but also from day to day and throughout the different times of the year. The demand is projected to be highest in the summer months and peak in July and August. There is less air traffic in the winter months and correspondingly also less projected LH_2 demand.

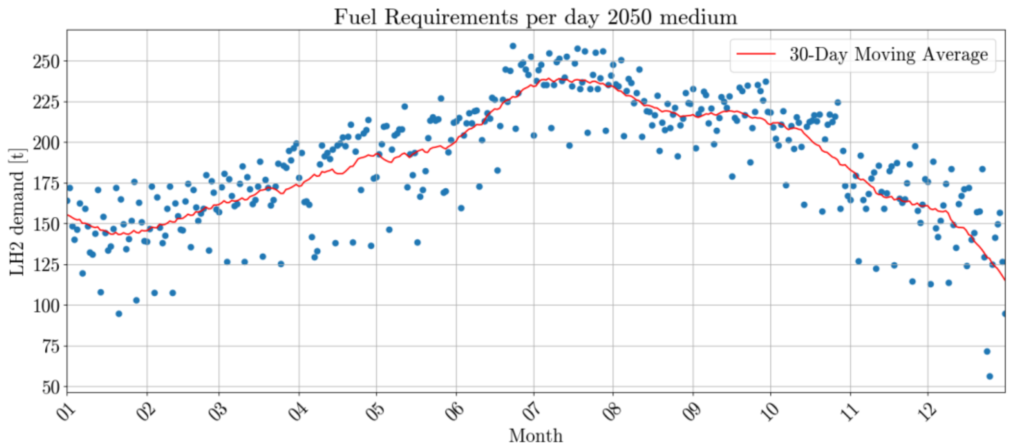
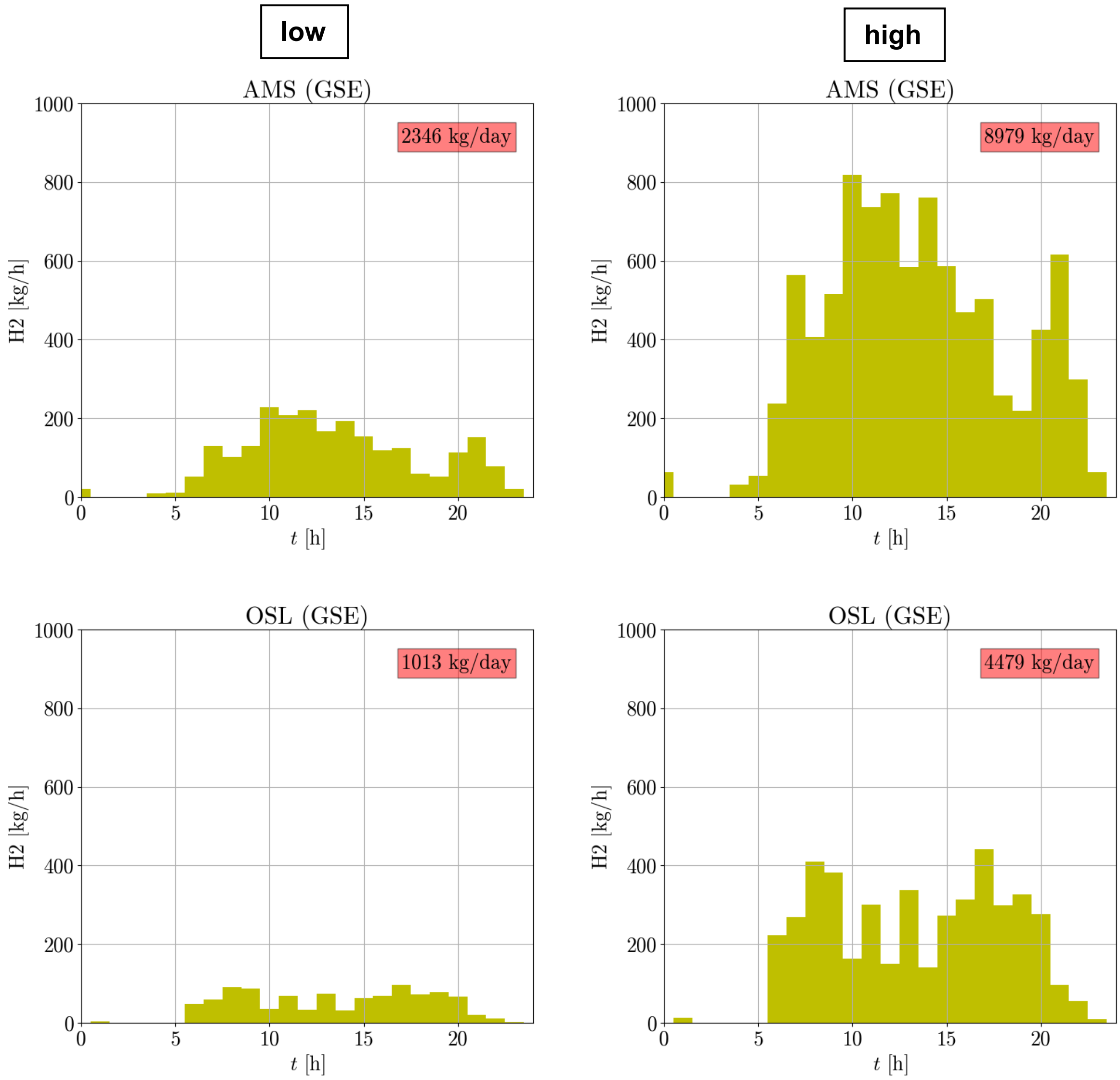


Figure 10 LH_2 demand for flights from OSL in 2023.

The hydrogen demand to power GSE throughout a day at AMS, OSL, LCA and TRN is visualized in Figure 11 for a low scenario, in which only the first operations projected to run on hydrogen are considered and a high scenario in which all ground handling operations are considered to run on hydrogen (see 5.2.2). Between the low and high scenario is approximately a factor of four, which shows that it is critical to define which ground handling operations can and should be powered by hydrogen. The peak demand throughout the day does not only vary in quantity between the different airports, but also in time.

The low scenario for GSE at AMS is based on partner input on which GSE operations are most likely to run on hydrogen. The remaining GSE operations can also run on battery-electric or plug-electric power. The low scenario is therefore more likely to occur than the high scenario for airside CGH2-needs, but the potential H2-consumption landside and for regional industry is not included in the analysis.

OSL is a newer airport than AMS, and also more compact. Thus, more of the GSE applications on OSL are already electrified. Therefore, fewer applications are considered to be future hydrogen-powered operations. During the winter season, snow sweepers are operating with heavy duties. These can potentially run on hydrogen, but we do not have information on the potential energy consumption for these vehicles.


low
high
AMS (GSE)
2346 kg/day
AMS (GSE)
8979 kg/day
OSL (GSE)
1013 kg/day
OSL (GSE)
4479 kg/day
H2 [kg/h]
t [h]
0
200
400
600
800
1000
5
10
15
20

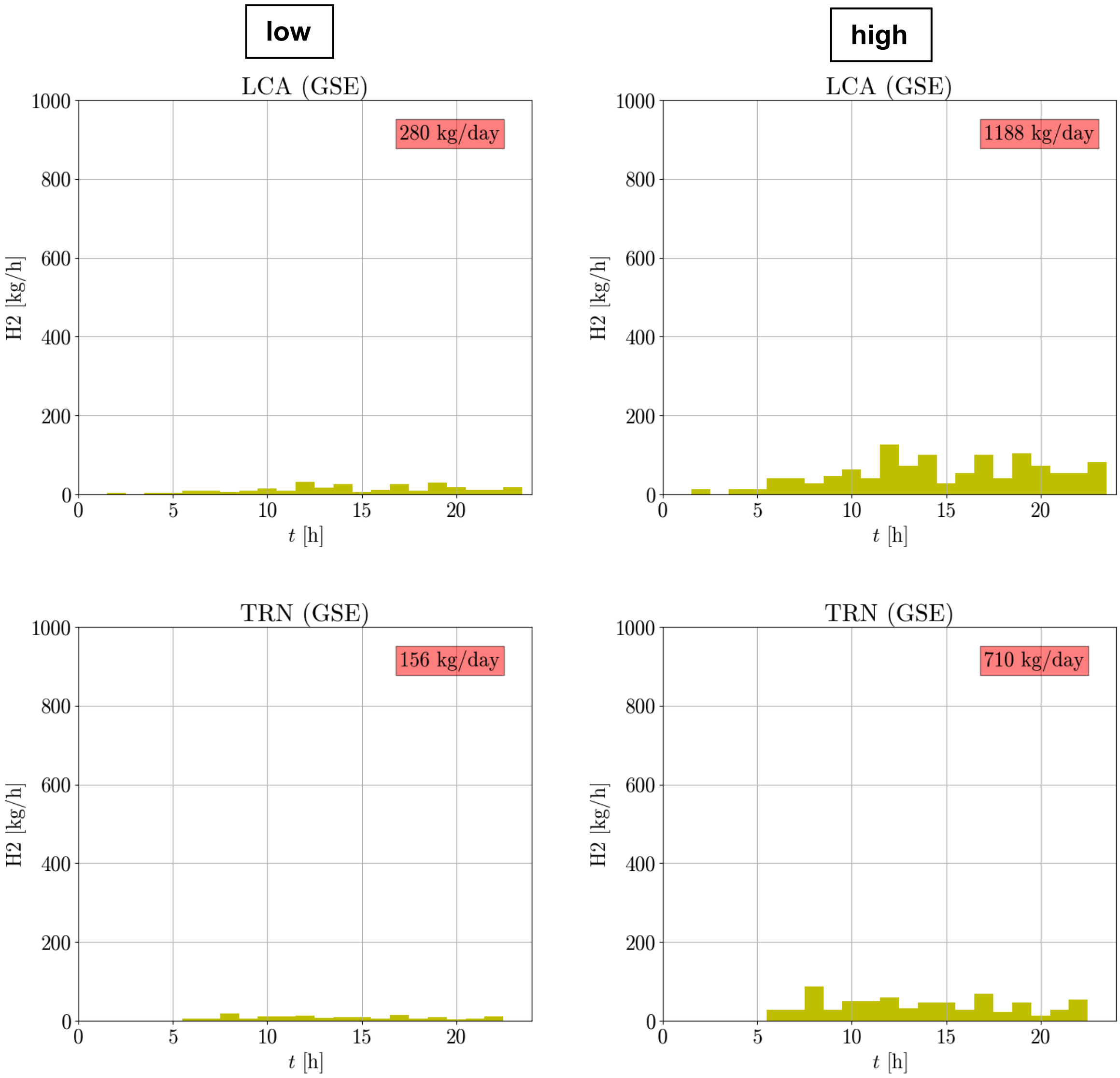


Figure 11 Hydrogen demand to power GSE throughout a day at AMS, OSL, LCA and TRN for a low and high scenario with hourly resolution.

5.4 Summary

The hydrogen demand at the TULIPS airports has been quantified for the transition to hydrogen-powered aircraft, as well as GSE. The analysis is based on a flight-by-flight analysis using BADA. This enables a time-resolved analysis of future hydrogen demand. It is apparent that there exist considerable variations both within a day and throughout a year. In addition, the results vary significantly depending on the analyzed airport and the considered scenarios, i.e., market penetration of hydrogen-powered aircraft and GSE. This shows that there is still a great deal of uncertainty in projecting future hydrogen demand at airports. Nevertheless, the analysis here gives indication of future demand, covering a wide range of scenarios and airports. Finally, the here developed methodology can easily be expanded to other airports and scenarios and adapted as the market penetration of hydrogen-powered aircraft and GSE takes shape in the future. In section

6 the LH2 demand for powering aircraft is correlated with the H2 demand for GSE and set into context with realistic boil-off rates.

6 Large-scale concept for LH2 infrastructure

6.1 Introduction

The medium and high demand scenario for AMS amount to the consumption levels where pipeline systems can be economically favourable. These volumes of LH_2 are unprecedented in history, and the parallel systems for Jet-A1 have been developed over decades to the level of maturity and optimization they are found today.

The two closest resembling systems for LH_2 are i) the refuelling of the launcher in the space shuttle program[49], and ii) LH_2-filling stations for vehicles[87]. The storage tank's size and system size of the launch pad are relevant for airports, but the filling pattern and residence time of LH_2 of the launch pad is far from how the airport will operate. The reported high LH_2 losses from the space program are therefore less relevant for the airport case. On the other hand, the operation of an airport is likely to resemble the operation of LH_2-filling stations for vehicles which reports negligible LH_2 losses, however, the airport is a significantly larger system. Appendix I describes these systems and the relation to the proposed airport system in greater detail.

In summary, Section 6 analyses a system concept that is developed with the purpose of

- Minimizing evaporation from the storage tank by having nearly continuous use of LH_2 and avoiding seasonal storage.
- Avoiding the need for precooling, by requiring all aircraft to have residual LH_2 that keeps aircraft cold and circulate LH_2 through the ground systems, except during maintenance
- Defining a system with local liquefaction of hydrogen supplied through the European hydrogen backbone (relevant for AMS). Another alternative for AMS is import through LH_2 pipelines from i.e. an importing Port.

The system concept is introduced in Chapter 6.3, together with the main research questions addressed and analysis approach selected. The subsequent sections present a model-based evaluation of the refuelling system. Finally, estimates of LH_2 evaporation from normal operation are analysed, as a basis to validate feasibility of the system and propose boil-off handling opportunities.

6.2 System size

The medium scenario for 2050 are selected to illustrate potential system sizes for LH_2 production, and storage at the airport. For OSL, the peak demand season from Figure 10 is selected. Table 6 presents the LH_2 need, and suggested technologies for storage, production and liquefaction.

Table 6: Estimated ballpark capacities for LH_2 storage, liquefaction and electrolysis

*– and compared to current state of art technologies. *Electrolysis may be places elsewhere, if hydrogen is transmitted via pipelines.*

Air-port	LH_2 need [tpd]	Tank farm [tanks]	Available liquefaction technology	Power for liquefaction [MW]	Electrolyser* [MW] (rounded)
OSL	250	3x3450 m^3 + 1x1100 m^3	No, Mixed refrigerant technology needed	73	600
AMS	327	4x3450 m^3 + 1x1100 m^3	No, Mixed refrigerant technology needed	95	800
TRN	30	1100 + 300 m^3	Yes	9	70

Whenever a pipeline transmission system is available the hydrogen production can be done remotely, and hydrogen can be purchased from the merchant market (pipeline) for local liquefaction. This still require significant energy for liquefaction. Based on the review in Chapter 3.4, a specific liquefaction energy of 7 kwh/kg H_2 is used to estimate the needed power for the liquefaction capacity. The resulting estimates for necessary electric power for liquefaction is provided in Table 6. The extra energy required for the subcooling of LH_2 assumed in the following work, is not included. As an alternative to local liquefaction, LH_2 can be imported by ship and stored in a nearby port. However, this increases the number of LH_2 transfers needed – with the risk of evaporation. Potentially, the relative evaporation is lower from LH_2 carriers than LH_2 trucks, due to the difference in volume and surface area. Unfortunately, there is little information available on the evaporation from bunkering and de-bunkering of LH_2 carriers, but the research project LH2Pioneer is focussing on relevant challenges[88,3].

To understand the capacity for electrolysis needed to supply renewable hydrogen to the airport, the electrolyser capacity to produce the given tonnes per day is estimated based the production capacity ambition of the 100 MW REFHYNE 2 electrolyser (see 3.3). What is seen, is that the smaller airports (TRN) can be supported by electrolysers with a capacity that is close to what will soon be in operation – while the larger airports (OSL, AMS) will require new records to be made as the needed capacity is 3-5 times the planned largest European electrolyser Normand'Hy, unless the hydrogen is purchased from a backbone that receives hydrogen from multiple sources (including low carbon hydrogen). As a final remark, the liquefaction energy is around 12 % of the

[3] LH2Pioneer project: https://www.sintef.no/prosjekter/2021/lh2-pioneer-ultraisolert-lagersystem-for-global-skipstransport-av-flytende-hydrogen/

electrolysis energy. Thus, the major energy system challenge is the hydrogen production from renewable energy itself.

Liquid hydrogen processing (liquefaction/re-liquefaction) can have a significant geographic footprint. A preliminary review performed by Aerospace Technology Institute suggests land requirements for liquefaction are in the order 25-300 m^2/tonnes[89]. There are large differences in estimated footprint of a liquefaction plant, and the reported range is used to estimate the area needs in Table 7.

Area estimates for the fuel farm are also made. The liquid hydrogen fuel farm may typically consist of storage tanks with sufficient capacity for 3 days of aviation fuel consumption. Table 6 proposes a combination of available tank sizes (based on available tank sizes reviewed in 3.5) to fulfil this need. The geometric footprint of the storage facility depends on tank geometry, safety distances and other considerations for accessibility. Standard safety distances are typically derived for smaller storages, and inter-LH_2 storage distances for systems of 8 meters[4]. However, given the larger amount of storage and the need for practical accessibility – the inner zone of the tank is likely to be higher. Safety distances for airport LH_2 fuel farms is a topic for other ongoing research projects. The fuel farm area is approximated as a rectangle around an area with all tanks placed along a line, with an assumed 20 m safety distance around each tank. The 3450 m^3 have an outer diameter of 21 m[90] and for simplicity the remaining tanks – both the spherical 1100 and laying cylinder tank of 300 m^3 have a footprint diameter of 12.8 m. The resulting area is provided together with the liquefaction area range in Table 7. For comparison, the area needed for the preliminary concepts proposed in the LH_2 Airport requirements study (Brewer, 1976) are also provided.

Table 7: Area estimates for fuel farm and liquefaction.

San Francisco (SFO) data from Brewer 1976 [59]

Air-port	LH_2 [tpd]	Tank farm area, m^2	Liquefaction area, m^2	Total area, m^2 (rounded)
OSL	250	10 700	6250 – 75 000	17 000 – 86 000
AMS	327	13 200	8175 – 98 100	21 400 – 111 300
TRN	30	4500	750 - 9000	13 500
SFO	846.5			245 135
SFO	250			60 800

The range of the total area is highly sensitive to the uncertainty in the area for liquefaction. The SFO study is more detailed, and area needs for i.e. the 250 tpd concept can be compared to OSL.

[4] Air Products, information to the TULIPS project

The area is within the upper part of the OSL, range. Further work is needed to understand both the area availability at the airports, and how liquefaction plants can be assembled to reach the lower bound in the area estimate.

6.3 System concept and analysis approach

Some general operative principles for the large scale LH_2 system are discussed in 6.1. A pipeline system concept that enables maintaining a low system temperature also overnight can consist of a LH_2 circulation loop, a main LH_2 pump and connection points (hydrants) for flexible hoses to the aircraft. These hoses are relatively short. In order to maintain one-phase flow and avoid evaporation of $LH_{2,}$ the selected strategy is to have subcooled LH_2 as a starting point. Throughout the system, the fluid will take up heat, but the system shall at all time operate such that LH_2 in maintained the subcooled state.

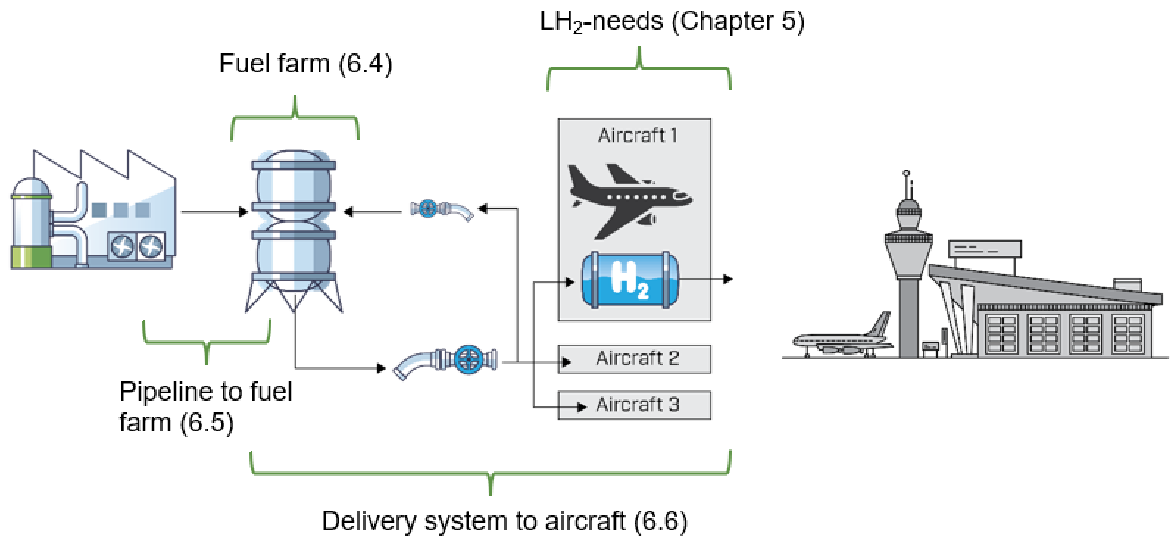


Figure 12: High level illustration of the concept system

The system is described more in detail in the following sections, in which we aim to address these main technical questions related to the scale up of LH_2 infrastructure to the AMS medium scenario for 2050:

> **Q1: What are the limiting factors and practical distance away from the airport the hydrogen liquefaction plant has to be placed, and can LH_2 technically be imported from a LH_2 reception terminal in a port?**

A dynamic process model for a pipeline and pump is developed to enable analysis of temperature, pressure and mass flow dynamics in LH_2 pipelines for distribution of LH_2 to the fuel farm at the airport. Key aspects of interest are the required insulation as a function of length, as well as the effect of pump parameters. The model will be used to understand the critical design parameters and feasible length a of a LH_2 pipeline for the AMS medium scenario in 2050 and can be used to find possible locations for the liquefier in or near the airport forecourt, and better understand the technical feasibility of importing LH_2 from the port. See section 6.5.

Q2: What are the requirements for subcooling in the airport distribution system, and how much LH_2 is evaporated during refuelling of an aircraft?

A dynamic process model for the distribution system within the airport is developed. The model is used to analyse the requirements to keep LH_2 subcooled by using a pump in order to avoid two-phase flow.

Q3: How does the fuel farm inventory evolve for a given fuel farm configuration?

Based on available thank designs, a fuel farm configuration is proposed. A mass balance model is developed to analyse the fill level in the tank, as a function of inflow and outflow, i.e. filling of the fuel farm, supply from the fuel farm to the refuelling system and evaporation losses. The evaporation loss is based on a modelled thermal ingress in the tank. See section 6.4.

Q4: What is the level of boil-off that can be expected during nominal operation of the proposed system?

The developed dynamic model for the distribution system will be used to simulate the refuelling of aircraft tanks at short timescales. From the results, estimates of gas formation will be generated and aggregated into estimates for the total boil-off during a day of normal operation.

Q5: Can the evaporated H2 be used for ground operations?

Finally, the total boil-off will be compared to the GSE-need for gaseous compressed H_2, to better understand the potential for integrating hydrogen delivery to ground vehicles as a strategy for boil-off handling.

6.4 LH_2 fuel farm

In this section we address the **question Q3**.

6.4.1 Fuel farm model and evaluation

The fuel farm of AMS in 2050 for the medium scenario can consist of 4 x 3450 m^3 tanks as suggested in Table 6. The level of LH_2 in these tanks will vary throughout the day, as they i) continuously filled with LH_2 from the liquefaction plant (filling rate), ii) used to supply LH_2 for refueling of multiple aircraft through the day, and iii) there will be some level of evaporation due to heat ingress in the tank (evaporation rate).

To better understand how the filling level of the fuel farm changes, and how fast the tanks will be filled and drained, a mass-balance model was created, where the change of LH_2 mass in each tank is

$$\frac{dm}{dt} = - \text{evaporation rate} + \text{filling rate} + \text{total refuelling rate}$$

The evaporation rate, also called the boil-off rate (BOR), is calculated by utilizing the in-house developed *pytank* module, used to assess thermal ingress into a tank, based on tank design and material choices. Boil-off of liquid H2 into the gas form is a process that happens due to the heat that ingresses through the layers of the tank. The convective heat transport between the outer and the inner fluids and their adjacent walls, as well as the thermal conduction through the tank layers combine to produce an effective heat transfer. In the present model, all heat ingress is assumed to go to the liquid phase, causing it to boil off. Since the heat ingress is a function of the structural and thermal properties of the tank and insulation materials that are constant, the BOR also remains constant with time. Pressure inside the tank is set to be constant at 1 atm.

The *pytank* model of thermal ingress in the fuel farm used design information for the 3450 m^3 NASA Kennedy Space Center tank from 1965 with three feet (0.9144 m) of evacuated perlite insulation[91]. In the simulation, the structural and mantle material is set to be stainless steel with a thickness of 0.06 m. The dimensions of the supporting structure are unknown, however, by adding a supporting skirt of the same material with thickness 0.0001 m and height 5 m, we manage to match the reported BOR. This design and material configuration results in a heat ingress of around 0.418 W/m^2.

The total refueling rate is based on the expected fuel demand for the flight schedule on a winter day in the medium scenario for AMS in 2025. For this scenario, the total demand of fuel in a day is 360 tons/day. A histogram showing the frequency of the fuel demands is shown below. This flight schedule is repeated for day 2 and 3, meaning the analysis winding is 3 identical consecutive days. The model assumes that LH_2 is supplied from one tank at a time. LH_2 is supplied from the storage tank until the minimum specified liquid level of 10 % is reached – to ensure the temperature in the tank is always low.

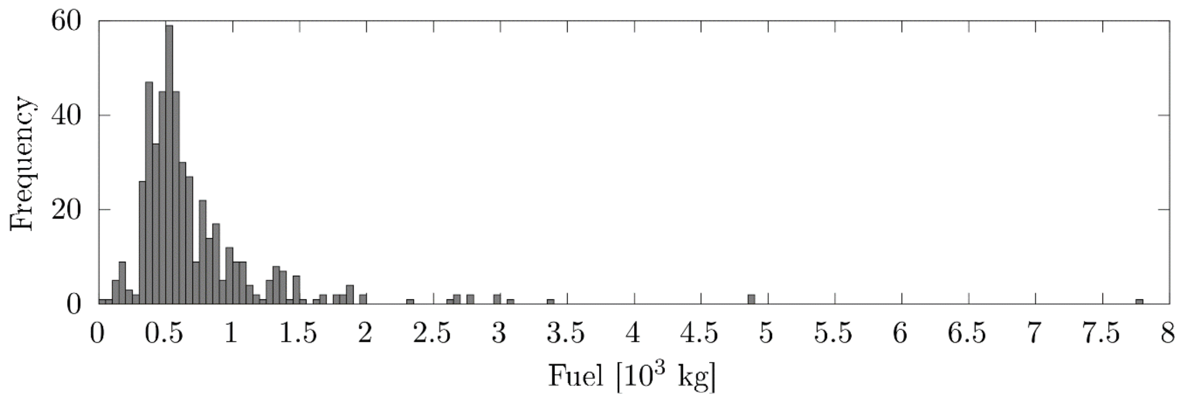


Figure: Frequency of the fuel demands on a winter day in the medium scenario for AMS in 2025

When a tank has reached its minimum fill level, filling starts. Several tanks can be filled simultaneously. The tank is filled up to 93 %, which is the same as the set ullage (3.5). Based on the total demand of 360 tons/day, the liquefaction rate is set to be a constant value of (360000 / 24 / 3600) = 4.2 kg/s. The filling rate of each tank will then be the liquefaction rate divided by the total number of tanks being filled at that moment of time. This way, the liquefier operates at a constant production rate.

6.4.2 Results

The simulated fill level of the fuel farm tanks are shown in Figure 13.

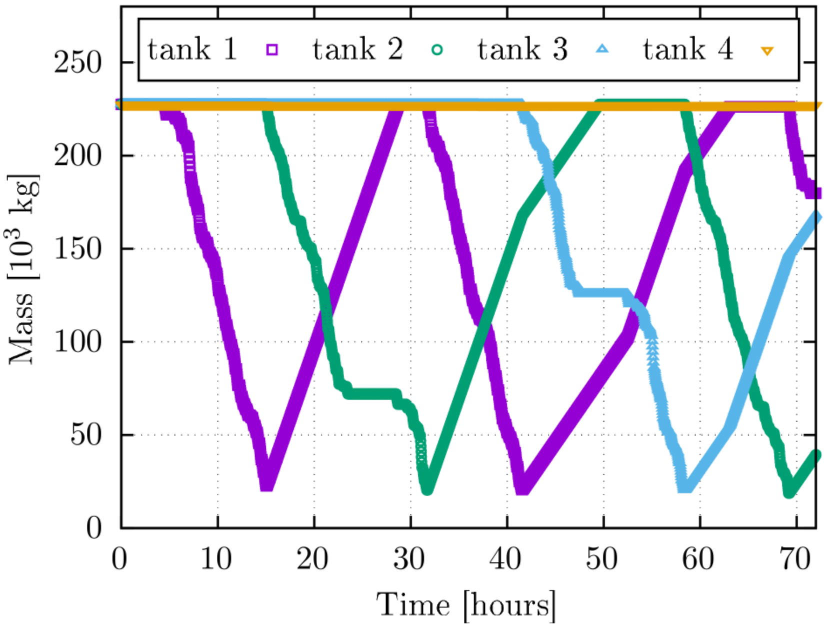


Figure 13 LH_2 fuel farm fill level

The simulated scenario starts with draining of tank 1. The mass contained in tank 1 decreases with the fuel demands that vary with time. When the mass reaches below the minimum allowed around 15.1 hours, tank 2 takes off the supply for refueling while tank 1 is re-filled at a constant rate until the max fill level is reached 14.4 more hours later. It can also be seen that the filling stops when the mass reaches the maximum limit.

Overnight, there is no fuel demand, and the fill level only changes slightly due to evaporation. This constant slow contribution to a decrease of LH_2 mass in the tanks also contributes in the daytime and constitutes the boil-off rate. It is found to be 0.00103 kg/s from each tank. With a constant BOR, the total amount boiled off from four tanks during three days should be approximately 0.00103 kg/s * 3600 s * 72 h *4 tanks ≈ 1068 kg. In the simulation shown, the total amount of LH2 received, including the start masses, is around 1527038 kg, which gives a relative evaporation (BOR) of 0.07 %. This is as expected and similar to Table 3.

6.4.3 Aircraft tank thermal ingress and capacity

The aircraft tank influences the specifications of the ground refueling system. Aircraft tanks were briefly reviewed in section 3.7, and for the purpose of having preliminary data the design as proposed by Rompokos et al was chosen[69]. The authors estimated themselves the thermal ingress using heat transfer principles and calculated the pressure rise in the tank during flight missions.

In order to acquire preliminary data for the heat ingress in the aircraft tank for the refuelling system modelling, the *pytank* module was used to create a model on an aircraft tank inspired by Rompokos et al. The tank is set to be cylindrical with an external diameter of 2.5 m and external volume 99.8 m^3. It is set to be made up of aluminium as its structural material with a thickness of 0.005 m. Furthermore, it is covered in a 0.124 m thick insulation layer of Polyvinyl Chloride with thermal conductivity 0.0046 W/(mK). Temperatures inside and outside are assumed to be 20 K and 300 K respectively. Pressure inside the tank is constant at 1 atm. With these parameters, the total heat ingress per area was calculated to be 9.3 W/m^2. The boil-off rate was calculated to be 0.0035 kg/s which corresponds to 5.5 % per day of the maximum LH_2 mass stored that is around 5742 kg.

6.4.4 Simplified calculation of BOG amounts for AMS 2050 medium scenario

We perform a simple initial estimate of the BOG formation at AMS for the 2050 medium demand scenario. The BOG amount is estimated by multiplying the total mass of LH_2 in the distribution system with a daily BOR. The LH_2 mass in the system is the density times the total volume, and we consider the following volumes:

- The tank farm for AMS in Table 6.
- The pipes in Section 6.6, Table 11:
  - A supply pipe from the tank farm to the aircraft stand with diameter of 0,45 m (18'') and 2 km long.
  - A return pipe of 0,17 m diameter and 2 km length.
- 5 aircraft with a tank of 96 m^3; see Table 10.

We assume a daily BOR of 0,2% for the entire system. This is a reasonable value for the tank farm (i.e. large spherical tanks) based on Berstad[92], and it is close to the cylindrical storage tanks of Linde in Table 3. This is also reasonable for the entire system since the majority of the LH_2 is in the tank farm in our simplified calculation ($\approx 92\%$).

This simplified estimate gives 2,2 tpd of BOG. This is significantly higher than the more detailed analysis in Section 6.4.1 to 6.4.3, but we see that the BOG amounts is well within the GSE needs for AMS 2050 (2.3 tonnes/day for low scenario and 8.9 tonnes/day for the high scenario).

6.5 Pipeline transport from liquefaction plant to LH_2 fuel farm

In this section we address the question **Q1.**

We consider pipeline transport of 327 tons/day LH_2, which corresponds to the medium demand scenario for AMS in 2050 described in Section 5.3. The considered system is visualized in Figure 14. To avoid vaporization of LH_2 throughout the distribution chain to the aircraft, we set as **a critical requirement that the LH_2 is subcooled when reaching the airport fuel farm** (point 4 in Figure 14).

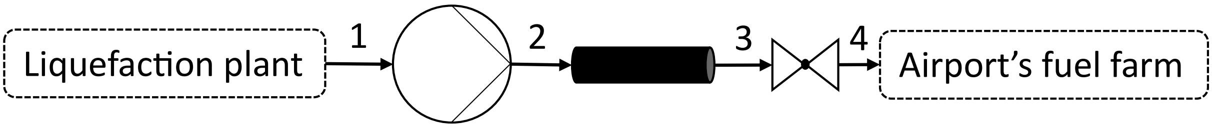


Figure 14: Subsystem considered. Points 1 and 4 are boundary conditions,

while 2-3 is the insulated pipeline of interest.

The pipeline is insulated with fibreglass-vacuum modelled as in Hofmann[93]. Fibreglass-vacuum offers better thermal properties than e.g. perlite-vacuum, which motivates this choice for insulation material for LH_2. However, there are many choices of insulation materials for commercial pipes today[65], and it is not straightforward to say which material is optimal from an overall cost perspective. We consider two separate cases regarding the pipeline length.

Case 1: We study in detail a pipeline using an insulation thickness similar to existing cryogenic pipelines[65]. The pipeline length is restricted to 4 km to have a suitable degree of subcooling of the LH_2 at the airport's fuel farm. We consider two pipeline diameters, 0.16m (6'') and 0.22m (8''), respectively. The smaller 6'' pipe means lower CAPEX, but higher OPEX compared to the 8'' pipe since the pressure drop is higher which calls for a more powerful pump. A radius of 4 km from AMS' fuel farm facilitates placing the liquefaction plant in proximity to the European Hydrogen Backbone (EHB).

Case 2: We consider a pipeline length of 25 km and check the required insulation thickness of the pipeline to have a marginal subcooling of LH_2 at the fuel farm. A radius of 25 km from AMS is sufficiently large to place the liquefaction plant on a barge at sea or at the port, facilitating LH_2 import with ships or liquefaction of hydrogen from the EHB.

The considered boundary conditions for both cases are given in Table 8; the pressure and temperature at the liquefaction plant (point 1 in Figure 14) correspond to a subcooling of 1,05 K. The model is simulated in Dymola with the library TIL[94].

We perform an uncertainty and sensitivity analysis to study how the subcooling at the fuel farm varies with respect to insulation thickness, pump's efficiency, pump's sizing and ambient temperature.

Table 8: Boundary conditions considered in the model,

with reference to points in Figure 14. Temperature at point 4 is the outcome of the simulation.

	Value
Pressure at point 1	1.1 barA
Temperature at point 1	19.5 K
Pressure at point 4	1.1 barA

6.5.1 Case 1: Existing insulation thickness, 4 km pipeline

The main objective in this study is to study the degree of subcooling of LH_2 when it reaches the fuel farm (point 4 in Figure 14). Secondary objectives are to quantify the heat added to the fluid due to heat ingress from the ambient and heat due to inefficiencies in the pump. To assess how the subcooling temperature varies with important parameters, we performed an uncertainty analysis and a global sensitivity analysis[95] to figure out which of the uncertain parameters influenced the variance of the subcooling temperature the most.

A model of an LH_2 pump is required to simulate the system. In this work, a centrifugal pump is selected and the pump's model is described in Appendix J.1.

The following parameters were assumed uncertain in the simulation:

Table 9: Uncertain parameters considered in the uncertainty and sensitivity analysis.

The parameters were assumed to follow a uniform distribution. Pump's V_0 is a sizing parameter of the pump described in Appendix J.1.

Uncertain parameter	**Low bound**	**High bound**
Ambient temperature, T_{amb}	15°C	35°C
Pump's nominal efficiency, η^{pump}	50%	70%
Pump's V0, V_0^{pump}	0.08 m^3/s	0.10 m^3/s
Insulation thickness	2.5 cm	5 cm

The bounds for the uncertain variables in Table 9 are selected for the following reasons. For pipe diameters of 6'' and 8'', the insulation thickness in an existing product sheet[65] is approximately 2.5 cm; this product sheet uses, however, a more effective insulation (multi-layer insulation), and therefore we assume that doubling the thickness is reasonable. For pumps, we selected a typical efficiency range. The high bound is close to the reported pump efficiency (73%) for the NASA Low Pressure Fuel Turbopump, which is referred to by Mangold et al[62]. Values for the sizing parameter V_0^{pump} is motivated in Appendix J.1.

The histogram of the uncertainty analysis are given in and Figure 15, and summary statistics are in 0, Table 32. Here, $T_{SC}^{fuelfarm}$ is the subcooling temperature of the LH_2 at the fuel farm, $\boldsymbol{Q}_{ave}^{pipe}$ is the average heat ingress through each meter of the pipe and $\boldsymbol{Q_{total}^{pipe}}$ is the total heat ingress through 4km pipe. The total work of the pump is given by $\boldsymbol{P_{shaft}^{pump}}$ while the heat transferred from the pump to the LH_2 due to inefficiencies in the pump is P_{loss}^{pump}.

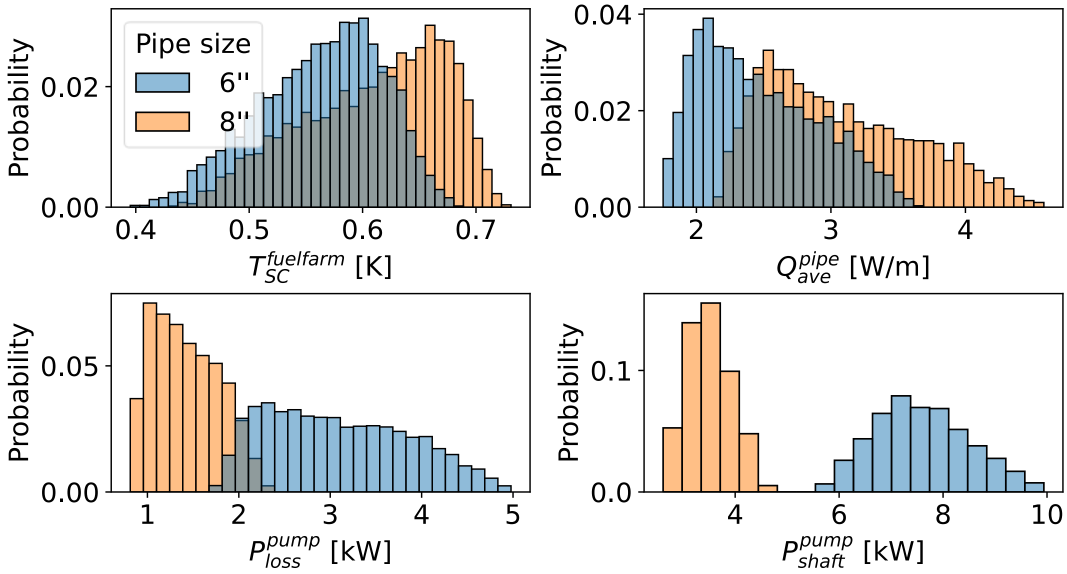


Figure 15: Uncertainty in the desired variables. Grey bars are overlap between 6'' and 8'' case.

The following observations from the uncertainty analysis (Figure 15) are made.

- The average heat ingress through the pipe, Q_{ave}^{pipe}, is smaller for the 6'' pipe than the 8'' pipe due to less surface area.
- The pump is more important in the 6'' pipe case, which is expected since a small pipe gives a higher pressure drop
- For both the 6'' and 8'' pipeline, the heat ingress through the pipe $\boldsymbol{Q_{total}^{pipe}}$ is more important than the heat transferred from the pump $\boldsymbol{P_{loss}^{pump}}$. However, both factors have a large magnitude and are important

In the case of a shorter pipe, the heat ingress through the pipe would obviously be smaller, but the sizing of the pump would also be different (less dP is required) and therefore the loss term would also be smaller. Short pipelines are always beneficial for transporting fluids, but this is especially important for LH_2.

The total sensitivity (ST) indices in Figure 16 shows that the variance in the subcooling temperature is mostly originating from the uncertainty in insulation thickness for both the 6'' and 8'' pipe. Effects originating from the pump plays a lesser role, but the pump is more important for the smaller pipe. For the heat flux through the pipe, the specified uncertainty in the vacuum thickness is significantly more important than the specified uncertainty in the ambient temperature. Finally, the performance of the pump is more influenced by uncertainty in the efficiency η^{pump} than the sizing parameter V_0^{pump}.

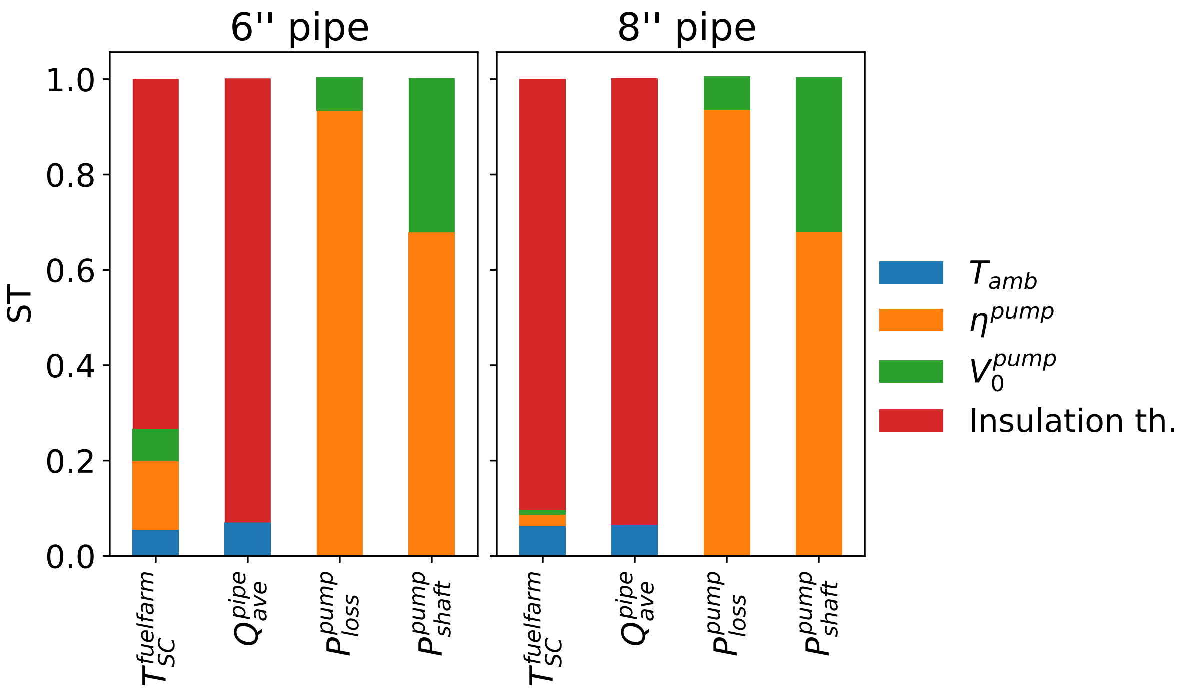


Figure 16: Total sensitivity indices.

It is important to note that these results are subject to i) the specified uncertainty in Table 9, and ii) our model, which we discuss in Section 6.5.3.

6.5.2 Case 2: Required insulation thickness for a 25 km pipeline

For a 25 km pipeline we only consider the pipe size of 8''. The subcooling temperature at the fuel farm and heat ingress through the pipeline is simulated for various insulation thicknesses as shown in Figure 17. It is observed that to obtain a marginal subcooling at the fuel farm, the insulation thickness must be at least 12 cm thick; a thinner insulation yields two-phase flows in our simulations. In practice, one would design the pipe with a margin on the insulation thickness, meaning that the insulation thickness would be more than 12 cm (e.g. 20 cm). Note that we assumed fibreglass-vacuum as insulation, while a better insulation method such as multi-layer insulation (MLI) should yield lower insulation thicknesses.

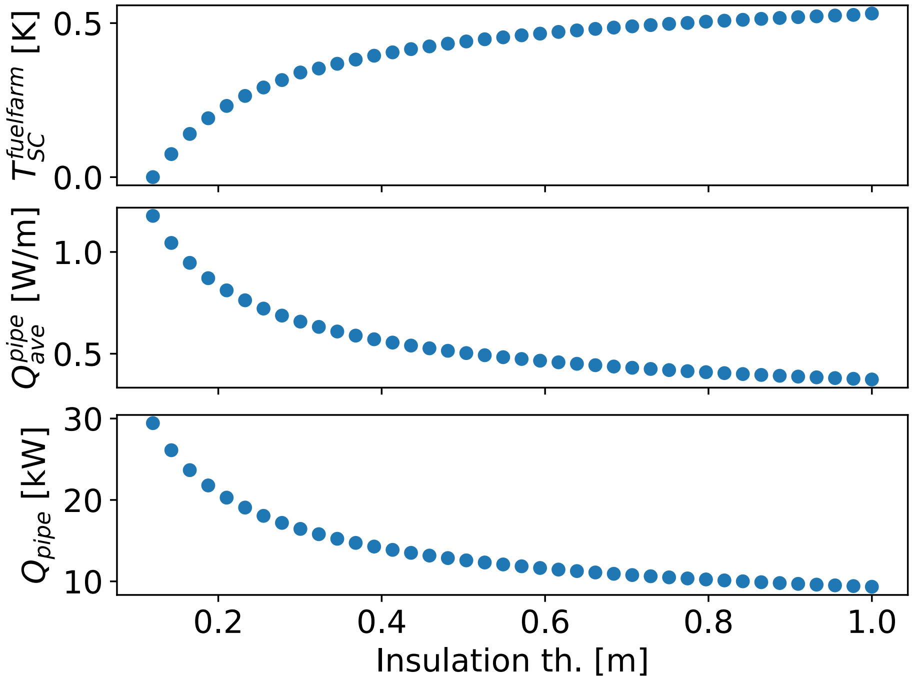


Figure 17: Subcooling at the fuel farm and heat ingress through the 25 km pipeline for various insulation thicknesses.

The simulations used 25°C ambient temperature. Since the pipe is longer, a more powerful pump is required; pump specifications for this case were a pump efficiency of 60%, $V_0^{pump} = 0.11\, m^3/s$ and $dp_0^{pump} = 1.35$ bar, where the meaning of these parameters are clarified in Appendix J.1.

6.5.3 Discussion and limitations of the model

A low margin for "unexpected" pressure drops is chosen for the simulations by designing the system to have a low pressure drop over the valve in Figure 11 (the pressure drop was in the range of 0.22 to 0.45 bar). In a real system, it is likely that the pump is designed for a higher delivery pressure at the valve (point 3 in Figure 11), as a safety margin to ensure that the correct quantity of LH_2 is transported to the airport. Increasing the delivery pressure translates to a more powerful pump, implying that that more heat is transferred to the LH_2 and it is likely that the pump's parameter would play a more prominent role in the sensitivity analysis in Figure 16. Therefore, a high pressure drop (safety margin) translates to worse system performance and increased OPEX (more power to the pump). Our choice can be regarded as the optimal value from the operational point of view, although it is unlikely that it will be chosen in practice.

Other sources of uncertainty in our model are

- There is a lack of experimental data to verify the pressure drop model in the pipes. We used the pressure drop model of Konakov[96] in our simulations, which assumes smooth pipes and might therefore be an optimistic approach (underestimates the pressure drop).

- The model may not consider all possible thermal bridges that occur in a realistic pipeline (i.e. in connections, supports and instrumentation), which implies that the higher bound of heat ingress per meter Q_{ave}^{pipe} in Table 32 can be slightly underestimated.
- Pump characteristics, e.g. the efficiency, play an important role. There is a lack of knowledge to validate if the assumed parameters in Table 9 are reasonable for a LH_2 pump, although the efficiency range is typically valid for other fluids.

6.5.4 Summary

We investigated the feasibility of locating the hydrogen liquefaction plant at either 4 km from AMS's fuel farm or 25 km. When the distance is 4 km, the liquefaction plant can be in proximity to the EHB while the 25 km case means the liquefaction plant can be at the port or on a barge. We assume that the LH_2 has a subcooling of 1,05 K from the liquefier, and our key requirement is that the LH_2 is still subcooled when reaching the airport (in order to avoid two-phase flow).

For the 4 km case, we performed an uncertainty and sensitivity analysis to investigate which uncertain parameters influences our quantity of interest (i.e. the degree of LH_2 subcooling at the airport) the most. The considered uncertain parameters were the LH_2 pump's parameters (a sizing parameter and the pump's efficiency), ambient temperature and the insulation thickness of the pipeline. **The analysis revealed that the insulation thickness of the pipeline influences the LH_2 subcooling at the airport the most.** For the 25 km case, we investigated how thick the insulation must be to obtain subcooling at the airport's fuel farm.

For both the 4 km and 25 km case, it is technically possible to deliver LH_2 to the airport by insulating the pipeline "enough". The required insulation thickness for the 25 km case is, however, quite high (two-phase is formed at 12 cm insulation thickness), which is likely to give high CAPEX. Note that we assumed fibreglass-vacuum as insulation method, while e.g. MLI would reduce the required insulation thickness. A cost analysis investigating which insulation material is preferred is out of scope for this report, but we note that such a work is interesting for future research.

The identified limiting factors for long-distance LH2 transport in pipelines are:

- Pipeline must be heavily insulated, which can give high CAPEX.
- High capacity LH2 pumps is not yet commercially available.

6.6 LH_2 delivery system to aircraft and refuelling

In this section **question Q2** is addressed: "What are the requirements for maintaining subcooling in the airport distribution system, and how much LH_2 is evaporated during refuelling of an aircraft?"

6.6.1 System description

We consider the system in Figure 18, where the liquefaction plant supplies a steady flow of 330 tpd LH_2 to the fuel farm and the supply pump refuels the aircrafts with LH_2.

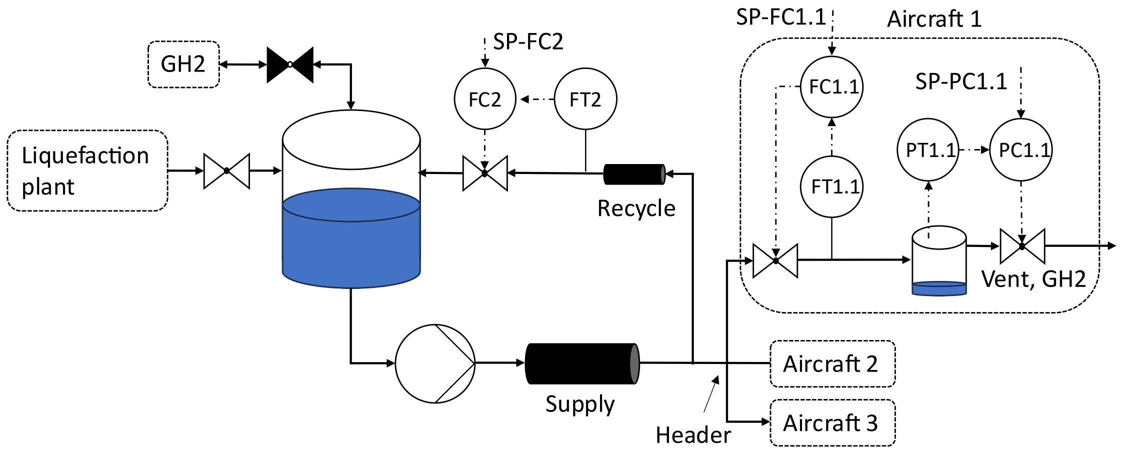


Figure 18: Simplified overview of the delivery system from the fuel farm to the aircrafts.

FT are flow transmitters (measurements), FC flow controllers and SP-FC its set-point (desired value). PT, SP-PC and PC are similar but for pressure control. The pipeline and flexible hose connecting the header to the aircraft is not shown for simplicity.

The refuelling is happening in discrete events throughout the day, and we assume all aircrafts will be refuelled with 6200 kg LH_2. This size corresponds to an SMR aircraft and is estimated based on tank sizes found in literature, which varies slightly (see 3.7 and 6.4.3). We assume that the fuel farm is located 2 km from the aircrafts, hence, both the supply line the recycle line are 2 km long. The recycle line is required for i) keeping the pipes cold, ii) start-up of the pump, and iii) avoiding turning on/off the pump between the filling of each aircraft, which is often desired to reduce wear and tear of the equipment.

Gaseous H_2 (GH_2) must be handled at both the fuel farm storage tank and aircraft tank. At the fuel farm, the GH_2-line may be used for i) extracting GH_2 from the storage tank to avoid over-pressurization, which can be the case after maintenance or when there is a low consumption of LH_2 at the airport (not many planes to fill), or ii) supplying GH_2 to the tank to avoid pressures less than 1 atm ("vacuum"), which may happen in times with very high demand. In this work, the pressure in the fuel farm's storage tank was always in the range 1.03 to 1.3 bara which we considered to be acceptable, hence, the GH_2 valve is marked as closed (black) in Figure 18. For the aircraft's tanks, the GH_2 line is used to control the pressure less than the maximum operating pressure which is set to 1,7 barA as in Gomez [70]; see also Section 3.7. The maximum operating pressure of the aircraft tank is an important parameter to limit the boil-off, and we note that higher tank pressures may be permittable as aircraft tanks are under rapid development in other research programmes, e.g. COCOLIH_2T[97].

We consider that airplanes are filled from 06:00-22:00, i.e. “daytime” is defined to be 16 h and the night 8 h. Planes are not filled during the night, but the storage tank is receiving LH_2 from the liquefaction plant and we pump LH2 through the recycle line to keep the pipes cold.

6.6.2 Specification of equipment and parameters

Parameters of the tanks are given in Table 10. The tanks are modelled as separators in TIL[94], with the assumption that the liquid and gas phase are in thermodynamic equilibrium. We qualitatively discuss the validity of this equilibrium assumption for both tanks in Appendix K.4, and we will further discuss potential impacts of this assumption on our results in Section 6.6.3.1.

Table 10: Specifications of storage tanks.

Tank	Size [m^3]	Heat ingress [kW]
Fuel farm's storage tank	8000 m^3	5
Aircraft	96 m^3	1.3 kW

For simplicity, a single 8000 m^3 tank is modelled for the fuel farm. The calculation of heat ingress to the fuel farm's storage tank follows the approach from Berstad[92]. We assume a well-insulated, spherical storage tank, and the heat ingress is estimated by selecting an overall heat transfer coefficient $UA = 0.009 \frac{W}{m^2K}$ (see Berstad), assuming ambient temperature of 35 Celsius and the saturation temperature of LH_2 at 1.2 bara (i.e., 20.86K). Although an 8000 m^3 LH_2 spherical storage tank does not exist yet, Kawasi Heavy Industries[98] has completed the basic design of a spherical 11200 m^3 LH_2 tank.

For the aircraft tank, we based the numbers in Table 10 on the calculations in 6.4.3 and literature review in Section 3.7. We assumed an initial filling level of 5%, and after filling an additional 6200 kg of LH_2 the tank allows for 3% ullage as in Gomez[70]. Gomez calculated the heat ingress for his considered cargo system, where 17 700 kg LH_2 is split in two tanks (i.e. each tank in Gomez is slightly larger than our considered tank). Our considered heat ingress in Table 10 is slightly lower than one of the tanks in Gomez.

The pipelines are modelled with the parameters in Table 11. To simplify the simulation, the pipes were modelled with a constant heat ingress instead of detailed modelling of the insulation. The specified heat ingress for the 6'' and 8'' pipes were taken as the high bound from Table 32, where an uncertainty analysis was done for these pipe sizes for various insulation thicknesses and ambient temperatures. The heat ingress to the 8'' insulated flexible hose is 10% higher than insulated 8'' standard pipe. We estimated the heat ingress for the 18'' pipe by doing a linear regression based on tabulated heat ingress (for liquid N_2)[65] for pipe sizes ranging from 2'' to 8'', added 10% to these tabulated numbers as our fluid is LH_2, and used the resulting linear model to extrapolate heat ingress to 18''. Note that the diameter of the recycle line (6'') limits the recycle flowrate of LH_2. This recycle flowrate is important to keep the supply- and recycle pipe cold through the night, as we will investigate in the next Section.

Table 11: Specifications of pipelines.

Heat ingress for 6" and 8" pipe are the high bound from Table 32, where these pipe sizes with insulation were considered.

Pipeline	Length [m]	Diameter [m]	Heat ingress [W/m]
Supply	2000	0.45 (18")	10
Recycle	2000	0.17 (6")	3.6
Header, to hose	5	0.2 (8")	4,6
Flexible hose	10	0.2 (8")	5

The pump is specified with the parameters $dp_0^{pump} = 0.9$ bar, $V_0^{pump} = 0.8m^3/s$ and $\eta^{pump} = 60\%$, where the meaning of the pump's parameters are described in Appendix J.1.

6.6.3 Key results from the simulation

We present only the key results in this Section for brevity; see K for the full analysis.

We consider the following supply and demand of LH_2 at the airport:

- A constant supply of LH_2 to the fuel farm's storage tank of 3.8 kg/s (330 tpd). The supplied LH_2 has a temperature and pressure from a conservative value from the results in Section 6.5.1.
- Filling of multiple aircrafts throughout the defined daytime period (16 h). Each aircraft is filled with 6200 kg LH_2, and the total amount of LH_2 filled for all airplanes are 360 tpd (i.e, a busy day). Since the inflow to the fuel farm's storage tank is 330 tpd, its level will decrease in a 24 h period. The filling rate to each airplane is 20 kg/s, based on the analysis in Mangold et. al[62].

The "free" control variable, in this case, is the recycle flowrate. The recycle flowrate is operated in the following manner:

- Daytime, airplanes being filled: set-point for the recycle is 0.2 kg/s.
- Daytime, airplanes *not* being filled: set-point for recycle is 3 kg/s.

Important considerations are how should we operate the recycle during the night to:

- Keep the pipelines cold (to prevent formation of GH2) for the next day
- Filling of the first airplane after a night

We consider two different values for the recycle flowrate through the night, either a low flowrate of 2.8 kg/s or a higher flowrate of 3.8 kg/s.

Figure 19 shows the effect of the two different recycle rates during nighttime (the shaded grey area). A low recycle rate (solid line) gives a low subcooling temperature in the supply pipe at the end of the night ($t = 24$ h), while a higher recycling rate (dashed lines) yields a colder pipeline.

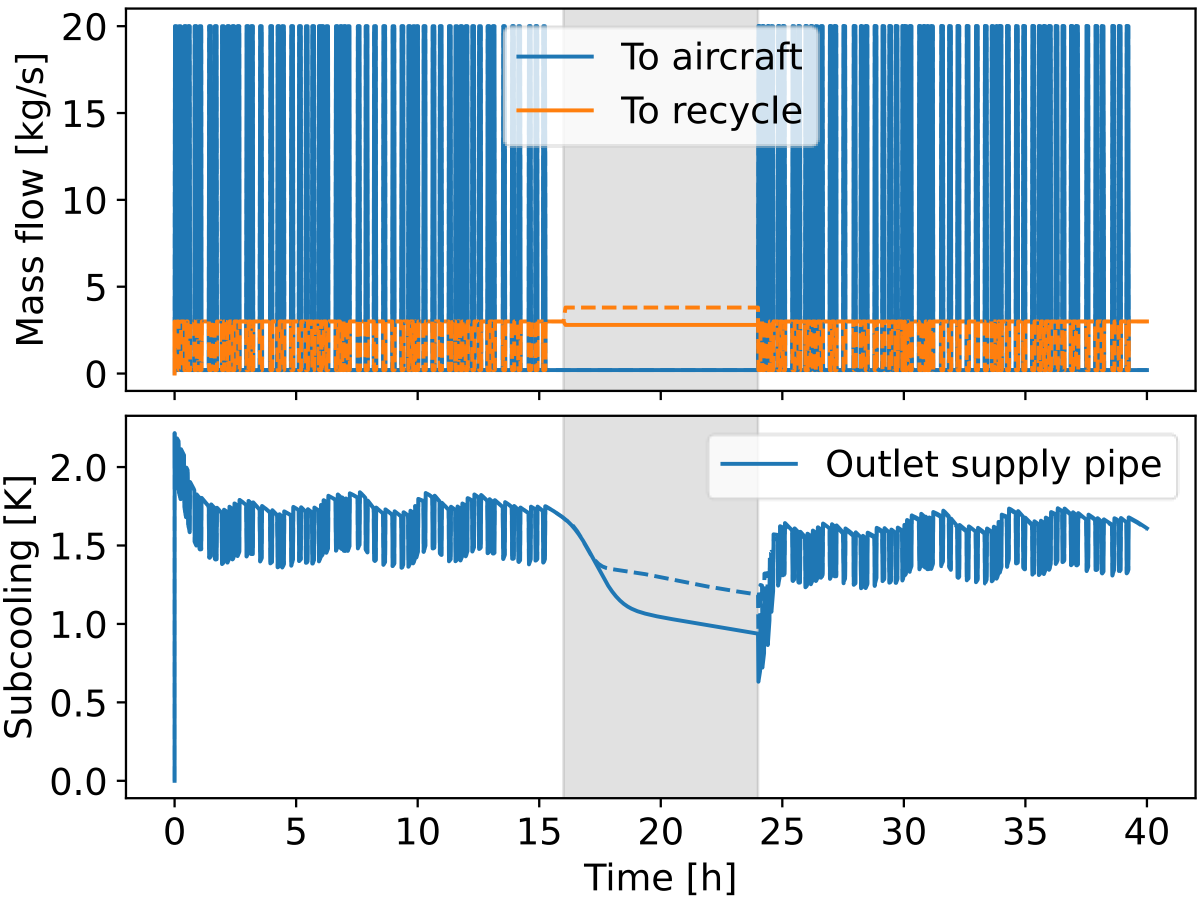


Figure 19: Mass flows of LH_2 to aircraft, recycle and its effect on the supply pipe temperature.

A "warm" supply pipe can transfer a significant amount of heat to the LH_2 due to the large dimensions of the pipe. Therefore, a higher pipe temperature implies that more BOG is generated when filling aircraft.

Fuelling of an aircraft happens in a timescale of minutes, and not hours/days as in Figure 19. Therefore, we created a more detailed simulation model which captures relevant effects in the "refuelling timescale" (see K for details). The pipe temperatures in Figure 19 are used as initial conditions to our detailed refuelling-of-aircraft-model, where the BOG amounts are calculated. In our refuelling model, we consider the following cases (or initial conditions):

1. "Start of day", which corresponds to the first flight at 06:00 in the morning. Initial conditions for the temperatures in the pipelines are taken from $t = 24$ h in Figure 19 for
    a. Recycle rate of 2.8 kg/s through the night
    b. Recycle rate of 3.8 kg/s through the night.
2. "End of day", which corresponds to the last flight at 22:00 in the evening. Initial conditions are taken from $t = 40$ h in Figure 19. In this case, the pipes are colder than in the previous

case. Furthermore, the effect of recycling during nighttime has vanished after 16h of operation.

In each case, we fill first aircraft 1 and subsequently aircraft 2 and 3 in parallel. The conditions in the three fuel tanks are shown in Figure 20; since aircraft 2 and 3 are filled in parallel, their trajectories are overlapping.

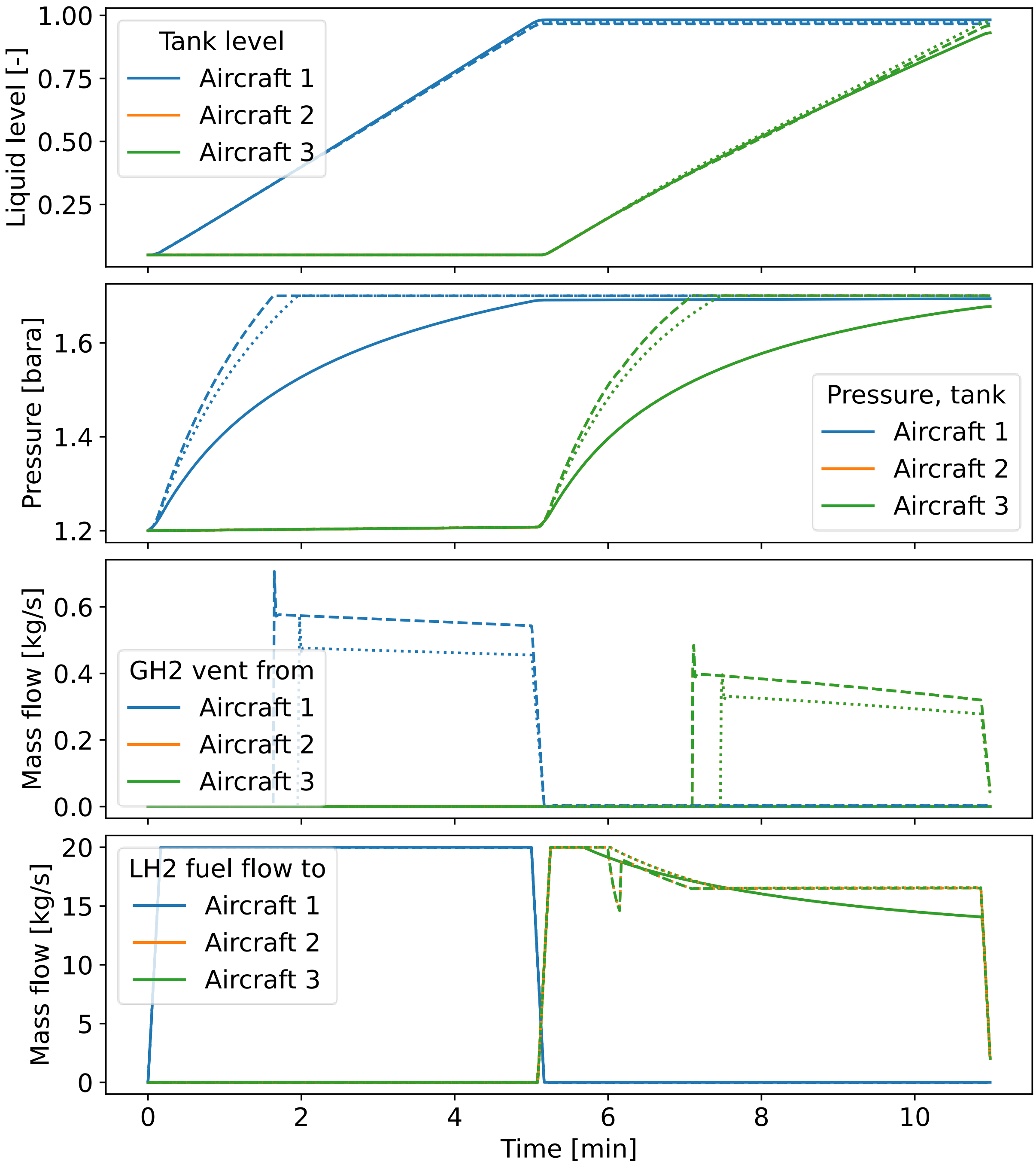


Figure 20: Development in the three aircraft tanks

for i) the filling at 06:00 with 2.8 kg/s of recycle flow through the night (dashed lines), ii) the filling at 06:00 with 3.8 kg/s of recycle flow through the night (dotted lines), and iii) the filling at 22:00 (solid lines). Aircraft 2 and 3 are filled in parallel, and their lines are therefore overlapping.

For each aircraft, Figure 20 shows that the pressure in the aircraft tank increases as the fuelling progresses. When we start with “warm” pipes (i.e., both fillings at 06:00 – dashed and dotted lines), the pressure reaches the maximum operating pressure of 1.7 bara and GH_2 is vented from the tank to a separate GH_2 system (e.g. the suction to a compressor – the vented GH2 may be compressed and utilized for ground support equipment or returned to the central storage in a gas return line). If the recycle rate is high during the night (dotted lines – 3.8 kg/s recycle rate), the pipes are colder at 06:00 and less GH_2 is vented compared to a lower recycle rate during night (dashed lines – 2.8 kg/s recycle rate).

When we start with cold pipes (plane filled at 22:00, solid lines), the pressure in the tanks reaches 1.68 barA at the end of the filling (i.e., slightly below the maximum operating pressure of 1.7 barA) and venting does not occur. However, if the plane is left overnight, BOG (GH_2) will be generated due to heat ingress in the tank. We investigate and summarize BOG (GH_2) generation during filling and overnight in Section 6.6.4. Finally, a more detailed discussion regarding the refuelling results are available in Appendix K.

6.6.3.1 Discussion

Some major sources of uncertainty for the results in this Section are:

- The assumption of thermodynamic equilibrium between liquid and vapor phase in all storage tanks. This is important, since it may be possible that the LH2 at the suction of the fuel pump is sub-cooled (the supplied LH_2 from the liquefaction plant *is* sub-cooled, see Section 6.5). If the LH_2 at the suction of the pump is sub-cooled, the temperatures in all pipes would be lower. This implies that the pressure increase in the aircraft’s fuel tanks would be slower and less BOG generated. We discuss this assumption further in Appendix K.
- Pump characteristics and a non-verified pressure drop model in the pipes, as discussed in Section 6.5.3.
- The pipeline model assumes a straight pipe, but note that bends and other fittings in a physical pipe can be converted to *equivalent lengths*, which is a common engineering method[99].

Although the uncertainties are large, the results still give valuable insights about the following:

- There is a substantial difference between filling the first plane in the morning (warm pipes) and the last plane in the evening.
- Subcooling is maintained by recycling LH_2 during the night.
    - The minimum recycle rate during the night to maintain subcooling is 2.8 kg/s.

  - A higher recirculation rate during the night means that the pipeline is colder in the morning, and less GH_2 is vented when the planes are being filled.
  - However, a higher recirculation rate in the nighttime correspond to a higher power consumption from the pump. An "optimal recirculation rate" which balances the power consumption from the pump vs the amount of GH_2 formed may exist, and investigating this further is interesting for future work.
- Filling several aircraft in parallel can cause vapor formation in the pipelines, especially for "warm" pipelines (i.e. when filling in the morning when the nightly recirculation rate was low). Filling aircraft in parallel means an increased mass flowrate through the pump, which corresponds to a reduced discharge pressure (we assumed a centrifugal pump). The reduction in pressure can cause vapor formation if the pipeline is "warm" enough. Potential work-arounds are:
  - Reducing the pipeline temperature, by increasing the nightly recirculation rate.
  - Increasing the discharge pressure from the pump, by installing a more powerful pump.
  - Having the subcooling temperature as an input to the control system.

6.6.4 BOG (GH_2) generation and utilization

Here, we aim to answer **Q4** and **Q5.**

The third pane in Figure 20 shows the mass flows of vented GH_2 from the aircraft tanks. Regarding the vented GH_2, we do the following observations

- Filling of aircraft in the morning (dashed and dotted lines) creates boil-off while filling in the evening (solid line) just avoids boil-off, which is shown in the third pane in Figure 20. This is attributed to a low LH_2 flow through the pipelines in the night, which makes the pipe warm.
- If we increase the LH_2 flow through the pipelines in the night, less boil-off is generated when we start filling airplanes in the morning; this is seen by comparing the dashed and dotted lines in Figure 20.
- The amount of GH_2 vented decreases quite substantially from filling aircraft 1 to aircraft 2 and 3, which is seen by comparing the dashed (or dotted) lines in the third pane in Figure 20. The total amount of GH_2 vented during each filling is given in Table 12.
- The projected need for GH_2 for ground-support equipment was found to be in the range of 2.3 to 9 tons BOG/day in Figure 11. We considered a full day of operation in Section 6.6.3, where in total 58 airplanes of 6200 kg LH2 were filled. If we consider the worst-case BOG scenario for all planes in Table 12, we obtain 98 kg BOG/airplane * 58 airplanes/day $\approx$ 5.7 tons BOG/day, which fits the identified projected GH_2 need well. This value is, however, likely to be too pessimistic (it is an overestimate of generated BOG).

Table 12: Accumulated vented GH2 for each aircraft during the fuelling period in Figure 47.

	Aircraft 1	Aircraft 2	Aircraft 3
GH2 vented for the case «start of day» (06:00 hrs) with 2.8 kg/s recirculation rate through the night	98 kg	82 kg	82 kg
GH2 vented for the case «start of day» (06:00 hrs) with 3.8 kg/s recirculation rate through the night	74 kg	55 kg	55 kg
GH2 vented for case the «end of day» (22:00 hrs)	0 kg	0 kg	0 kg

Finally, we are interested in how much GH_2 is vented if the aircraft is filled at 22:00 and left over night. In this case, the heat ingress causes first the pressure to increase to the maximum operating pressure (1.7 bara) before the vent valve releases GH_2 to keep the pressure at its set-point, as shown in Figure 21. The accumulated BOG for an overnight period is also shown in Figure 21. Note that the value for the accumulated BOG is, dependent on our assumptions, specifically i) how well each fuel tank in the aircraft is insulated (i.e., the heat ingress), and ii) the allowed maximum operating pressure.

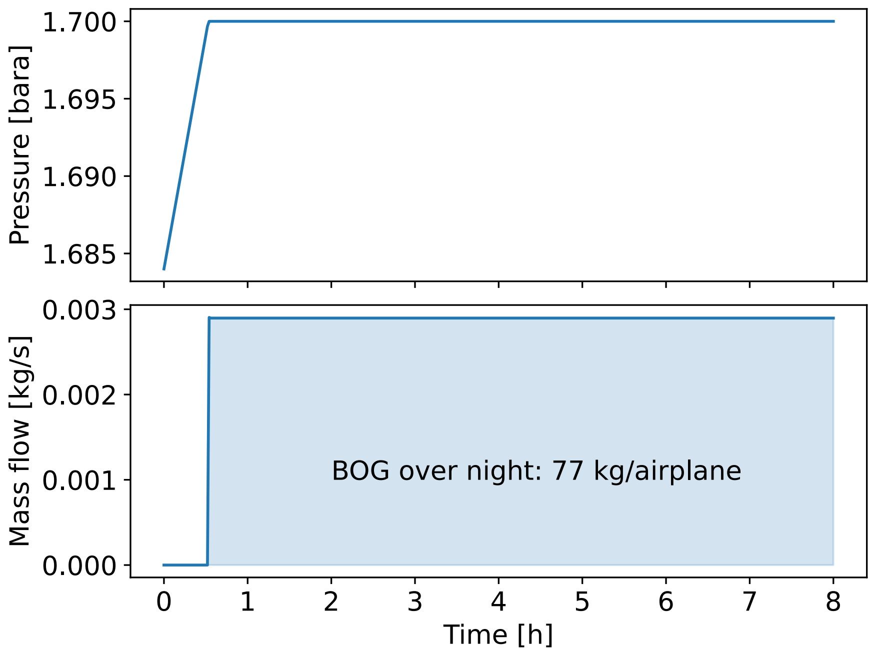


Figure 21: Pressure rise in the aircraft tank and vented GH_2

when the airplane is left over night. Total BOG vented is the integrated mass flow (shaded area).

A summarized, crude estimate of the BOG generated for the entire distribution system is provided in Table 13, under the assumptions of this work. The refuelling BOG low estimate is 74 kg + 2*55 kg + 55*0 kg = 184 kg, while the high estimate is 98 kg + 57*82 kg = 4772 kg, where the numbers are from Table 12 and we consider 58 aircraft in total. The high scenario for aircraft overnight holding considers 10 aircraft.

Table 13: Crude estimate of BOG generation for the airport distribution system.

	Low	High
Refuelling BOG	184 kg	4772 kg
Stationary storage BOG	356 kg	356 kg
Aircraft overnight holding BOG 77 kg/ac	0 kg	770 kg
Total amount of BOG generated	540 kg	5898 kg

By comparing the level of boil off with scenario for GSE needs, it is seen that the mass balance has a fairly good match. This means that there is a valuable potential in investigating integration of CGH2-GSE systems with BOMS.

6.6.5 Summary

We investigated how operation of the airport's distribution system affects the BOG formation. It is a requirement to always have sufficiently cold distribution pipelines to avoid gaseous H_2 formation in the pipelines. Pipelines are kept cold by flowing LH_2 through them, either when fuelling aircraft (high flowrate) or by having a minimum flowrate through the recycle loop when no aircraft are filled. Therefore, the most problematic period to keep the pipelines cold in an airport is in the morning, since the LH_2 flow is low for a long period as no aircraft are filled in the night. During a filling operation, GH_2 can be formed when the LH_2 reaches the aircraft but the quantity depends on how cold the distribution pipelines are.

We showed that how the recycle loop is operated during night greatly affects the quantity of GH_2 when filling aircraft in the morning. In our case study, a low nightly recirculation rate (2.8 kg/s) through the distribution system caused 98 kg GH_2 to be formed when filling the first aircraft, while a high nightly recirculation rate (3.8 kg/s) reduced the GH_2 formation to 74 kg. Importantly, filling subsequent aircraft reduces the GH_2 formation significantly as the distribution pipelines become colder; in the evening the pipelines are so cold that no GH_2 is formed when refuelling in our model.

Aircraft which departs early in the morning can be fuelled the prior evening. In our simulation, we do not have any GH_2 formation while filling in the evening. However, heat ingress to the aircraft tank during the night results in an accumulated 77 kg GH_2 /airplane left overnight.

The considered sources for forming GH_2 are i) refuelling aircraft, ii) leaving filled aircraft overnight, as described in the above paragraph, and iii) heat ingress to the airport's fuel farm storage tank. We stress that this GH_2 should *not* be considered as lost, but compressed and used for ground support equipment. We estimated the accumulated GH_2 formation for an entire day to be 540 kg (low scenario) and 5898 (high scenario), which corresponds well with the estimated need for GH2 for ground support equipment in Section 5.3 (2.3 tonnes/day for low scenario and 8.9 tonnes/day for the high scenario).

6.7 Conclusion

This Section investigated infrastructure and operations of the medium LH_2 demand-scenario for AMS in 2050 found in Section 5.2, i.e. a demand of 330 tonnes LH_2 per day. This Section addressed the following questions:

Q1: What are the limiting factors and practical distance away from the airport the hydrogen liquefaction plant has to be placed, and can LH_2 technically be imported from a LH_2 reception terminal in a port?

We considered placing the liquefier in proximity to the EHB (4 km from the airport) or at the port (25 km from the airport), and the key technical requirement was that the subcooled LH_2 from the liquefier was still subcooled when reaching the airport. We considered that the transfer pump's parameters, ambient temperature and insulation thickness of the pipeline were uncertain, and our sensitivity analysis revealed that the most important factor was the insulation thickness.

We conclude that it is technically feasible to transport LH_2 to the airport. The limiting factors are

- Pipeline must be heavily insulated, and the required insulation thickness grows with pipeline length. This can give high CAPEX.
- High capacity LH2 pumps is not yet commercially available.

Q2: What are the requirements for subcooling in the airport distribution system, and how much LH_2 is evaporated during refuelling of an aircraft?

Nighttime is the most problematic period for keeping the pipelines cold in the airport's distribution system. We showed that it is required to have a minimum recycle flowrate during the nighttime to keep the distribution system cold enough. However, the temperature in the distribution system's pipeline will still increase, and therefore GH2 will be formed when fuelling aircraft in the morning.

In our case study, 98 kg GH_2 was formed when filling the first aircraft in the morning when the nightly recirculation rate was at a minimum (2.8 kg/s). By increasing the nightly recirculation rate to 3.8 kg/s, the pipelines are colder in the morning and the GH_2 formation decreased to 74 kg. Since the pipelines get gradually colder during the day, filling subsequent aircraft results in gradually less GH_2 formation until and eventually there will be no GH_2 formation when refuelling aircraft.

Aircraft which departs early in the morning can be fuelled the prior evening. In our simulation, we do not have any GH_2 formation while filling in the evening. However, heat ingress to the aircraft tank during the night results in an accumulated 77 kg GH_2 /airplane left overnight.

Q3: How does the fuel farm inventory evolve for a given fuel farm configuration?

A fuel farm configuration with 4 tanks were analysed, where one tank was used to fuel aircraft while another one was filled with LH_2 from the liquefaction plant. The draining/filling time of one tank was approximately 15 hours which is significantly faster than the systems for space applications which has a LH_2 demand in the same order of magnitude. This highlights that the BOMS for airports will be different than for space applications.

Q4: What is the level of boil-off that can be expected during nominal operation of the proposed system?

The accumulated daily value of BOG/GH2 was estimated to 540 tonnes/day in our low scenario, and 5898 tonnes/day for our high scenario.

Q5: Can the evaporated H2 be used for ground operations?

Yes; the formed GH_2 is not released but can be compressed and used for ground support equipment. The daily BOG scenarios reported in Q4 correspond well with the estimated need for GH_2 for ground support equipment in Section 5.3 (2.3 tonnes/day for low scenario and 8.9 tonnes/day for the high scenario).

Note that although the GH_2 is used, the energy used for liquefying the produced H2 from electrolysis is partly lost. We say partly, because the GH_2 is still cold and may be used as e.g. a shield gas in the pipelines to reduce BOG generation (this possibility is however not studied in this report). However, producing H_2 by electrolysis is far more energy intensive than liquefaction: Section 3.3 discusses REFHYNE 2, a PEM electrolyser plant to be built at 100 MW producing 150 ktonnes H_2/year, giving a specific energy consumption of 57.6 kWh/kg H_2 produced. Liquefaction plants operate with a specific energy consumption of 6 to 10 kWh/kg (see Section 3.4). Therefore, it is clear that the BOG must be used by ground support equipment (or other reasonable consumers), meaning that the only *loss* is the energy used for liquefaction.

7 Safety of large-scale liquid hydrogen handling

7.1 Learnings from the demo

Rotterdam The Hague Airport (RTHA) is pursuing the transition to sustainable aviation and the airport is used as an innovation platform for tests and experiments. Safety when introducing hydrogen for tests and experiments at the airport is therefore a priority. In the RTHA conceptual study (see Chapter 4), different locations for the hydrogen storage equipment have been considered and the effects of those on the safety risk zoning at the airport are investigated (for both the demonstration and the commercial phases). A detailed quantitative risk assessment (QRA) was in fact performed to obtain the risk profiles (as LSIR contours and societal risk) for different configurations.

The study proposed in the following of this chapter builds on the findings from the conceptual design and safety analysis of hydrogen storage at RTHA.

7.2 Study basis

Risks related to scaled up production and related transport services by truck were addressed by Hankinson et al, who performed a qualitative risk assessment in the IDEALHY project, for production plants up to 50 tpd[100]. A key takeaway was that there is higher risk related to handling and storage of LH_2 near population dense areas and during transfer procedures. This was due to the presence of third parties not under control by the operator, and manual operations requiring physical presence of operators. Therefore, the focus of this work is the phases of LH_2 delivery to aircraft shown in Figure 22. These phases may involve both manual operations and vicinity to personnel and passengers.

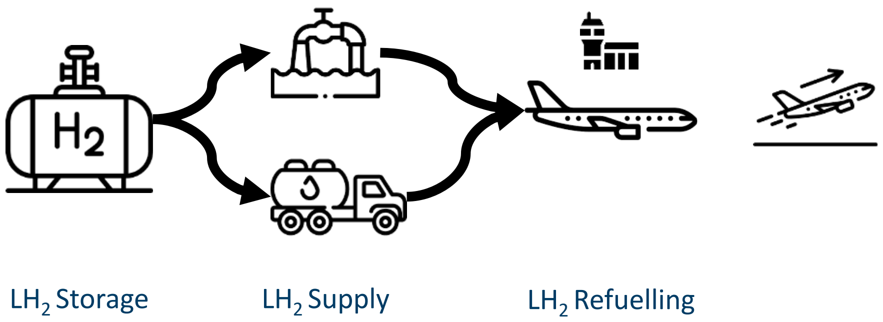


Figure 22 LH_2 value chain at the airport.

LH_2 is firstly supplied (by hydrogen trucks or via pipeline) and stored at dedicated premises at the airport facilities (LH_2 Storage). From the storage area, LH_2 is supplied to the gate at the airport terminal by either pipeline or truck (LH_2 supply). The LH_2 is then refuelled to the aircraft (LH_2 refuelling), which is then ready for take-off from the runaway. Fast and efficient refuelling at the gate is the ultimate goal, due to the economic penalty of adding extra time- and resource-consuming operations related to refuelling at fuelling-only positions[56].

In the current analysis two refuelling cases are defined, as follows:

A) Refuelling by hose; and
B) Refuelling by tank swap.

In refuelling case A), the hose is connected to the aircraft tank and either a truck delivering liquid hydrogen at the gate or a hydrant delivering liquid hydrogen at the gate by pipeline. For the refuelling case B), the empty liquid hydrogen tank is swapped with a full one delivered at the gate by a dedicated truck. Refuelling case B) requires the lifting operation of a full liquid hydrogen tank.

In the refuelling by hose case (A), the Boil-Off Gas (BOG) return line from the aircraft tank is connected directly and only to the delivery truck. If excessive hydrogen boil off is produced, this is vented to safe location via the delivery truck. When the refuelling by hose is performed using the liquid hydrogen pipeline grid at the airport, the BOG is returned in a dedicated hydrogen gas pipeline. In this second case the BOG is not vented, but it is routed in the airport systems and used for power generation or refuelling of GSE powered with hydrogen gas. The first alternative is relevant to the TULIPS demonstration, advanced demonstration and commercial phase at RTHA, the latter alternative is relevant to the scaled up system for AMS addressed in Chapter 6.

7.3 Methods

7.3.1 Hazard Identification (HAZID)

A HAZard IDentification (HAZID) is methodological approach aimed at identifying and describing potential hazards and hazardous scenarios associated with a system. The causes, consequences and risks are typically assessed during a hazard identification session. HAZID studies are usually carried out in early design stage. The HAZID workshop includes a brains-storming session with experts from safety engineering and management.

The HAZID methodology applied in this study considers the following steps:

Step 1) Definition of the systems, its operations and its boundaries;
Step 2) Identification of hazards and definition of hazardous scenarios;
Step 3) Assessment of consequences; and
Step 4) Identification of risk reducing measures.

The abovementioned steps are adapted from the Preliminary Hazard Analysis methodology [101]. Hazard identification and analysis are required studies to be considered as part of the risk management process[102].

Step 2 in the methodology proposed above has been carried out considering a list of guidewords. The guideword, per category, considered for the HAZID workshop are listed in the table below:

Category	**Guidewords**
Leak	Dangerous substances (flammable, toxic) Corrosion Air ingress External impact Fatigue Vibrations
High/low pressure High/low temperature	Cold processes Flares, vents, location of outlets Cryogenic conditions
Escalation	Boiling Liquid Expanding Vapor Explosion (BLEVE) Fire detection Gas detection Fire fighting equipment, deluge Emergency preparedness
Operations	Simultaneous operations New/temporary personnel, shift changes Start-up/Shut-down after/prior maintenance Emergency stop (procedures, placement of buttons)
Mechanical and electrical issues	Rotating equipment High voltage and electrical hazards Static electricity Grounding/earthing EX-zones/EX-equipment No go zones
Utilities	Cooling system Control system Instrument air Power/blackout Inert gas Communication systems Fire water Bund
External environment	Extreme weather Lightning Wind Ice
Organizational factors	Procedures Responsibilities Compliance Training and competence Planning Emergency preparedness
Transport	Transport of goods at site Accident Impact Truck impact / collision
Lifting equipment	Falling/swinging loads Crane/lifting equipment collapse

Results from the HAZID workshop are presented in a dedicated table. In this analysis an overview of the table used for presenting the identified hazards is shown below.

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures

The HAZID table include an "ID" column, representing the unique tag assigned to a hazard. The hazard is presented in a dedicated column ("Hazard"). Example of hazards are: overpressure, low pressure, high temperature, low temperature. A third column, "Scenario", provides the description of the hazardous scenario. The fourth and fifth column describes the "Cause" of the identified hazard and its potential "Consequences". Lastly, the safety barriers and proposed ones to prevent the hazards and/or mitigate their consequences are presented in the "Risk Reducing Measures" column.

7.3.2 Fault tree analysis (FTA)

Fault tree analysis (FTA) is the most commonly used method for causal of hazardous events in risk assessment[101]. It shows the interrelationship between a potential critical event in a system (top event) and the causes of this event[101]. The causes at the lowest level are called basic events and may be, for example, component failures, environmental conditions, human errors. The top event and the immediate causal events (down to the basic events) are connected with a logic gate. The immediate causal events are also identified and connected using logic gates.

The objectives of an FTA are[101]:

- To identify possible combination of events that might result in a critical event in the system;
- To find the probability of the critical event; and
- To identify the components and/or safety barriers that need to be improved (and/or monitored) in order to reduce the probability of the critical event.

The FTA is a binary analysis, i.e. all the events from the top event down to the basic events are assumed to be binary events that either occur or do not occur.

FTA is suitable for both qualitative and quantitative analysis. It is one of the most commonly used methods for risk and reliability studies and it has been used successfully within the aerospace industry [103]. Therefore, it is deemed appropriate to be used in the current analysis.

7.4 Results

7.4.1 Hazard identification

A summary of the HAZard IDentification (HAZID) session conducted for the LH_2 refuelling operations is presented in the form of HAZID tables in Appendix L.

A total of 14 risks (R1-R14) are identified. For each risk, the HAZID tables present the hazardous scenario as well as causes, consequences and potential risk reducing measures to implement to control and/or mitigate the risks.

Several risk reducing measures that can be implemented in the design, inspection and as procedures for the refuelling operations, as follows:

- Design principles should minimize the number of connections.
- Establish fuelling safety zones, ATEX zoning, no-go zones and ignition source control measures.
- Procedures for handling hose/arm positioning, connection and disconnection shall avoid air ingress. Eliminaition of the need for purging should be considered.
- Procedures for checking initial tank fill level and temperature, choosing right refuelling protocol for the tanks size and state, and verification of terminal fill-level, as well as defueling procedures.
- Monitoring: Pressure during refuelling, frosting and condensation on external surfaces, leaks and fire (potentially use thermal camera both for cold and hot temperature detection).
- BOG operational specifications to handle non-nominal situations and redundancy.
- Pressure-relief and boil-off handling designed to handle loss-of-vacuum.
- Recirculation processes and procedures that enable control of sub-cooling in the system.
- ESD-links and emergency stop procedures – stop at safe-state conditions.
- Consider Extraction-systems of H_2 from the aircraft tank.
- Procedures for emergency situation management and fire extinguishing.
- Periodic inspections and maintenance: Leak test, monitoring and inspection routines for insulation and mechanical parts containing hydrogen.
- Procedures for start-up after inspection and maintenance operations.
- Appropriate training of personnel handling hydrogen.
- Compatibility of ground surfaces with LH_2-leaks.
- Mandatory use of personal protective equipment (PPE) suitable for cryogenic fluid handling for all the personnel handling manually equipment containing LH_2.

7.4.2 FTAs

For the hazards identified in Table 33, a semi-quantitative Fault Tree Analysis (FTA) is carried out. The Fault Trees are presented in detail in Appendix M.

Three Fault Trees are presented in this analysis, based on the risk scenarios identified and developed in the HAZID tables. The FTs represent the causal events chain leading to:

- Overpressure and increased pressure;
- LH_2 release; and

- Fire and explosion at the airport.

The analysis aimed at qualitatively identify the *basic events* to be monitored for the LH_2 refuelling by hose and by tank swap methods. The basic events identified from the FTs above can be summarized as:

i) Individual failure of equipment leading to a hazardous state. E.g.: Pressure switch sending the wrong signal, wrong calibration of the switch, external stress preventing the correct functioning go the switch, no signal from the switch. Automation failure for the automated operation is also a factor. Temperature control systems and insulation integrity and suitability are also other critical item (potentially leading to too high boil off gas rates and increased pressure in the tank).

ii) Common cause of failures, leading to the loss or partial loss of set of instruments and equipment. E.g. electric and electronic problems, blocked taps (by ice for example, given the operating temperature of LH_2 equipment).

iii) Material degradation and material suitability for use with hydrogen and cold-cycles (corrosion, embrittlement, cold fatigue). These could also interest support systems not in contact with hydrogen but holding equipment containing hydrogen (for example: failure of the hose support system for hose refuelling case).

iv) For the hose refuelling case, the sealing of the connection between the hose and the hydrogen tanks is of paramount importance. Monitoring of the correct sealing as well as the presence of dirt potentially affecting the sealing shall be implemented.

v) Implement a proper ignition source control, including protection from electrical sparks (EX zone, EX equipment shall be implemented when required, EX-proof of equipment shall be monitored and maintained at all the time) and electrostatic sparks (grounding of equipment, monitoring of grounding equipment integrity, use of right specifications and design for grounding of equipment in presence of hydrogen).

vi) External fires are critical events potentially leading to catastrophic consequences. These include fire at the airport terminal and fires from GHE and others (battery fires from electrical vehicles shall also be considered).

vii) Impact prevention shall be implemented. This is relevant for the tank swap refuelling case: if the tank has been subject to an impact, it should be inspected prior to use on aircraft. Impact with dropped objects is also a factor that should be considered. Lifting of the full LH_2 tank for tank swap refuelling case is a critical operation which should require special training and permits. GHE is also a potential impact factor: GHE movement on the ground should be analysed and limited nearby hydrogen handling equipment. Re-routing of GHE when refuelling shall be implemented.

viii) Procedures for hydrogen handling operations (completeness, clarity, suitability for the specific operation). Dedicated procedure for maintenance and inspection of hydrogen equipment and start up/shut down after/prior activities.

ix) Human factor, such as personnel experience and training to perform a task and to choose the right procedure for the right operation. Communication is also of paramount importance to coordinate the hydrogen related activities.

x) Weather factors, such as ice leading to slippery conditions and potential loss of position, extreme wind, lightning (which represents an ignition source). Damaged lightning protection, wrong lighting protection (it needs to be compliant to be used in presence of hydrogen) or wrong design of lighting protection are also parameters to monitor at the airport.

7.5 Discussion

7.5.1 Consequences from hazards for a scaled up LH_2 system

LH_2 introduces new hazards to the aerodrome environment. The HAZID and FTA shown in the previous chapters identify some hydrogen-specific hazards that are not equally found for conventional aviation fuels. The top events shown in the FTAs for the overpressure, leak or fire and explosion are relevant for both hydrogen as an aviation fuel and JET-A1. Anyway, hydrogen ignitability and flammability different characteristics that requires a specific management of safety and risks. The wide hydrogen flammability range and its extremely low minimum ignition energy calls for a special safety risk management framework which focuses on the prevention and control of the loss of containment scenarios as a priority, followed by ignition source control and consequence mitigation.

Furthermore, liquid hydrogen introduces cryogenic systems handling in the airport. Cryogenic hazard and hazards related to extreme evaporation and overpressure in the tank are therefore new safety issues to be handled when using liquid hydrogen as aviation fuel.

The quantitative risk assessment performed for RTHA (Chapter 4) makes it clear that the system size and the amount of hydrogen stored and used at the airport significantly influences the size of the hazardous zones. For large airports, the amount of LH_2 may be 10 times higher than commercial phase of RTHA and the consideration zones for the fuel farm even larger.

7.5.2 Risk reducing measures

Risk reduction is typically prioritized in the following order: i) Prevent leaks, ii) Prevent ignition, iii) Minimize consequences. The HAZID identifies several potential risk reducing measures that can be implemented in the design, inspection and as procedures. As reviewed in 3.2.1, the majority of hydrogen incidents are caused by factors within the hydrogen system – but external causes have lead to more severe consequences. Below, we distinguish risk reduction measures for internal and external factors and give an overview of their status and compliance with large scale LH_2 systems.

Proposed risk reducing measures

The HAZID and FTA analyses serve as basis to (qualitatively) identify potential risk reducing measures (RRMs) to implement at the airport facilities to enable the use of LH_2 as an aviation fuel. The following sections present RRMs categorized as follows:

i) Procedures;
ii) Temperature control and BOG handling;
iii) Material integrity and cryogenic conditions;
iv) Vent stacks;
v) Cryogenic risks to personnel.

Procedures

The need of a systematic procedure for carrying out the LH_2 refuelling operation at the airport is also highlighted by the HAZID and FTA performed as part of this study. Procedures for maintenance, simultaneous operations and spill handling shall be defined and implemented at the airport premises. For the hose refuelling case, dedicated procedures for connection and disconnection of the refuelling hose shall be developed and implemented considering the peculiar behaviours and characteristics of cryogenic fluid transfer. Procedures must be complete and clear to understand. Training on existing procedures and supervision of personnel shall be implemented to ensure the correct application of procedures. Furthermore, procedures must be developed and kept updated through time to avoid the use of obsolete standards.

Human error can be limited by clear, complete and suitable procedures for maintenance and inspection as well as for coupling and handling of equipment containing liquid hydrogen. Training and good communication culture can also prevent the use of wrong procedures to carry out specific and safety critical tasks.

Procedures for the establishment of EX-zones and no-go zones as well as ignition control are also of paramount importance when handling hydrogen.

Tank temperature control and BOG handling

Monitoring of the aircraft tank temperature is of paramount importance to avoid excessive evaporation while refuelling and excessive BOG rate exceeding the capacity of the BOG system. This situation might lead to overpressure and potential failure of connections or the tank with subsequent release of hydrogen to the environment.

Relevant for R.2 and R.3 is the capacity of the pressure relief system. During the storage phase after refuelling, available modelling results for a 700 kg tank filled with LH_2 shows that a pressure relief mechanism is sufficient for non-nominal conditions such as loss of vacuum or engulfing fire[104]. The burst disk is activated at conditions for loss of insulation in combination with high ambient temperatures. However, the model is not developed for the analysis of flashing and pressure increase in the refuelling phase (R.1), which is one of the most critical phases identified by Hankinson, due to lack of pressure control and ad-hoc refuelling[100]. The current analysis in Chapter

6.6 suggests some BOG rates, but in this system the initial state is quite cold such that precooling was not needed. However, the analysis does demonstrate that control of even small temperature differences in the tank and transfer line is important to predict the boil-off generation. Additional efforts are needed to understand the BOG formation as a function of refuelling protocol and tank and refuelling system design.

Material integrity and cryogenic conditions

The integrity of equipment containing hydrogen must be monitored at all times. Hydrogen specific characteristics might cause specific degradation in some materials, such as hydrogen embrittlement, that should be assessed during the design phase and addressed through material choice. A wrong material choice might lead to the catastrophic failure of the LH2 tank with severe consequences for people lives, the environment and loss of assets.

The resistance to the cryogenic environment is another factor to consider in the design of the systems, equipment and operations to avoid mechanical failure. Furthermore, for the nature of the refuelling operations, a certain degree of thermal fatigue on the materials exposed to cold environments shall be expected. Thermal fatigue stress shall be monitored, and preventive actions shall be undertaken during maintenance to minimize the occurrence of loss of integrity events.

Vent and flare stacks

Gaseous hydrogen released from the vent stacks can also potentially ignite and radiate heat to the ground. Un-flared vent stacks were in 3.2.1 identified as vulnerable to unexpected ignition

Determining the temperature and release rate (and height) of hydrogen from vents or release points, and further dispersion, is important to determine safety zones. The TULIPS demonstration has introduced a spiral vent stack to allow for sufficient heating of the boil-off, such that condensation of oxygen at the vent exit is avoided. However, as much as possible of the hydrogen should be conserved and not vented. It is therefore a future challenge to resolve, how safety systems can be designed to increase safety an minimize venting of hydrogen to the atmosphere.

Defining safe locations for venting at the airport might also be constrained by the confinement and congestion of the airport premises themselves.

An alternative to venting is to use a flare stack in which the ignition is intended, and combustion is controlled. The analysis of the dispersion and heat generation of the burning hydrogen from the stack should also accompany the safety engineering design. The stack needs to be tall enough or positioned at a dedicated point to avoid exposing people (crews, personnel and public) to doses of heat above allowed thresholds.

Cryogenic risks to personnel

LH_2 represents a cryogenic hazard that needs to be handled by trained personnel wearing adequate safety personal protective equipment.

External risk reduction measures

Ignition source control should be implemented in the airport. H_2 has a Minimum Ignition Energy (MIE) 10 times lower than Jet A1 fuels[62]. Electrical equipment at the refuelling location should be explosion proof and the grounding equipment shall be up to standard for hydrogen operations, as well as not damaged.

Weather has a significant impact on refuelling operations. Ice and extreme wind might cause slips and slaps and loss of position of the equipment, leading to a release of hydrogen.

External fires impacting the LH_2 systems might have catastrophic consequences in terms of human lives, environment and loss of assets. The LH_2 systems shall be protected from fire and it is important to be able to safe disconnect the LH_2 supply trailer from the airplane tank as fast as possible to reduce the amount of LH_2 exposed to the heat loads. External fires can lead to the catastrophic failure of LH_2 tanks, which have severe consequences in terms of fires and explosions.

Furthermore, the ground movements may increase due to the introduction of new ground operations such as (mobile) charging and hydrogen refuelling. Impact and crashes with the GHE cannot be excluded, especially in situation of high loads in the airport. These might result in LH_2 releases. Ground movements such as moving aircraft fall under the sub-category “Ground Collision” (GCOL). The GCOL category will also be impacted due to the increase of ground service equipment (GSE) vehicles such as hydrogen trucks or other designated equipment, which might increase the risk of collisions with moving aircraft.

Schmidtchen et al discussed the advantages and drawbacks of protecting storage tanks for external impact (debris and heat radiation) by covering the tanks with earth or placement in dugouts[56]. The effectiveness of such barriers should be investigated further.

The amount of LH_2 at the airport in the scaled-up case study is higher than the one for the test demo. In reality, the total amount of hydrogen in the airport can be significantly higher than the scaled-up case considered in this analysis. This can have potential safety implications with regards to storage and refuelling locations, as well as safety distances from the terminals.

7.6 Summary

The refuelling operations is often addressed as a potential critical factor for LH_2-powered aviation, due to potentially longer turn-around times. The study conducted as part of this work is meant to identify potential risk factors and critical operations and/or configurations that need to be monitored and/or controlled.

A HAZID workshop was carried out to identify the risk scenarios which formed the basis for the development of the proposed three Fault Trees (FTs). The FTs represent the causal events chain leading to Overpressure (pressure above max threshold limit) and increased pressure (pressure above normal operation limits), LH_2 release, and fire and explosion at the airport. From the FTA, a set of basic events to be monitored during LH_2 refuelling by hose or swap tank were identified. These are:

- Failure of a single individual equipment item;
- Common cause of failure among different equipment items;
- Material degradation and compatibility with use in presence of hydrogen;
- Ignition source control;
- External fire affecting the hydrogen carrying equipment;
- Impact;
- Complete, clear, suitable procedures for hydrogen handling;
- Human factor (experience of personnel, training); and
- Weather factors (wind, ice, lightning).

Factors within the hydrogen system and/or external causes have lead in the past to severe consequences. From both the HAZID workshop and the basic events identified, a set of risk reducing measures (RRMs) have been proposed. RRMs have been prioritized in the following order:

1) Prevent LH_2 releases;
2) Prevent ignition; and
3) Minimize consequences.

Systematic procedures for carrying out the LH_2 refuelling operations at the airport are needed. These should be developed in an understandable, complete and clear way. Especially: procedures for maintenance, simultaneous operations, spill handling, ignition control, connection and disconnection of the refuelling hose as well as lifting of the swapping tank. The use of clear, complete and easy to understand procedures together with training and a good communication culture can help preventing and finally limiting human errors.

Handling of the BOG from the aircraft tank is another operational control to implement. Monitoring of the aircraft tank temperature can avoid excessive evaporation while refuelling and an excessive BOG rate exceeding the capacity of the BOG system, leading to increased pressure and potential release of hydrogen. This is also proven by the finding of the analysis presented in 6.5.5: the control of even small temperature differences in the tank and transfer line is important to predict the boil-off generation. Additional efforts are needed to understand the BOG formation as a function of refuelling protocol and tank and refuelling system design.

Leaks due to loss of material integrity and cryogenic conditions shall be avoided by using suitable material for equipment containing hydrogen compatible with both hydrogen properties and cryogenic temperatures. **Cryogenic conditions are a hazard also for the personnel,** which should be equipped with suitable safety personal protective equipment while handling hydrogen systems.

Vent stacks shall be designed (in terms of temperature, release rate and height) to vent at safe location (both if the vent is flared or not). However, as much as possible of the hydrogen should be conserved and not vented. Minimize the hydrogen venting is a challenge to solve.

External factors (such as ignition source control at the airport, fires at the terminal, operating windows in given weather conditions) should also be monitored. Increased traffic at the airport can potentially also increase the risk of crashes and impacts. The trade-offs of physical barriers to protect hydrogen carrying equipment should be assessed and their design optimized to reduce/limit the risk of hydrogen gas accumulation (and potential explosion) as well as the risk of debris and fragments.

8 Conclusion

This study investigated large scale LH_2 infrastructure at airports, with the focus of identifying a concept where the amount of boil-off is limited, and the BOG can be compressed and used for ground support equipment (i.e. no flaring of H_2 in normal operation). Models and simulations for the identified concept were performed to obtain an initial performance estimate, and a safety analysis (HAZID and fault tree analysis) were conducted.

To identify a suitable concept, we performed a literature on available technology bricks (production, liquefaction, storage, transport, distribution and refuelling). Since the system scale is a key factor when selecting the most appropriate technology, we also developed scenarios for the LH_2 demand at the TULIPS airports

The literature review incorporates elements from other relevant sectors. Historically, LH_2 have been used as a fuel onboard space launcher system, road vehicles and vessels. The refuelling, and pipeline capacity and length for the space launcher has the most representative system scale, and previous tecno-economic studies have suggested that for large airports pipeline distribution systems for LH_2 are a preferred solution above truck-based refuelling. However, the filling pattern and storage profiles (seasonal) of LH_2 of the launch pad is far from how the airport will operate. The reported high LH_2 losses from the space program are therefore less relevant for the airport case. Within the automotive sector, the strong focus on the development of refuelling processes with reduced evaporation loss have resulted in strong improvements; however, the airport constitutes a significantly larger system. Thus, a new system concept is needed to meet capacity, performance and safety levels needed for large scale LH_2 infrastructure at airports.

A systematic method to estimate the hydrogen demand at airports has been developed. The method was used to quantify the LH_2 demand for aircraft and H_2 demand for GSE at the TULIPS airports. The analysis uses the flight plan from an airport and estimates the hydrogen demand on a flight-by-flight basis using BADA. However, since not all aircraft will use LH_2, we assume market penetration scenarios for hydrogen-powered aircraft (i.e., low, medium and high scenarios). This enables a time-resolved analysis of future hydrogen demand for any airport, given a market penetration scenario. It is apparent that there exist considerable variations both within a day and throughout a year. In addition, the results vary significantly depending on the analyzed airport and the considered scenarios, i.e., market penetration of hydrogen-powered aircraft and GSE. There is obviously a great deal of uncertainty in projecting future hydrogen demand at airports, and the developed method may only provide ballpark estimates of future demand.

At AMS the low, medium and high market penetration scenario suggests a daily LH_2 consumption of 178, 360 and 609 tonnes of LH_2 respectively (in 2050). At OSL, in the medium 2050 scenario, the daily LH_2 consumption varies from around 100 tonnes (low-day in low-season) to 250 tonnes (high-day in high-season) per day. The same scenario for LCA scenario suggests a LH2 need below 100 tonnes per day, while TRN has the smallest LH_2 needs, 30 tonnes per day. We stress that these are ballpark estimates, following the assumptions of our method.

The ballpark estimates for the larger airports (AMS, OSL) shows that the scale of the LH_2 system will be unprecedented. To this end, we propose a refuelling infrastructure concept aimed at reducing the evaporation of LH_2. The system is based on LH_2-pipeline distribution; from liquefaction to the airport fuel farm, and from the fuel farm to the aircraft stands. The pipelines are insulated with commercially available systems, and a conceptual centrifugal pump is used to ensure the required mass flow to aircraft. To minimize evaporation, the system is kept continuously cold by always (re)cycling a certain amount of LH_2.

A dynamic process model was developed to analyse the system concept for the AMS 2050 medium scenario. In the model, a receiving aircraft tank of 6200 kg is used, which is in line with published research on LH_2 aircraft tank design. However, the LH_2 need scenario demonstrates that the majority of departures need less than 1000 kg of fuel (but this number does not include a fuel buffer for safety reasons).

The modelling and simulation result of the refuelling system suggest that:

- It is technically possible to supply LH_2 from an airport forecourt 4 km from the airport fuel farm (i.e. near the EHB), as well as from a point 25 km away (port region). While the 4 km pipeline can be constructed from commercially available products, a significant additional amount of insulation is needed for the longer pipeline. The CAPEX for the LH_2 supply pipeline is therefore not linear. Both cases are able to deliver hydrogen in liquid phase when starting with 1.05 K subcooling from the liquefaction site.
- The refuelling infrastructure addressed is sensitive to insulation thickness and pump efficiencies. An identified challenge is how to operate the system pressure such that the pump is not prone to cavitation.
- At the airport, the refuelling system requires a sufficient recycling rate of LH_2 during the night to stay within the subcooling requirements of the system. In the presented case, where a number of aircraft are sequentially refuelled at 20 kg/s LH_2 throughout the day, a recycling rate in the night and in between aircraft of 2.8 kg/s is needed. The recycled LH_2 is returned to the LH_2 fuel farm as a liquid and can be re-used.
- The formation of BOG from the refuelling of aircraft depends on the level of subcooling and is therefore higher in the morning than in the afternoon. With the settings tested, in the situation with little subcooling buffer, close to 100 kg of LH_2 can be evaporated when refuelling the already cold aircraft tank with 6200 kg LH_2 (i.e. in the morning). With more subcooling (i.e. afternoon), refuelling can be performed without boil-off. These values are strongly sensitive to the onboard tank design.
- The amount of BOG generated when refuelling aircraft in the morning depends on the recirculation rate of LH_2 during the night. With a nightly recirculation rate of 2.8 kg/s, the

generated BOG when filling the first plane in the morning was close to 100 kg GH_2, while increasing the recirculation rate to 3.8 kg/s means the pipes are colder and the generated BOG decreased to 74 kg when refuelling the first plane. However, increasing the recirculation rate increases the power consumption of the pump.

The preliminary estimates of BOG formation during refuelling and overnight indicate that there is a reasonable mass balance of BOG and CGH_2 needs for ground support equipment. This implies that BOG could potentially be integrated with other end use. However, their values are specific for the applied system parameters and will change as specifications are updated.

Note that although the BOG is used, the energy used for liquefying the produced H_2 from electrolysis is partly lost. We say partly, because the BOG is still cold and may be used as e.g. a shield gas in the pipelines to reduce BOG generation (this possibility is however not studied in this report). However, the liquefaction energy is around only 10-20 % of the electrolysis energy. Therefore, it is clear that the BOG must be used by ground support equipment (or other reasonable consumers), meaning that the only *loss* is the energy used for liquefaction.

A safety analysis consisting of HAZID and fault tree analysis were conducted for the proposed concept. LH2 safety management is very different from kerosene management, as LH2 introduces new risk phenomena related to low temperature and overpressure. The safety analysis identified potential risk factors and critical operations and/or configurations that need to be monitored and/or controlled. The safety strategy shall aim to i) prevent releases, ii) prevent ignition and iii) minimize consequences. To this end, the following set of risk reducing measures are proposed:

- **Procedures**: Clear, systematic and comprehensive procedures and operator training that covers normal operation, maintenance operations, comprehensive non-nominal operations and establishment of safety zones. The human and organizational factor is also an important element that limits influence of human error.
- **Handling of BOG:** Monitoring of temperatures within the LH_2 system, and operational procedures to avoid and handle excessive evaporation. BOG handling system with sufficient capacity to handle situations with excessive evaporation.
- **Material integrity and cryo-hazards:** Selection of materials with sufficient compatibility with hydrogen and low temperatures. Monitoring of material health and control of thermal stress. Personnel also need protection towards low temperatures.
- **Vent/flare:** The concepts investigated is based on conserving all BOG, but for situations where venting is necessary the vent/flare stacks should be designed for safe venting in terms of vent temperature, ignition control and thermal radiation from flares.
- **External factors:** Establishment of ignition control zones, focus on effect of weather, avoidance of ground collisions, and barriers towards external fires.

Finally, this work contains significant uncertainties regarding the model's ability to adequately represent the reality. This is true for all model-based analysis, but it is especially relevant for LH_2 applications as there is a lack of experimental data to *validate* LH_2-models. Relevant future work can therefore be to publish data from well-documented LH_2-experiments from e.g. storage tanks or pipeline transfer. Furthermore, there are many interesting concepts which may reduce the BOG formation which are not investigated in this report, such as using cold BOG as shield gas in the pipelines.

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B LH2 INFRASTRUCTURE FOR RTHA

B.1 Introduction

Rotterdam The Hague Airport (further RTHA) is a regional airport specialized in scheduled traffic towards European destinations as well as facilitating private business traffic, holiday flights, recreational general aviation and HEMS operations. Around two million passengers utilize the airports facilities each year. The airport is part of the Royal Schiphol Group.

With an objective to become a leading airport in the transition to sustainable aviation, RTHA has adopted the ambitious goal of being one of the first hydrogen compatible airports. For that purpose, RTHA adopted a so-called ‘Hydrogen Roadmap’ which elaborates on the steps to move from a demonstration phase towards commercial flight, that will allow RTHA to be a hub for the first regional roots serviced by sustainable hydrogen fuelled flights. To guide this process RTHA has adopted a hydrogen road map (Figure 23).

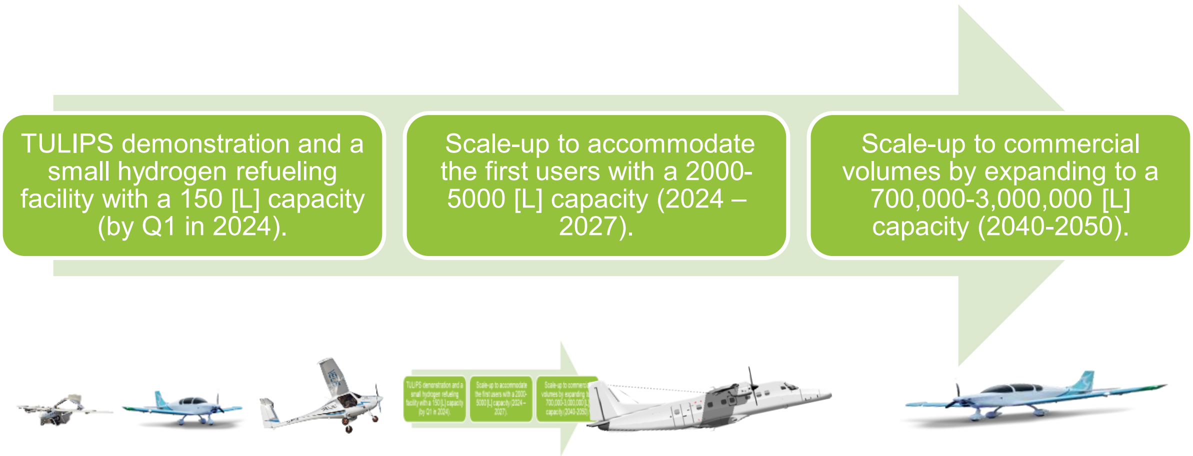

Figure 23: RTHA Hydrogen roadmap.

The first step on the route to achieving such an ambitious goal is to gain the necessary know how, licenses, and certifications through implementing a small-scale project. With that in mind, RTHA established a partnership with NLR through the TULIPS project that aims to fly a vertical takeoff and landing (VTOL) drone fuelled with liquid hydrogen on site in 2024. This project is referred to as the **Initial Demonstrator**.

With the knowledge gained from the Initial Demonstration phase, hydrogen fuel operations can be expanded through the **Advanced Demonstrator** phase. In this phase RTHA will accommodate multiple hydrogen fuelled aircrafts that are currently in development, like a Sling-4 and Cessna Skymaster. For this purpose, a larger volume of hydrogen will be necessary and more frequent refuelling procedures will be carried out throughout the year.

The gained operational know-how gained from both demonstration phases will allow RTHA a high level of preparedness for when hydrogen fuelled aircraft will be ready for **commercial flights**. Such preparedness and in-house knowledge will be necessary to serve the increasing demand on hydrogen fuel when aircraft operators start transitioning to hydrogen fuel use.

Because of the intended introduction of flammable hydrogen on the RTHA site, studies must be performed to evaluate its safe usage. One important question to be answered is which location(s) on RTHA is/are suitable for positioning the hydrogen containing equipment.

B.1.1 Scope

The objective is to address the safety concerns related to the positioning of hydrogen facilities on the airport premise. This report covers the conceptual design & safety analysis for the Initial Demonstrator, Advanced Demonstrator, and Commercial phases. The level of detail considered is limited to the main requirements of the necessary facilities, such as volume of storage vessels, and the general assumptions on operation. Table 14 presents the cases which are investigated in this safety assessment.

Scenario	LH_2 Storage Size [L]
Initial Demonstration	125
Advanced Demonstration	5,000
Commercial Use	3,000,000

Table 14: Overview of cases studied in this Safety Assessment

Please note that this study is not intended as a QRA of the entire RTHA site but is limited to the above-mentioned installations and the selected locations.

B.1.2 Approach

The starting points of the approach are defined by mapping out requirements of the expected hydrogen demand; potential spatial constraints; and the operational characteristics of the system. This allows to estimate required plot areas for operations and the applicable safety envelope around the infrastructure.

Potential locations are identified and evaluated on feasibility in collaboration with RTHA, DCMR and NLR. Royal Haskoning DHV has aided RTHA in determining potential locations for positioning equipment for the demonstrator phase and commercial phase. The location selection process was based on ‘Operability’, ‘Land side access’, ‘Expandability’ and ‘Phase ability’ parameters. Subsequently, preliminary layouts of the hydrogen facilities have been prepared for the locations that were considered favourable.

Based on safety standards and after consulting with RTHA it was decided to use the safe distances outlined in Table 15 as guidelines for positioning the hydrogen facilities. The selected locations are presented in Chapter B.2.2.

LH_2 relative to structures	Safety Distance [m]
Airport buildings & public roads	20
External public buildings	60
Vulnerable public buildings	125

Table 15: Used values for safe distance.

Finally, a quantitative risk analysis is performed based on technical specification of equipment, the location of the equipment on the airport site and dedicated (legally prescribed) risk modelling software Safeti-NL. The resulting design was tailored on the requirements for ease of operation while applying low risk and high safety standards.

B.2 Locations and layout for hydrogen facilities

As indicated in the first chapter, workshops have been organized with the purpose of identifying possible locations within the RTHA perimeter where the hydrogen storage and refuelling systems may be positioned. In this chapter the current airport layout is presented, as well as the selected locations for future hydrogen related installations.

B.2.1 Current airport layout

Several aspects are taken into account to assess the viability of various locations for hydrogen facilities. Such aspects include:

- Proximity to different zoning areas
- Safety distances
- Available area and expandability
- Obstacle height
- Access to land and air sides
- Other ground services
- Future airport plans

Figure 24 indicates the current layout of zones and areas within and around the airport that are relevant to this study. The suggested areas for future implementation of hydrogen infrastructure and truck refuelling operations are presented in the same figure. The following three locations are considered for the demonstrator phases:

A. North West next to Fire drill area
B. Aviation Club (i.e. vliegclub)
C. Parallel to H_2 Truck fuelling

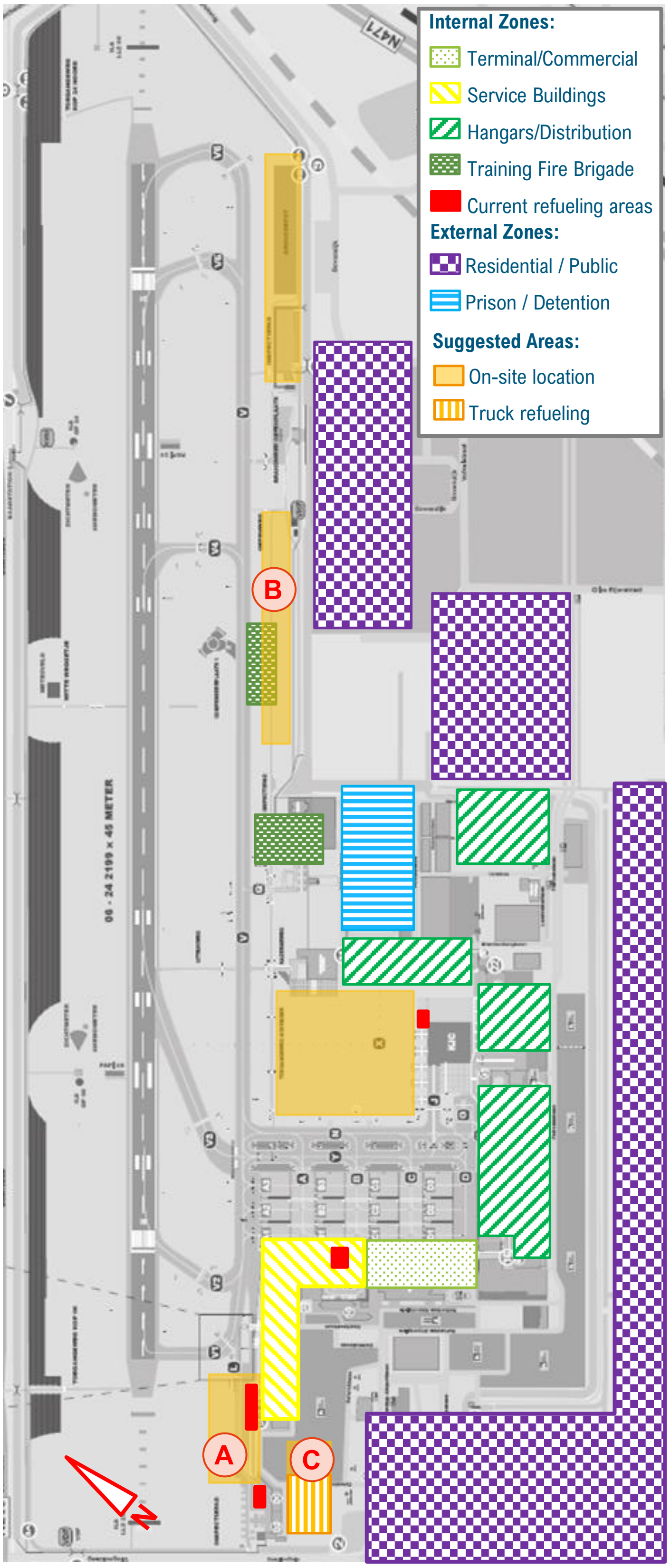

Figure 24: Current airport layout

B.2.2 Layout of hydrogen facilities

Due to the large difference in the volume of hydrogen demand between the initial stages of hydrogen use and the later commercial uptake, three phases were selected for analysis (Table 16). This study considers facilities necessary for all three stages with the level of detail required for the safety analysis. At this stage, no detailed design parameters are necessary (for example line sizing, flowrates, fuel truck specifications). Where required, assumptions were made based on expert judgement.

Phase	Initial Demonstrator	Advanced demonstrator	Commercial Use
Timeline	2023	2024	2040-2050
Aircrafts	Drones	Code-A Aircrafts	Commercial Aircrafts
Storage	125 [L]	2000 – 5000 [L]	700,000 - 3,000,000 [L]
Supply	LH_2 – Air products	LH_2 - Air Products GH2 - Shell	TBD
Location	A	B	C

Table 16: Three phases of hydrogen implementation at RTHA

(location are specified in Figure 24)

B.2.2.1 Layout of the Initial Demonstrator

The Initial Demonstrator phase aims to serve as a proof of concept to demonstrate the feasibility of refuelling an air-vehicle with liquid hydrogen on site. Allowing the involved staff to familiarize with the process and gain the know-how necessary for the later stages. This will be done in connection with the TULIPS and NLR Hydra 2 drone project.

Figure 25: Example storage facility of Liquid Hydrogen at the Marknesse Facility of NLR.

The aim will be to reproduce an equivalent setup to the NLR Liquid Hydrogen Storage Facility. The infrastructure around the Aviation Club Rotterdam provides sufficient space for such facility and access for a 13 meter refuelling truck. The height of this location is restricted to 7 meter due to the proximity to the runway.

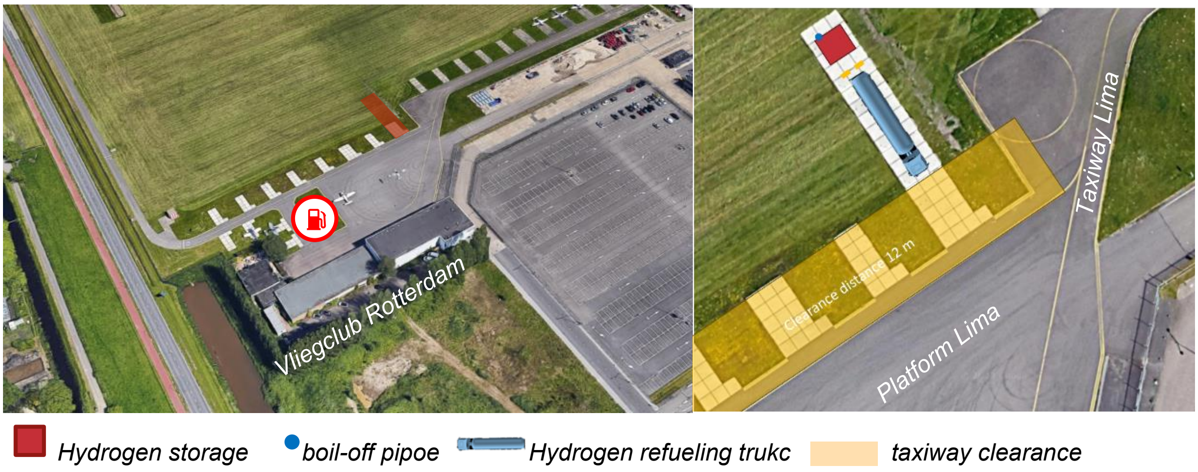

Figure 26 Hydrogen Storage set up at location B (Vliegclub)

B.2.2.2 Layout of the Advanced Demonstrator

The Advanced Demonstrator phase will provide the necessary facilities for refuelling hydrogen fuelled experimental aircrafts during their test campaigns. This includes aircrafts from projects such as Sling 4 by AeroDelft, Pipistrel Velis Electro by NLR, and Cessna Skymaster by TUDelft. This facility will be limited to refuelling drones and Code-A aircrafts with a maximum wingspan of 12 [m]. The selected layout for the facility (as shown in Figure 27) assumes that the liquid hydrogen distribution will take place using one storage tank and a flexible 9 [m] LH_2 hose. Alongside liquid hydrogen facility an area is reserved to host a gas hydrogen refuelling truck.

The selected position and layout for both the Initial and Advanced Demonstrator facilities allows for an expansion from the first phase to the second.

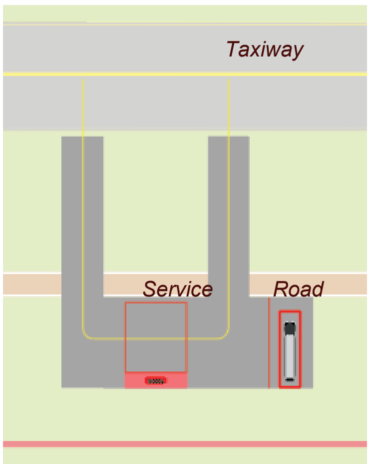

Figure 27: Proposed layout for the Advanced Demonstrator phase.

B.2.2.3 Layout of the Commercial phase

The demand during the Commercial Phase, is based on the Tulips hydrogen demand forecast for 2050. The commercial phase requires a refuelling facility with a storage capacity of 700,000 - 3,000,000 [L] hydrogen.

To minimize the boil-off of liquid hydrogen in the storage tanks, spherical tanks were selected. Spherical tanks offer a higher storage efficiency due to the smaller surface area when compared to the cylindrical storage tanks. With the downside being, a higher footprint area.

The high demand, the choice of storage tank type, and the need to facilitate a large number of refuelling truck movements both on the airside and landside, all translate to a large ground-area requirement. The required ground area is available on the South-Western side of the airport.

To minimize initial costs and account for uncertainty the facility can be implemented with a smaller number of tanks and then later expanded with the addition of more tanks. The expected demand in 2040 can be satisfied with 4 tanks and gradually expanded to 6 or 8 tanks for 2050 as shown in Figure 28. The spherical tank sizing and related facility height is similar to the JAXA liquid hydrogen facility.

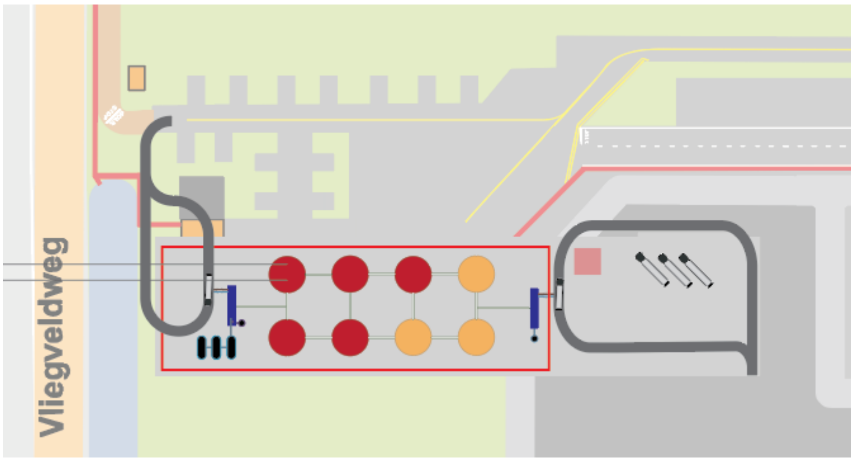

Figure 28: Commercial Phase infrastructure location and preliminary layout.

B.3 Quantitative risk assessment of selected locations

This chapter expands on the Quantitative Risk Assessment (QRA), which provides insight into the safety risks of persons being present at a location outside of an (hazardous) site (so-called 'external safety risk'). The basic concepts of a QRA includes the specific requirements and the legal framework are summarized in section B.3.1. In the subsequent sections, (B.3.2) the technical aspects considered, and (B.3.3) the starting points of the analysis including basic data sources are described. Finally, the results are presented in section B.4 followed by a discussion in section 4.1.

B.3.1 Assessment framework of QRA

Disclaimer: Please note the text in the following sections involve English translation and interpretation of Dutch national legislation. Please always refer to the original Dutch legislation as can be found on the government website for legal matters. No rights may be derived from the texts in the following sections.

A Quantitative Risk Assessment (QRA) provides insight into the safety risks of persons being present at a location outside of an (hazardous) site (so-called ‘external safety risk’). When assessing the external safety risk three criteria are evaluated, namely the ‘Location-specific individual risk’ (LSIR); the ‘societal (or group) risk’ (SR) and the Areas of interest (Dutch: “Aandachtsgebieden”):

- The LSIR is a measure of the likelihood that an individual who is continuously present at a particular location, without any protective means, becomes a fatality as a direct result of an unusual incident involving a hazardous substance (continuously in this sense meaning a whole year). The LSIR contour of 10^{-6} per year may not intersect locations where (highly) vulnerable buildings are present or are permitted to be developed according to the local zoning plans. The concept of a vulnerable building refers to it’s intended use such as hospitals, elderly homes, schools, restaurants.
- The SR is a measure of the likelihood that a group of people becoming fatalities as a direct result of an unusual occurrence occurring at a nearby installation, transport route or pipeline, involving a release of a hazardous substance. The societal risk is graphically represented by a so-called FN-curve. This curve provides the logarithmic relationship between the number of fatalities (N) and the cumulative likelihood (f) of the possible accidents involving a release of hazardous substances (and leading to fatalities). The potential number of fatalities is dependent on the population (density) outside the site boundary.
- Areas of interest (Dutch: “Aandachtsgebieden”) refer to the area impacted upon occurrence of specific failure modes. This measure does not represent the likelihood of failure, but the effective area impacted by a failure. The intersection of the area of interest with zoning plans will inform requirements for additional investigations or mitigation measures. The local government may prescribe additional measures to the construction of buildings to mitigate the risk to local population to acceptable levels.

For determining the risk profile of an installation, the risks related to the various (hazardous) activities are summated to a total LSIR and SR. The LSIR is independent of the actual presence of individuals, while the SR does consider the presence of individuals.

B.3.2 General assumptions of the safety analysis

Configuration of demonstrator based on initial technical design conditions

The safety analysis is performed using the Safeti-NL software[77]. In addition to the scenario specific technical assumptions, the following concepts are taken into account:

- Meteorological data of Rotterdam using
- Population data in the vicinity (500m) of the airport is obtained from the BAG population service
- Zoning plans

B.3.2.1 Configuration of the initial demonstrator

The initial demonstrator consists of a storage tank with a liquid hydrogen content of 125 [L] (further refed to as 'dewar'). The dewar is owned by NLR who will be using it for fueling of their (Hydra 2) drone. RTHA will facilitate this by providing a location for testing of hydrogen fueled flights. The Initial demonstrator phase will last one to two years.

The dewar operates at a pressure of 1.07 [bara] (design pressure of 3.5 [barg]). At these pressures the temperature of the hydrogen needs to be -253 [ºC] to ensure a liquid state (below bubble point). The dewar is designed as a double-walled tank with 'vacuum' insulation to ensure minimum heat being added to the hydrogen from the ambient surrounding. No active cooling of the dewar is foreseen. Without active cooling small amounts of liquid hydrogen will 'boil-off' over time. This boil-off gas is routed to a vent and released to atmosphere. It was estimated by NLR that the entire content of the dewar will evaporate within a single month if it is not refueled.

The design of the dewar is such that it complies with requirements set-out in the Pressure Equipment Directive[78] and the Dutch norm for Cryogenic vessels – vacuum isolated static vessels[79].This involves amongst others pressure sensing equipment and (pressure) protection. The dewar will be installed in an enclosure which consist of concrete plating at two sides and fencing at the other two sides. The roof consists of corrugated plating. At the entrance (fence) protection to prevent collision with the hydrogen supply truck.

The initial filling operation of the dewar is expected to last eight hours. This time is required to allow the temperature of the dewar to drop from ambient to the temperature for storing liquid hydrogen. For this initial filling operation, the liquid hydrogen which is supplied is the coolant. If the dewar becomes fully emptied, the dewar will heat-up and this cooling/filing operation will be required again. As it is intended to perform this cooling operation only at start-up, the dewar is re-filled regularly. For this Safety Assessment it is assumed that the dewar is filled twice a month to support the refueling of drones and to prevent it from running dry. Each filling operation is estimated to last one to two hours, a duration of one and a half hour is applied for this safety assessment.

Liquid hydrogen is supplied by truck twice a month. The truck has a storage capacity of 30m3. The storage conditions of the hydrogen are almost at ambient pressure and a temperature of – 253 [ºC]. It is assumed that the supply truck is equipped with the required safety measures, which include amongst others shutdown valves and a dry break coupling. It is assumed that the connection from the truck to the dewar is established by means of a hose connection with an inner diameter of 101.6 [mm] (4 [inch]). As mentioned above, the design involves collision protection to avoid the truck bumping into the storage facility when backing-up to position itself for refueling the dewar.

B.3.2.2 Configuration of the advanced demonstrator

No specifications of the advanced demonstrator are available yet, as such the starting points as mentioned in this section are to be considered as 'assumptions', though based on expert judgement and designs of similar facilities.

For the advanced demonstrator phase the volume of liquid hydrogen is increased to 5000 [L]. The storage pressure is assumed to be 1 [barg]. Further starting points on e.g., tank design and handling of boil-off gas are considered equal to the initial demonstrator phase.

Starting points for the liquid hydrogen supply truck are equal to the ones used for the initial demonstrator phase.

B.3.2.3 Configuration of the commercial installation

No specifications of the commercial installation are available yet, as such the starting points as mentioned in this section are to be considered as 'assumptions', though based on expert judgement and designs of similar facilities.

The commercial installation involves eight spherical storage tanks, each with a storage volume of 400 [m^3]. The total storage capacity is determined at 3000 [m^3] of liquid hydrogen. The hydrogen is stored at a pressure of 8[bara]. At these pressures the temperature of the hydrogen needs to be – 242 [ºC] to ensure liquid phase (bubble point). The tanks are well isolated resulting in a minimal boil-off. Any boil-off is recaptured, compressed, and stored in a buffer. As such, no onsite liquefaction is required. The compressed gas is used to fuel site bound vehicles. It is assumed that the buffer consists of 16 tubes, each with a storage volume of 1.5 [m^3]. The hydrogen is stored at a pressure of 350[barg] at ambient temperatures. An amount equal to one third of the total storage capacity is utilized for aviation daily. As such, the same amount needs to be supplied to the airport by means of trucks. Larger liquid hydrogen supply trucks may be used compared to the once used during the demonstrator phases, which have a volume of 30 [m^3]. Based on the previous it is assumed that a daily 1000 [m^3] delivery of liquid hydrogen is supplied using trucks capable of transporting 50 [m^3] each, this requires 20 deliveries each day. Apart from the storage volume, the design of the trucks is considered equal to that of the demonstrator phases. It is assumed that three locations are available for the trucks to perform unloading activities.

B.3.3 General starting points

B.3.3.1 Software

The risk profile of the installations is determined by using Safeti-NL software[77]. Use of this software is prescribed by the Dutch legislation for assessing risk profiles of (industrial) sites. Information such as equipment, process conditions, population, etc. is fed into the software which subsequently determines the risk profile. The risk profile is expressed in terms of location specific individual risk ("Plaatsgebonden risico" in Dutch), societal risk ("Groepsrisico" in Dutch), and as so-called areas of interest ("aandachtsgebieden" in Dutch) as per new legislation which will enact at the 1st of January 2024.

B.3.3.2 Meteorological data

The calculations are performed using the meteorological data of the weather station 'Rotterdam' as included in the software.

B.3.3.3 Population data

The population in the vicinity of the airport is obtained from the BAG population service[80]. This data source provides estimations of population(numbers) associated with existing buildings and buildings which are planned to be developed. Population in case of (temporary) recreational presence is also included. This could be considered as the 'existing situation'. Zoning plans may allow more population in a specific area than currently present. The theoretical maximum which could be allowed is not included in the data set (and therefore the QRA model). The relevant area where population resides, which is to be included in the model, is based on the largest effect distance. This distance is determined by assessing consequence results of the modelled scenario's (Summary of Maximum Effect Zones Report). Please note that apart from the external population the population residing within the airport boundary has also been inventoried. Although this QRA for external safety only needs to address the risk profile with respect to population outside the airport, it was deemed insightful to additionally present the risk profile when including population with the airport boundary. *As per Dutch legislation population within the airport boundary (and site boundaries in general) is considered as 'functionally bonded' ("functioneel gebonden" in Dutch), which means as much as them being part of the airport when present. The essence for being functionally bonded likely finds its origin in industrial sites where (onsite) personnel is aware of potential hazards and trained to act upon an incident. This does not (necessarily) apply to passengers and other population not being an employee. For instance, a restaurant and a detention center are located within the airport boundary.*

For the initial demonstrator and the advanced demonstrator, the distance is determined at around 430 meters (this is not necessarily the distance where fatalities may still occur as this distance is based on relatively low overpressure of heat radiation levels). To cater for small changes in the starting points, population within 500 meters from the Airport is included in the model, Figure 29 illustrates this area and specific locations where population may reside.

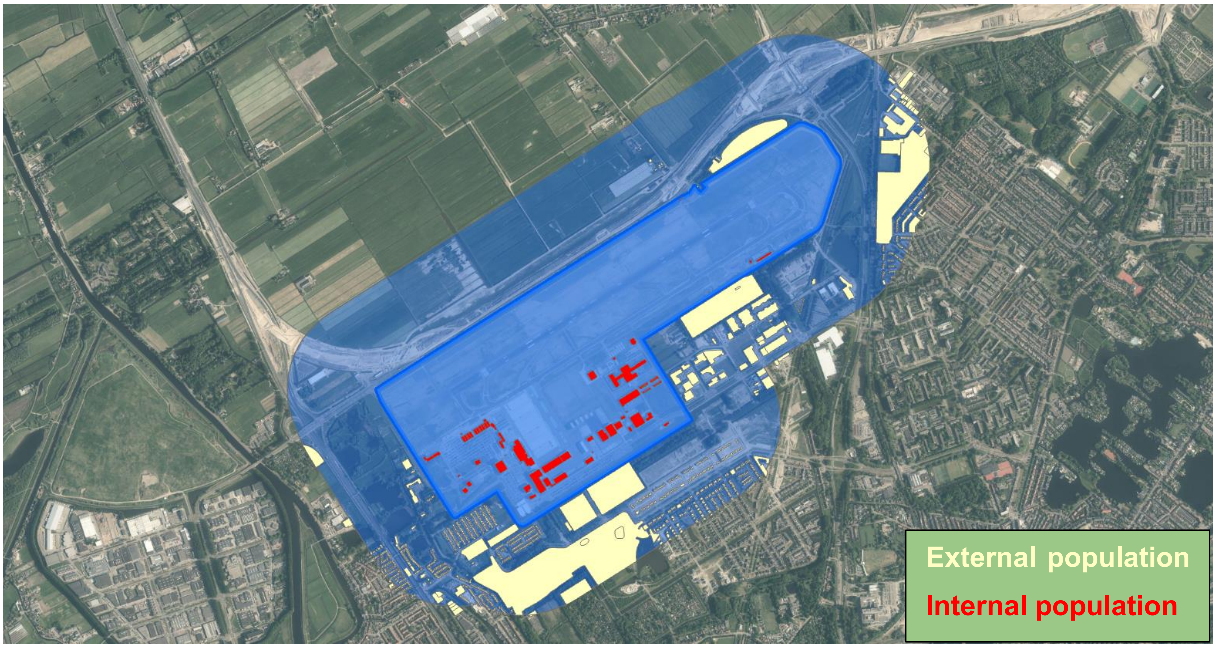

Figure 29: Populated areas within reach of the effect distance of incidents occurring at the location of the initial and advanced demonstrators.

B.3.3.4 Operational period of demonstrators

Both the initial demonstrator and the advanced demonstrator will be operational for a half year period. Fueling operation will only be performed during daytime. The truck filled with gaseous hydrogen will however be present all-day round (day and night-time). Detailing of the modelled scenarios, as included in Appendix C and Appendix D, is based on an operational period of a whole year. For determination of the risk profile it is conservatively assumed that the operational period also involves a whole year.

B.3.3.5 Modelling of fuel supply trucks

This study adheres to the (failure) scenarios as defined in a memo from the Dutch Centre for Public Health and Environment (RIVM = Rijkskinstituut voor Volksgezondheid en Milieu) on the topic of risk and effect distances of hydrogen fueling stations[81]. The memo advises to apply scenario's related to intrinsic failure, failure due external (mechanical) impact and external fires. Mitigating measures to prevent external impact and to create sufficient separation distance towards other flammable hazards could mitigate the latter two scenarios. Such measures are commonly applied within the design of process installations. However, it was decided to conservatively include these scenarios for all designs, especially for the demonstrator phases, given the nature of intended 'experimental usage', operations may not be as 'routinely' compared to commercial facilities.

Hydrogen is classified as an ADR class 2 substance (gaseous at ambient pressure and a temperature of 20° Celsius). According to the Dutch manual for risk calculations the trucks used to transport hydrogen (both gaseous and liquid phase) are therefore to be considered as 'pressurized' (and not atmospheric storage). It is assumed that the trailer for transport of liquid hydrogen is 'double walled'. It is assumed that the trailer for supply of gaseous hydrogen carries multiple cylindrical gas containers.

B.3.3.6 Modelling of liquid hydrogen releases

This study assumes no means to prevent spreading of released liquid hydrogen is included in the design. During the early phase of the release no pool is formed as the liquid hydrogen will evaporate quickly. After a short period of time the substrate on which the hydrogen is released may be cooled sufficiently for some pool formation to occur. It is assumed that the facilities will be installed on a concrete substrate. The offloading locations of the trucks consist likely of concrete slabs with some form of drainage, this draining may reduce pool size. Drainage has however not been included in this study.

B.3.4 Ignition

Within the Dutch guidance for calculation of risk of sites[82], ignition probabilities for direct ignition are defined. Direct ignition refers to ignition directly after the release, prior to formation of a gas cloud or a large liquid pool. The direct ignition probability is based on the type of installation (stationary or mobile), flashpoint and reactivity of the material being released, and the release rate. For stationary installations the probability is within the range of 0,2 – 0,7. *Please note it is currently being discussed whether this range should be applied for hydrogen as well as literature studies and test indicate the probability of direct ignition of hydrogen is likely higher compared to other flammables on which the probability has been determined. With no conclusive literature available and no prescribed usage of other ignition probabilities, the ignition probabilities are not changed.*

Concluding for this study, the probability of direct ignition for stationary installation is determined by the modelling software and is within the range of 0,2 – 0.7.of 0,7 . The probability of direct ignition for release of mobile installations is based on the setting 'transport tank-wagon'. The latter adheres to values as prescribed by the guidance for calculation of risk[82].

B.4 Risk profile of the configurations

B.4.1 Demonstrator phase – Initial demonstrator and truck with gaseous hydrogen

Local Specific Risk Contour (LSIR)

The LSIR contours up to the LSIR 10^{-8}/year are presented in Figure 30. The red LSIR 10^{-6}/year does not cross the airport boundary, and as such complies with Dutch national legislation (Bevi).

The software calculates up to the LSIR 10^{-30}/year contour. However, as per legislation reporting up to the LSIR 10^{-8} is required.

Figure 30: Local specific Risk Contours of the initial demonstrator and truck with GH_2.

Societal risk

The Societal risk analysis of the initial demonstrator and truck with gaseous hydrogen is graphically represented by a so-called FN-curve (Figure 31). This curve provides the logarithmic relationship between the number of fatalities (N) and the cumulative likelihood (f) of the possible accidents involving a release of hazardous substances (and leading to fatalities). The initial demonstrator risk analysis results are below the non-legal orientation value as included in the Bevi[83]. Because only lower likelihood LSIR contours extend over a small area outside the airport boundary, an area which also has a low population density given the nature (communal gardens), no societal risk is applicable. *As per legal definition, according to external safety decree, a group is defined as consisting of 10 or more persons. In other words, the potential number of fatalities is less than 10 which is the legal definition of a group when considering external safety according to Dutch national legislation.*

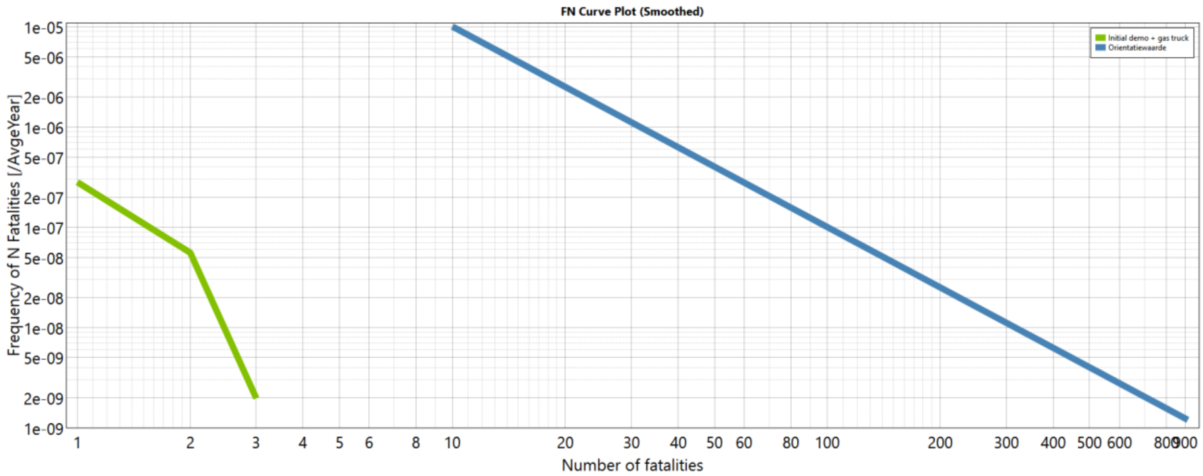

Figure 31: Societal risk of the initial demonstrator and truck with GH_2

(please note that the maximum fatalities are below ten and therfore no societal risk is applicable)

<u>Areas of interest (Dutch: “Aandachtsgebieden”)</u>

The areas of interest are outside the airport boundary. They do not intersect with existing vulnurable objects or areas within the zoning plan where vulnurable objects are allowed to be developed. It is however recommended to consult with local goverment on their position on the areas of interest.

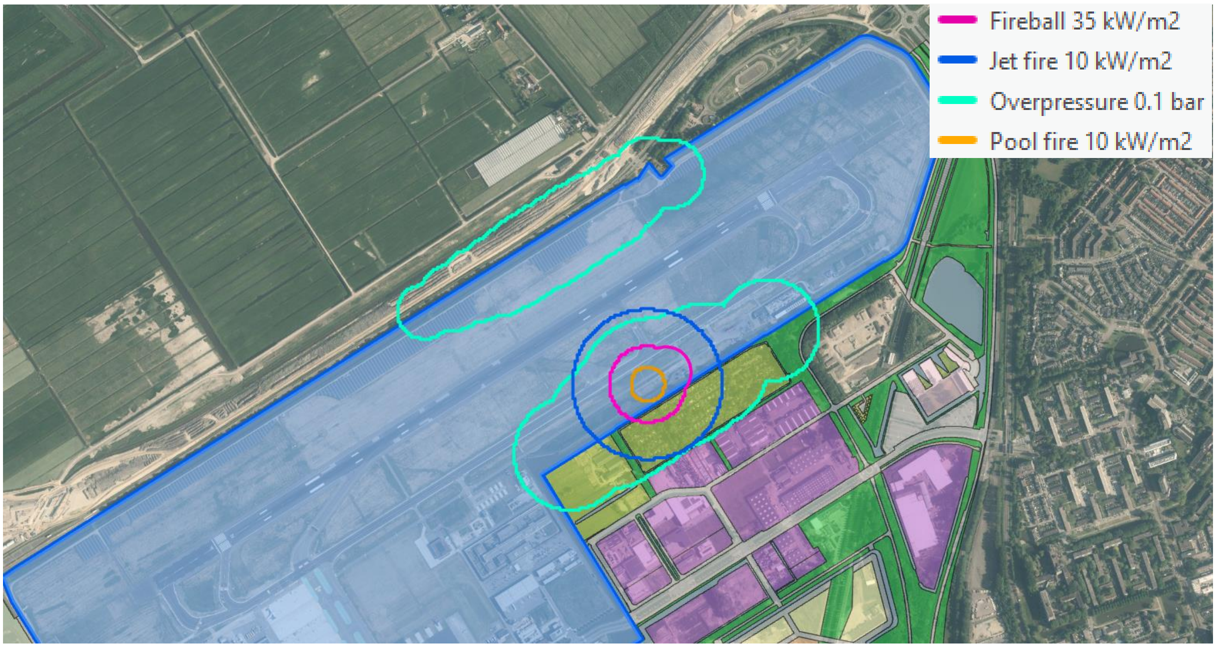

Figure 32: Areas of interest (Dutch: “Aandachtsgebieden”) of the initial demonstrator and truck with GH_2

B.4.2 Demonstrator phase – Advanced demonstrator

Local Specific Risk Contour (LSIR)

The illustration below presents the LSIR contours up to the LSIR 10^{-8}/year. The red LSIR 10^{-6}/year extent across the airport site with approximately 50 meters, and therefore intersect with the adjacent communal gardens. The communal gardens are however not considered as vulnerable objects according to the Bevi, and as such the orientation of the LSIR 10^{-6}/year contour complies with Dutch national legislation (Bevi).

The software calculates up to the LSIR 10^{-30}/year contour. However, as per legislation reporting up to the LSIR 10^{-8} is required.

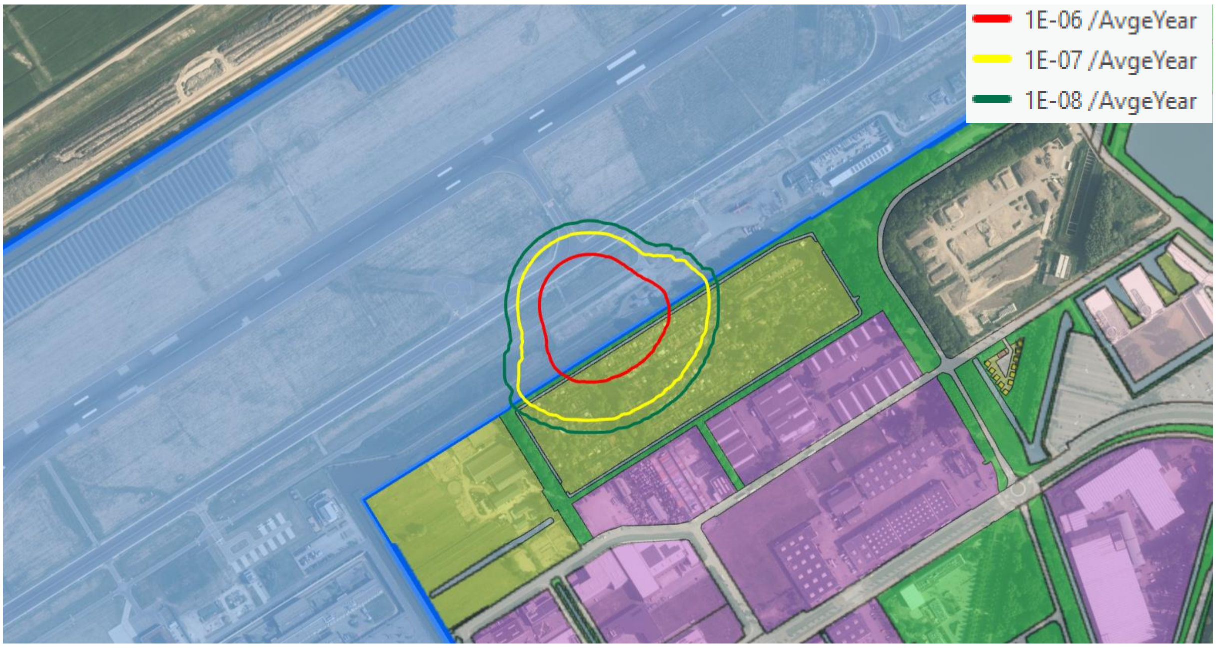

Figure 33: Local specific Risk Contours of the advanced demonstrator and truck with GH_2

Societal risk

Because the LSIR risk contours extend over a small area outside the airport boundary, an area which also has a low population density given the nature (communal gardens), a very small societal risk is assumed to be justifiable by local government.

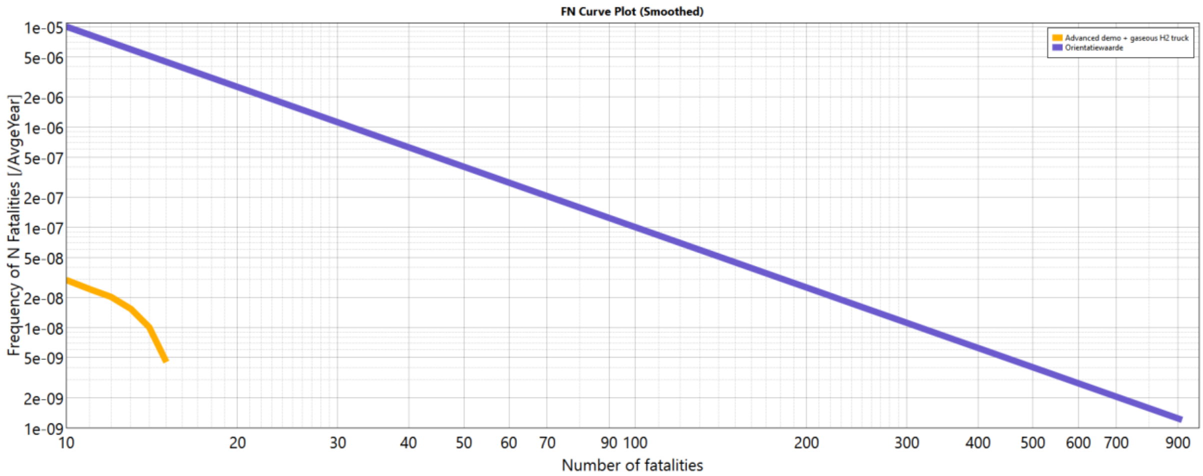

Figure 34: Societal risk of the advanced demonstrator and truck with GH_2

<u>Areas of interest (Dutch: “Aandachtsgebieden”)</u>

The aandachtsgebieden are outside the airport boundary. They do not intersect with existing vulnurable objects or areas within the zoning plan where vulnurable objects are allowed to be developed. It is however recommended to consult with local gouverment on their position on the aandachtsgebieden.

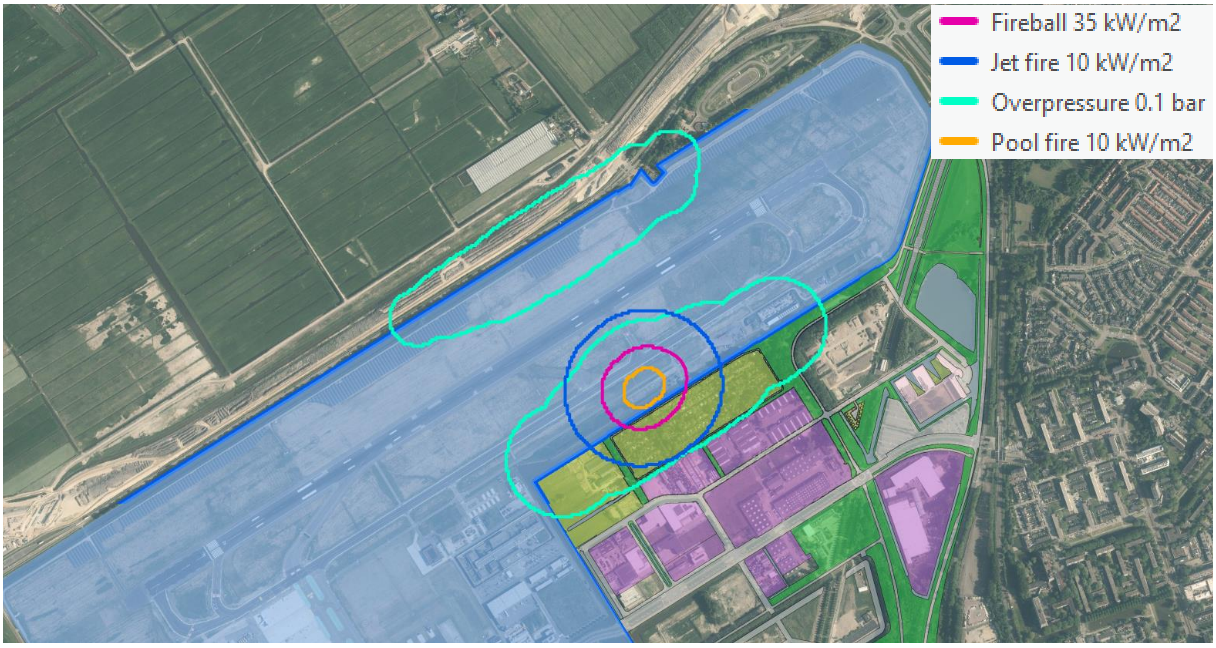

Figure 35: Aandachtsgebieden of the advanced demonstrator and truck with GH_2

B.4.3 Commercial installation

<u>Local Specific Risk Contour (LSIR)</u>

The illustration below presents the LSIR contours up to the LSIR 10^{-8}/year. The red LSIR 10^{-6}/year extent across the airport site with approximately 70 meters, and therefore (just) touches the light brown colored vulnerable object which concerns a maternity care. The close by located orange area marks the location of a hotel which is also a vulnerable object. Based on the previous, the LSIR 10^{-6}/year contour does not comply with Dutch national legislation (Bevi).

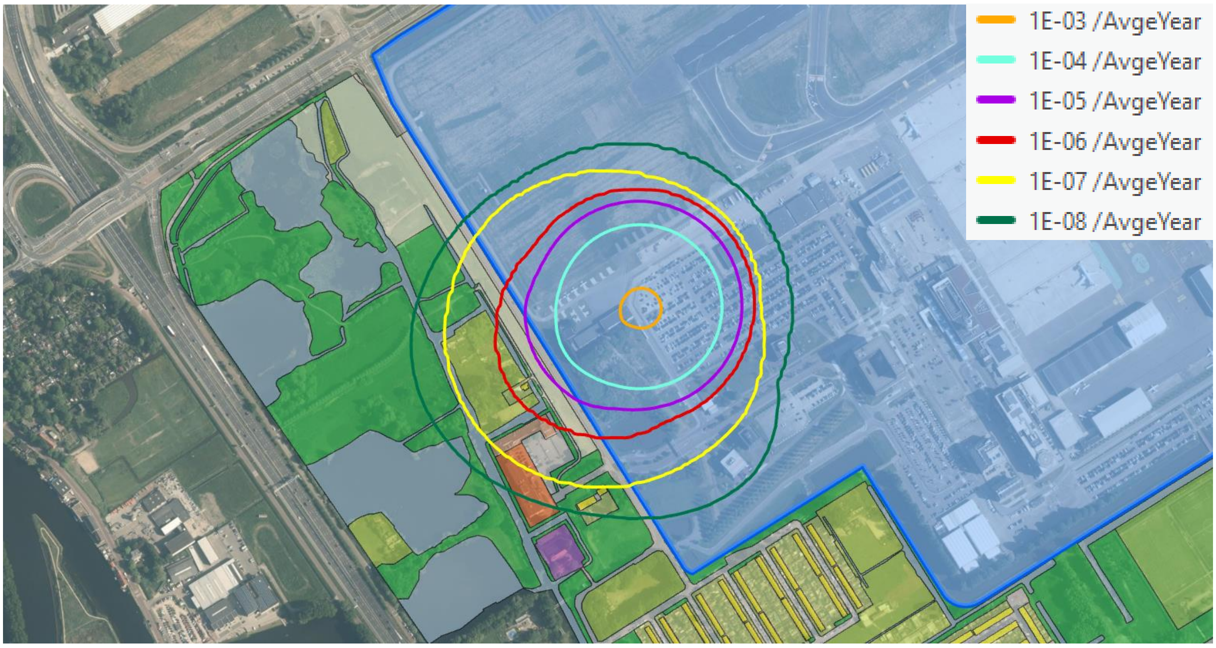

Figure 36:Local specific Risk Contours of the commercial phase

<u>Societal risk</u>

Because the LSIR risk contours extend over a larger area outside the airport boundary, an area which also has a high(er) population density given the nature, a high societal risk is applicable. At 400 fatalities, the determined likelihood is just below the orientation value. The societal risk is below but very close to the orientation value and requires justification by local gouvernment.

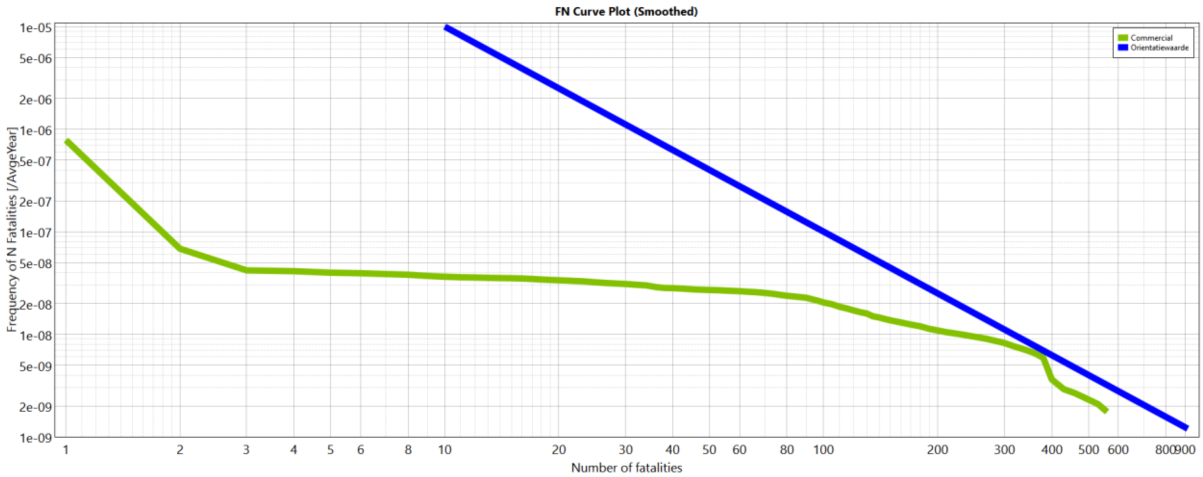

Figure 37: Societal risk of the commercial phase

<u>Areas of interest (Dutch: "Aandachtsgebieden")</u>

The aandachtsgebieden are outside the airport boundary and intersect with vulnurable objects. Because of the intersection with vulnurable objects, the aandachtsgebieden (or part of) will therefore be designated as 'voorschriftengebieden' requiring additional measures to be taken at the vulnurable objects to mitigate the risk.

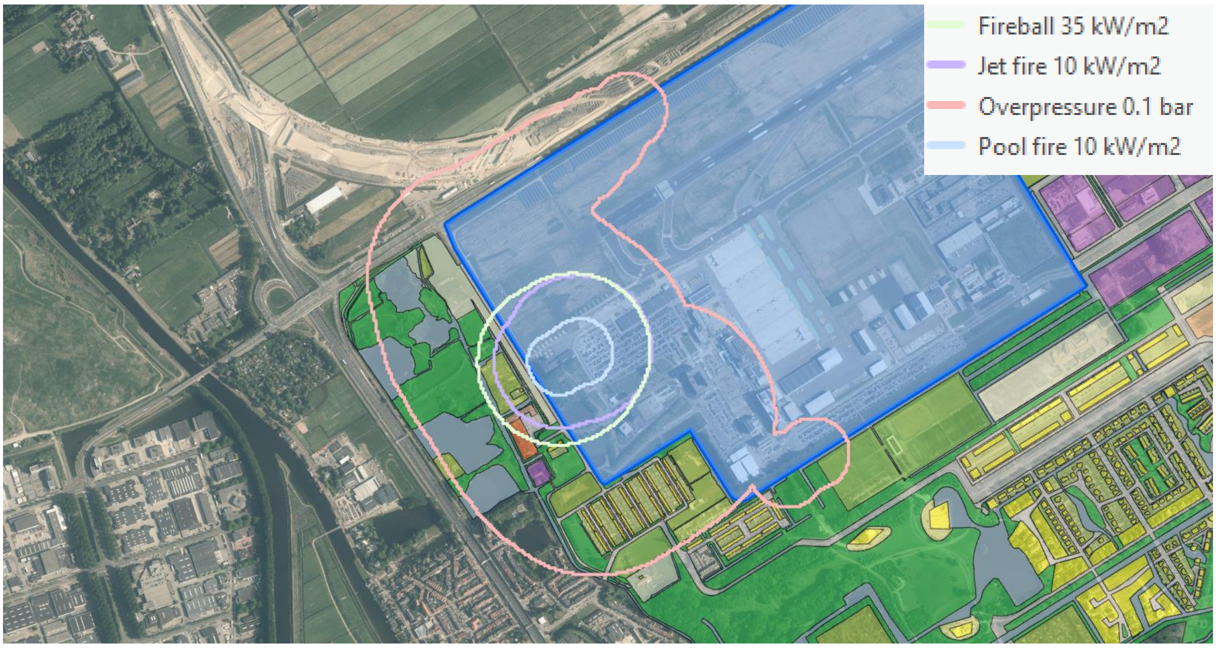

Figure 38: Aandachtsgebieden of the commercial phase

B.5 Discussion and summary

<u>Initial demonstrator phase</u>

The local specific risk 10-6/year contour is well within the airport boundary at RTHA. Due to the limited sizing of the process equipment, the LSIR contours relevant for the societal risk do not extend outside the airport boundary for a large distance. In fact, there is no societal risk according to the criteria as the potential number of fatalities is below 10 which is the threshold for the societal risk. No justification of the societal risk is therefore required. The aandachtsgebieden are outside the airport boundary. They do not intersect with existing vulnurable objects or areas within the zoning plan where vulnurable objects are allowed to be developed. It is however recommended to consult with local gouverment on their position on the aandachtsgebieden.

<u>Advanced demonstrator phase</u>

The local specific risk 10-6/year contour extents to outside the airport boundary for approximately 50 meters, thereby intersecting with adjacent communal gardens. These communal gardens are not designated as vulnerable objects and as such the intersection is permittable. Due to the limited sizing of the process equipment, the LSIR contours relevant for the societal risk do not extend outside the airport boundary for a large distance. A (small) societal risk is applicable, though well below the orientation value. It is expected that justification of this societal risk by local government poses no problem. The aandachtsgebieden are outside the airport boundary. They do not intersect with existing vulnurable objects or areas within the zoning plan where vulnurable objects are allowed to be developed. It is however recommended to consult with local gouverment on their position on the aandachtsgebieden.

<u>Commercial phase</u>

The local specific risk 10-6/year contour extents to outside the airport boundary. With the current layout it intersects with an vulnurable object (maternity care) and is very close to an hotel which is also an vulnurable object. This is not permittable according to the criteria setout in Dutch national legislation with respect to vulnurable objects. The societal risk is below but very close to the orientation value and requires justification by local gouvernment. The aandachtsgebieden are outside the airport boundary and intersect with vulnurable objects. Because of the intersection with vulnurable objects, the aandachtsgebieden (or part of) will therefore be designated as 'voorschriftengebieden' requiring additional measures to be taken at the vulnurable objects to mitigate the risk.

Determing of the riskprofile of the commercial phase was performed to give high level insight in the extent of the risk profile which is to be expected from such an installation. Further detailing of the installation will provide a more accurate risk profile. It is however recommended to carefully consider the desired location of the commercial installation in order to minimize the risk profile to external population, at least to acceptable levels. In addition it is recommend to consult with the local gouvernent on the (potentialy) desired future hydrogen facilities and discuss possible locations with respect to local zoning plans. Specifically it should be addressed where, with respect to the zoning plan, aandachtgebied (or voorschriftengebieden) are allowed to intersect with the surrounding, and conditions to do so. And how to ensure potential (vulnurable) developments in the vecinity of the airport, prior to obtaining a permit for the hydrogen facilities, do not complicate the hydrogen development or even prohibit the development.

In addition to the above it was noted that passengers present on the airport side are technically not ‘external population’ (and therefore not included in the societal risk), but it is recommended to discuss if the passengers should be considered as external population anyhow. This seems to be inline with Schiphol group internal regulations. In addition, the passengers cannot be expected to be self-reliant to the same extend as might be expected from personnel on the airport, as the latter receive more dedicated training and information on how to act upon potential hazards/treats related to their job.

C STARTING POINTS AND RELEASE SCENARIO'S APPLIED FOR THE INITIAL DEMONSTRATOR

This Appendix includes detailed information on how the scenarios of the initial demonstrator are modelled. Table 17 below presents the starting points for the QRA. Following this table are two tables which provide details on further development of the scenarios.

As per Dutch manual for risk calculation gas storage tanks with a volume equal to 150 liters of water or more are considered as pressurized tanks. Gas storage tanks with a with a volume equal to less than 150 liters of water, being are seamless and mobile are considered as cylinders. For the QRA, the Dewar is assumed as a pressure vessel though it has a volume equal to 125 liters of water. The reasoning behind this choice is that the Dewar will not be moved as it is installed within an enclosure, and that the Dewar is fitted with various smallbore connections for i.e., sensing equipment. As such the Dewar resembles more a pressurized storage tank than it does a cylinder. The Dewar is filled from the top, as such no backflow from the storage is possible in case of hose failure during loading of the storage.

Table 17: Input parameters storage tanks initial demonstrator

Item	Value	Unit	Comment
Hazardous substance	Hydrogen	[-]	-
Volume	125	L	-
Operational pressure	1,07	Bara	-
Design pressure	3,5	Barg	-
Operational temperature	Bubble point	Degrees Celsius	-

Fluid	LH_2
Liquid volume	125 L
Total volume	150 L
Design code	PED*, EN 13458
Design pressure	3.5 barg
Operation pressure	1.07 bar abs
Evaporation rate	< 2.0%/day
Weight (empty)	140 kg
Weight (full)	147 kg
Total diameter	750 mm
Total height	1750 mm
Fill / withdrawal connection	½ × 6" Linde Female Bayonet
Vent connection	Kenol® DN15 joint

Figure 39: Dewar specifications

Table 18: Input parameters liquid hydrogen truck initial demonstrator

Item	Value	Unit	Comment
Hazardous substance	Liquid hydrogen	[-]	
Modelstof for QRA	Hydrogen	[-]	
Containment System	Liquid trailer	[-]	
Number of compartments / tubes	1	[-]	
Size of compartments	30000	[L]	
Activity	Filling of Dewar	[-]	
Period	Day time only	[-]	
Trailer content	30	[m3]	
Hydrogen pressure	1	[barg]	Pressure is assumed little over ambient
Hydrogen temperature	Below bubble point	[°C]	Temperature varies slightly per scenario to ensure liquid release is modelled
Hydrogen density at given conditions	67,3	[kg/m3]	
Connection type	Hoses	[-]	
Diameter of connection	101,6	[mm]	
	4	[inch]	
Fueling rate	5,6	[kg/hour]	Based on dewar content of 125 liter, duration of fueling operation and density
Max number of hours of fueling	36	[hours/year]	
Max throughput	201,8	[kg/year]	
Number of fueling operations	24	[operations/year]	
Duration of fueling operation	1,5	[hours/operation]	
	36	[hours/year]	
Duration being present	2,0	[hours/operation]	Assumed 1/2 hour for all activities except actual fueling

Item	Value	Unit	Comment
			(activities such as positioning truck, connecting, etc.)
	48	[hours/year]	
Largest connection on trailer	6	[inch]	
Max number of trailers being parked	n.v.t.	[-]	
Parking duration per filled trailer	n.v.t.	[hours/year]	
Parking duration of filled trailers	n.v.t.	[hours/year]	
Safety measures	Yes	[-]	
Likelihood of successful performance	0,9	[-]	
Response time	120	[s]	

Table 19: Scenario's initial demonstrator phase - part 1

System	**Scenario**	**Initial failure frequency**		**Safety factor**	**Duration of activity**	**Calculated failure frequency**	**Direct ignition probability**
		[quantity]	**[unit]**	**[-]**	**[hours/year]**	**[/year]**	**[-]**
Liquid hydrogen trailer							
Presence	Instantaneous release	5,00E-07	per year	-	48	2,74E-09	Transport - tank wagon
	Release from largest connection	5,00E-07	per year	-	48	2,74E-09	Transport - tank wagon
	Instantaneous release - external fire	4,00E-08	per hour	-	48	2,19E-10	1
	Instantaneous release - external impact	9,60E-10	per hour	-	48	5,26E-12	Transport - tank wagon
Unloading	Hose rupture, ESD works	4,00E-07	per hour	0,9	36	1,30E-05	Transport - tank wagon
	Hose rupture, ESD fails	4,00E-07	per hour	0,1	36	1,44E-06	Transport - tank wagon
	Hose leakage	4,00E-05	per hour	-	36	1,44E-03	Transport - tank wagon
	Instantaneous release - ignited	5,80E-10	per hour	-	36	2,09E-08	1
Liquid hydrogen storage							
Dewar	Instantaneous release	5,00E-07	per year	-	8760	5,00E-07	Safeti-NL
	10 minutes release	5,00E-07	per year	-	8760	5,00E-07	Safeti-NL
	10 mm leak	1,00E-05	per year	-	8760	1,00E-05	Safeti-NL

Table 20: Scenario's initial demonstrator phase - part 2

System	**Scenario**	**Release - trailer side**			**Release - storage side**			**Release - scenario**			
		Rate [kg/s]	**Duration [s]**	**Quantity [kg]**	**Rate [kg/s]**	**Duration [s]**	**Quantity [kg]**	**Rate [kg/s]**	**Duration [s]**	**Quantity [kg]**	**Pressure**
Liquid hydrogen trailer											
Presence	Instantaneous release	-	-	2018	-	-	-	-	-	-	Design
	Release from largest connection	Safeti-NL		2018	-	-	-	Safeti-NL			Storage
	Instantaneous release - external fire	-	-	2018	-	-	-	-	-	-	Design
	Instantaneous release - external impact	-	-	2018	-	-	-	-	-	-	Storage
Unloading	Hose rupture, ESD works	0,0617	120	7,4	0,024	120	2,9	0,086[A)]	120	10,3	Storage
	Hose rupture, ESD fails	0,0617	1800	111,1	0,024	1800	8,4	0,086[A)]	1800	119,5	Storage
	Hose leakage	Safeti-NL		-	-	-	-	-	-	-	Storage
	Instantaneous release - ignited	-	-	2125,5	-	-	-	-	-	-	Design
Liquid hydrogen storage											
Dewar	Instantaneous release	-	-	-	-	-	-	-	-	8,9	Design
	10 minutes release	-	-	-	-	-	-	Safeti-NL		8,9	Storage
	10 mm leak	-	-	-	-	-	-	Safeti-NL		8,9	Storage

A) Backflow from the storage tank is not included as tank is filled from the top; only the release rate from the trailer side is included

D STARTING POINTS AND RELEASE SCENARIO'S APPLIED FOR THE ADVANCED DEMONSTRATOR

This Appendix includes detailed information on how the scenarios of the advanced demonstrator are modelled. Table 21 below presents the starting points for the QRA. Following this table are two tables which provide details on further development of the scenarios. The storage tank is filled from the top, as such no backflow from the storage is possible in case of hose failure during loading of the storage.

Table 21: Input parameters storage tanks advanced demonstrator

Parameter	Value	Unit	Comment
Hazardous substance	Hydrogen	[-]	-
Volume	5000	L	-
Operational pressure	2	Bara	Assumption
Design pressure	3,5	Barg	Assumed same as Dewar
Operational temperature	Bubble point	Degrees Celsius	-
Tank height	3	m	Assumption

Table 22: Input parameters liquid hydrogen truck advanced demonstrator

Item	Value	Unit	Comment
Hazardous substance	Liquid hydrogen	[-]	
Modelstof for QRA	Hydrogen	[-]	
Containment System	Liquid trailer	[-]	
Number of compartments / tubes	1	[-]	
Size of compartments	30000	[L]	
Activity	Filling of storage tank	[-]	
Period	Day time only	[-]	
Trailer content	30	[m3]	
Hydrogen pressure	1	[barg]	Pressure is assumed little over ambient
Hydrogen temperature	Below bubble point	[°C]	Temperature varies slightly per scenario to ensure liquid release is modelled
Hydrogen density at given conditions	67,3	[kg/m3]	
Connection type	Hoses	[-]	
Diameter of connection	101,6	[mm]	
	4,0	[inch]	
Fueling rate	224,3	[kg/hour]	Based on storage tank content of 5000L, duration of fueling operation and density
Max number of hours of fueling	18	[hours/year]	
Max throughput	4038	[kg/year]	
Number of fueling operations	12	[operations/year]	
Duration of fueling operation	1,5	[hours/operation]	
	18	[hours/year]	

Item	Value	Unit	Comment
Duration being present	2,0	[hours/operation]	Assumed 1/2 hour for all activities except actual fueling (activities such as positioning truck, connecting, etc.)
	24	[hours/year]	
Largest connection on trailer	6	[inch]	
Max number of trailers being parked	N.A..	[-]	
Parking duration per filled trailer	N.A..	[hours/year]	
Parking duration of filled trailers	N.A..	[hours/year]	
Safety measures	Yes	[-]	
Likelihood of successful performance	0,9	[-]	
Response time	120	[s]	

Table 23: Scenario's advanced demonstrator phase - part 1

System	Scenario	Initial failure frequency		Safety factor	Duration of activity	Calculated failure frequency	Direct ignition probability
		[quantity]	[unit]	[-]	[hours/year]	[/year]	[-]
Liquid hydrogen trailer							
Presence	Instantaneous release	5,00E-07	per year	-	24	1,37E-09	Transport - tank wagon
	Release from largest connection	5,00E-07	per year	-	24	1,37E-09	Transport - tank wagon
	Instantaneous release - external fire	4,00E-08	per hour	-	24	1,10E-10	1
	Instantaneous release - external impact	9,60E-10	per hour	-	24	2,63E-12	Transport - tank wagon
Unloading	Hose rupture, ESD works	4,00E-07	per hour	0,9	18	6,48E-06	Transport - tank wagon
	Hose rupture, ESD fails	4,00E-07	per hour	0,1	18	7,20E-07	Transport - tank wagon
	Hose leakage	4,00E-05	per hour	-	18	7,20E-04	Transport - tank wagon
	Instantaneous release - ignited	5,80E-10	per hour	-	18	1,04E-08	1
Liquid hydrogen storage							
5000 L storage tank	Instantaneous release	5,00E-07	per year	-	8760	5,00E-07	Safeti-NL
	10 minutes release	5,00E-07	per year	-	8760	5,00E-07	Safeti-NL
	10 mm leak	1,00E-05	per year	-	8760	1,00E-05	Safeti-NL

Table 24: Scenario's advanced demonstrator phase - part 2

System	Scenario	Release - trailer side			Release - storage side			Release - scenario			
		Rate [kg/s]	Duration [s]	Quantity [kg]	Rate [kg/s]	Duration [s]	Quantity [kg]	Rate [kg/s]	Duration [s]	Quantity [kg]	Pressure
Liquid hydrogen trailer											
Presence	Instantaneous release	-	-	2019	-	-	-	-	-	-	Design
	Release from largest connection	Safeti-NL		2019	-	-	-	Safeti-NL			Storage
	Instantaneous release - external fire	-	-	2019	-	-	-	-	-	-	Design
	Instantaneous release - external impact	-	-	2019	-	-	-	-	-	-	Storage
Unloading	Hose rupture, ESD works	8,9	120	1065,5	4,5	120	337	13,4[A)]	120	140	Storage
	Hose rupture, ESD fails	8,9	1800	2019	4,5	1800	337	13,4 [A)]	1800	2365	Storage
	Hose leakage	Safeti-NL		-	-	-	-	-	-	-	Storage
	Instantaneous release - ignited	-	-	2125,5	-	-	-	-	-	-	Design
Liquid hydrogen storage											
5000 L storage tank	Instantaneous release	-	-	-	-	-	-	-	-	337	Design
	10 minutes release	-	-	-	-	-	-	Safeti-NL		337	Storage
	10 mm leak	-	-	-	-	-	-	Safeti-NL		337	Storage

A) Backflow from the storage tank is not included as tank is filled from the top; only the release rate from the trailer side is included

E STARTING POINTS QRA COMMERCIAL FACILITIES

This Appendix includes detailed information on how the scenarios for the commercial facilities are modelled. Table 25 below presents the starting points for the QRA. Following this table are two tables which provide details on further development of the scenarios.

Table 25: Input parameters storage tanks commercial phase

Parameter	Value	Unit	Comment
Hazardous substance	Hydrogen	[-]	-
Volume	400	m3	-
Operational pressure	8	Barg	Assumed
Design pressure	10,6	Barg	8 barg operational pressure. Assumed PSV setting is 10% above. Inturn assumed design is 1,21 x PSV setting
Operational temperature	Bubble point	Degrees Celsius	-
Tank height	13	m	Not including support structure, assumed 1 meter high

Table 26: Input parameters liquid hydrogen truck commercial phase

Item	Value	Unit	Comment
Hazardous substance	Liquid hydrogen	[-]	
Modelstof for QRA	Hydrogen	[-]	
Containment System	Liquid trailer	[-]	
Number of compartments / tubes	1	[-]	
Size of compartments	50000	[L]	
Activity	Filling of storage tank	[-]	
Period	Day time only	[-]	
Trailer content	50	[m3]	
Hydrogen pressure	1	[barg]	Pressure is assumed little over ambient
Hydrogen temperature	Below bubble point	[°C]	Temperature varies slightly per scenario to ensure liquid release is modelled
Hydrogen density at given conditions	67,3	[kg/m3]	
Connection type	Hoses	[-]	
Diameter of connection	101,6	[mm]	
	4,0	[inch]	
Fueling rate	2243,3	[kg/hour]	Based on trailer volume, duration of fueling operation and density
Max number of hours of fueling	10950	[hours/year]	
Max throughput	25860250	[kg/year]	
Number of fueling operations	7300	[operations/year]	Based on 1000m3 consumption each day, supplied by 50m3 trucks
Duration of fueling operation	1,5	[hours/operation]	
	10950	[hours/year]	

Item	Value	Unit	Comment
Duration being present	2,0	[hours/operation]	Assumed 1/2 hour for all activities except actual fueling (activities such as positioning truck, connecting, etc.)
	14600	[hours/year]	
Largest connection on trailer	6	[inch]	
Max number of trailers being parked	N.A..	[-]	
Parking duration per filled trailer	N.A..	[hours/year]	
Parking duration of filled trailers	N.A..	[hours/year]	
Safety measures	Yes	[-]	
Likelihood of successful performance	0,9	[-]	
Response time	120	[s]	

Table 27: Scenario's commercial phase - part 1

System	Scenario	Initial failure frequency		Safety factor	Duration of activity	Calculated failure frequency [A]	Direct ignition probability
		[quantity]	**[unit]**	**[-]**	**[hours/year]**	**[/year]**	**[-]**
Liquid hydrogen trailer							
Presence	Instantaneous release	5,00E-07	per year	-	14600	8,33E-07	Transport - tank wagon
	Release from largest Connection	5,00E-07	per year	-	14600	8,33E-07	Transport - tank wagon
	Instantaneous release - external fire	4,00E-08	per hour	-	14600	6,67E-08	1
	Instantaneous release - external impact	9,60E-10	per hour	-	14600	1,60E-09	Transport - tank wagon
Unloading	Hose rupture, ESD works	4,00E-07	per hour	0,9	10950	3,94E-03	Transport - tank wagon
	Hose rupture, ESD fails	4,00E-07	per hour	0,1	10950	4,38E-04	Transport - tank wagon
	Hose leakage	4,00E-05	per hour	-	10950	4,38E-01	Transport - tank wagon
	Instantaneous release – ignited	5,80E-10	per hour	-	10950	6,35E-06	1
Liquid hydrogen storage							
400 m3 storage tank	Instantaneous release	5,00E-07	per year	-	8760	5,00E-07	Safeti-NL
	10 minutes release	5,00E-07	per year	-	8760	5,00E-07	Safeti-NL
	10 mm leak	1,00E-05	per year	-	8760	1,00E-05	Safeti-NL

A) Three offloading locations are foreseen, as such the frequency is divided over these locations equally (being one-third of the indicated frequency).

Table 28: Scenario's commercial phase - part 2

System	**Scenario**	**Release - trailer side**			**Release - storage side**			**Release - scenario**			
		Rate [kg/s]	**Duration [s]**	**Quantity [kg]**	**Rate [kg/s]**	**Duration [s]**	**Quantity [kg]**	**Rate [kg/s]**	**Duration [s]**	**Quantity [kg]**	**Pressure**
Liquid hydrogen trailer											
Presence	Instantaneous release	-	-	3365	-	-	-	-	-	-	Design
	Release from largest connection	Safeti-NL		3365	-	-	-	Safeti-NL			Storage
	Instantaneous release - external fire	-	-	3365	-	-	-	-	-	-	Design
	Instantaneous release - external impact	-	-	3365	-	-	-	-	-	-	Storage
Unloading	Hose rupture, ESD works	8,9	120	1065,5	21,5	120	2580	30,4	120	3645	Storage
	Hose rupture, ESD fails	8,9	1800	3365	21,5	1800	21146	30,4	1800	31913	Storage
	Hose leakage	Safeti-NL		-	-	-	-	-	-	-	Storage
	Instantaneous release – ignited	-	-	3365	-	-	-	-	-	-	Design
Liquid hydrogen storage											
400 m3 storage tank	Instantaneous release	-	-	-	-	-	-	-	-	21146	Design
	10 minutes release	-	-	-	-	-	-	Safeti-NL		21146	Storage
	10 mm leak	-	-	-	-	-	-	Safeti-NL		21146	Storage

F STARTING POINTS QRA TRAILER WITH GASEOUS HYDROGEN

This Appendix includes detailed information on how the scenarios for the commercial facilities are modelled. Table 29 presents the starting points for the QRA. Following this table are two tables which provide details on further development of the scenarios.

Table 29: Input parameters gaseous hydrogen truck initial and advanced demonstrator phase

Item	Value	Unit	Comment
Hazardous substance	Gaseous hydrogen	[-]	
Modelstof for QRA	Hydrogen	[-]	
Containment System	Tube trailer	[-]	
Number of compartments / tubes	9	[-]	
Size of compartments	2000	[L]	
Activity	Fueling airplanes	[-]	
Period	Day time only	[-]	
Trailer content	18	[m3]	
Hydrogen pressure	500	[barg]	
Hydrogen temperature	9,8	[°C]	
Hydrogen density at given conditions	31,1	[kg/m3]	
Connection type	N.A. As per methodology for calculating external safety risk, only filling of storage tanks from a truck or vice versa are to be considered, so not fueling of airplanes	[-]	
Diameter of connection		[mm]	
Fueling rate		[kg/hour]	
Max number of hours of fueling		[hours/year]	
Max throughput		[kg/year]	
Number of fueling operations		[operations/year]	
Duration of fueling operation		[hours/operation]	
Duration being present		[hours/operation]	
Largest connection on trailer	0,75	[inch]	
Max number of trailers being parked	1	[-]	
Parking duration per filled trailer	8760	[hours/year]	
Parking duration of filled trailers	8760	[hours/year]	

Safety measures	Yes	[-]	
Likelihood of successful performance	N.A. as no unloading to or loading from a storge tank operations are performed	[-]	
Response time		[s]	

Table 30: Scenario's gaseous hydrogen truck - part 1

System	Scenario	Initial failure frequency		Safety factor	Duration of activity	Calculated failure frequency	Direct ignition probability
		[quantity]	[unit]	[-]	[hours/year]	[/year]	[-]
Gaseous hydrogen trailer							
Trailer	Instantaneous release	5,00E-07	per year	-	8760	5,00E-07	Transport - tank wagon
	Release from largest connection	5,00E-07	per year	-	8760	5,00E-07	Transport - tank wagon
	Instantaneous release - external fire	4,00E-08	per hour	-	8760	4,00E-08	1
	Instantaneous release - external impact	9,60E-10	per hour	-	8760	9,60E-10	Transport - tank wagon

Table 31: Scenario's gaseous hydrogen truck - part 2

System	Scenario	Release - trailer side			Release - storage side			Release - scenario			
		Rate [kg/s]	Duration [s]	Quantity [kg]	Rate [kg/s]	Duration [s]	Quantity [kg]	Rate [kg/s]	Duration [s]	Quantity [kg]	Pressure
Gaseous hydrogen trailer											
Trailer	Instantaneous release	-	-	866	-	-	-	-	-	-	Design
	Release from largest connection	Safeti-NL		7,1	-	-	-	Safeti-NL			Storage
	Instantaneous release - external fire	-	-	866	-	-	-	-	-	-	Design
	Instantaneous release - external impact	-	-	866	-	-	-	-	-	-	Storage

G LEGISLATION WITH RESPECT TO ZONING PLANS

Disclaimer: Please note the text below involves English translation and interpretation of Dutch national legislation. Please always refer to the original Dutch legislation as can be found on the government website for legal matters. No rights may be derived from the following text.

A spatial plan is tested in the context of external safety in accordance with the national legal framework. This section provides the most relevant legislation and the assessment criteria against which a spatial plan is assessed in the context of external safety. In addition, the forthcoming changes under the Environment and Planning Act and their impact on this study are discussed.

Current legislation and regulations on external safety:

- External Safety Devices Decree, (Bevi). This Decree includes the risk standards for high-risk activities. The Regulation on External Safety of Facilities (Revi) lays down the associated calculation regulations, distance requirements, etc.
- Decree on external safety of transport routes (Bevt). This Decree contains the risk standards for the transport of hazardous substances by road, rail, and inland waterways.
- External Safety Pipelines Decree (Bevb). The risk standards for the transport of hazardous substances through pipelines have been laid down in the Bevb.
- Environmental Management Activities Decree. This decree includes safety distances and risk standards with respect to (limited) vulnerable objects. Safety distances have been established for, among other things, storage tanks with propane/propene, natural gas filling stations, and gas pressure measuring and regulating stations.
- Civil Airports Decree. In this decree, various restrictions in restricted areas are laid down for maintaining external safety and noise.
- Major Accident Risks Decree (Brzo). This decree is the Dutch implementation of the European Seveso Directive. This Decree regulates the requirements for companies that work with significant quantities of hazardous substances. The limits for significant are laid down in the appendices to the decree.

In the following subsections, the definitions for relevant risk factors, and the relevant terminology are presented.

G.1 External safety under the Environment and Planning Act: location-related risk and areas of attention

Please refer to **Error! Reference source not found.** for an explanation if the Environment and Planning Act in Dutch language.

With the entry into force of the Environment and Planning Act, the external safety policy will also change. The existing decrees will be incorporated in the Living Environment Quality Decree (Bkl), Living Environment Activities Decree (Bal) and the Living Environment Buildings Decree (Bbl). The most important change is that the quantitative societal risk policy will be canceled by the government; the qualitative societal risk policy and accountability for societal risk will continue to exist in an amended form. The duty of accountability as such will lapse, but it will remain mandatory to pay attention to aspects such as self-reliance, compatibility, risk communication and the assessment of risks for groups of people. Societal risk may still be calculated, and the Province of South Holland still prescribes the quantification of societal risk in specific cases. The individual risk will be maintained as a standard.

Instead of societal risk and associated accountability, focus areas are identified around sources of risk. These areas of concern may be a fire concern area and/or an explosion concern area and/or a toxic cloud concern area. Within these focus areas, attention must be paid to the relevant risks and associated effects.

For the fire and explosion focus area, the competent authority for spatial planning (the municipality) must, in principle, designate so-called regulation areas in the environmental plan. It is possible to deviate from this for vulnerable and moderately vulnerable buildings. For very vulnerable buildings, the municipality is legally obliged to designate a regulation area. Within a designated regulatory area, there is an obligation to take structural (or equivalent) measures for new construction. This obligation always applies if a regulatory area has been designated, both for slightly vulnerable, vulnerable, and very vulnerable buildings (see Annex VI, Bkl for the definitions). Under the Environment and Planning Act, the term 'buildings' replaces the old term 'objects'.

A regulatory area need not apply to the entire area of concern. A municipality can choose to designate only part of a focus area as a regulatory area (with the exception of locations where highly vulnerable buildings are present or permitted).

There will be no technical changes to the policy on airports under the Environment and Planning Act. The restricted areas laid down in airport decrees are maintained in the Bkl and the Bal.

H DESCRIPTION OF TULIPS AIRPORTS

This appendix provides background material of the considered airports of the Tulips project.

Amsterdam Airport Schiphol (AMS) was opened in 1916. The airport tolled 72 million passengers in 2019, making it the 3rd busiest airport in Europe. AMS was the busiest airport in terms of aircraft movements, nearly 500 000 in 2019. Schiphol is one of the main aviation hubs in the world, serving more than 300 destinations in Europe and to other continents. Rotterdam The Hague Airport (RTHA) is a part of the Royal Schiphol Group, and a smaller airport that often tests new technologies prior to rolling out at AMS. The airport is hosting the LH_2 demonstration in TULIPS, and the airport is described more in detail by van Dijk et al[15].

Oslo Gardermoen Airport (OSL) was opened in 1998 and was expanded in 2017. The airport has around 30 domestic routes and 140 international routes, mostly to European destinations and some direct flights to Asia, Africa or Northern America. The airport is the 23rd largest in Europe and registered in 2018 29 million passengers and 250 000 aircraft movements.

Larnaca International Airport (LCA) opened in 1975. As Cyprus is a tourist destination, the traffic is increasing. In 2023, LCA hosted more than 8 million passengers, and 52 000 aircraft movements. More than 50 airlines have services to and from LCA.

Turin Airport (TRN) was built in 1953. In 2022, the airport serviced more than 4 million passengers and 42 000 aircraft movements. TRN is also a site for the airframe company Leonardo, for ground and flight tests of prototype aircraft. This is of relevance when it comes to rolling out hydrogen infrastructure at airports.

The key numbers and information related to the airports are synthesized from Wikipedia (as of May-June 2024)[5].

[5] AMS: https://en.wikipedia.org/wiki/Amsterdam_Airport_Schiphol
OSL: https://no.wikipedia.org/wiki/Oslo_lufthavn_(Gardermoen)
LCA: https://en.wikipedia.org/wiki/Larnaca_International_Airport
TRN: https://en.wikipedia.org/wiki/Turin_Airport

I PROPOSED SYSTEM COMPARED TO NASA'S LAUNCH PAD AND VEHICLE'S LH2 FILLING STATIONS

This appendix aims at providing background material about existing LH_2 systems, which are important background information when deciding the refuelling system at airports described in Section 6.

The closest resembling system for LH_2 is the refuelling of the launcher in the space shuttle program. Reports from 30 years of experience estimated an average of 46 % boil-off through the value chain[49]. The performance is far better in other sectors. For example, it is shown that efforts to optimize LH_2-filling stations for vehicles reduced vehicle filling times from 1 hour to 3 minutes, and LH_2 losses from ~50 % to negligible liquefaction energy loss[87]. However, the storage tank size and system scale at the launch pad are more relevant for the airports, even though filling pattern and storage time is better represented by filling-stations. Based on the reported boil-off from different stages in the value chain, we propose a system concept aimed to mitigate some of the losses.

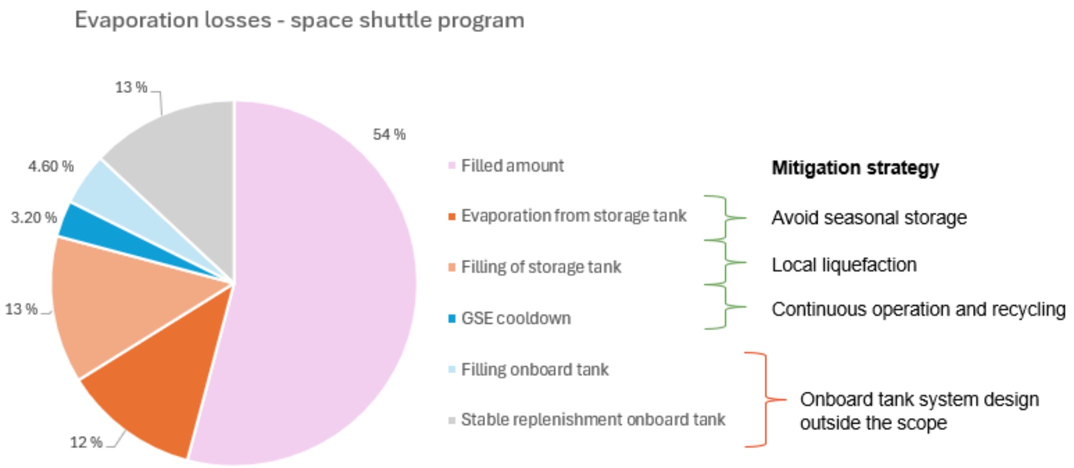

Figure 40: Sources of boil-off and mitigation strategy, adapted from Partridge et al[49]

Figure 40 shows the source of boil-off as reported by NASA[49]. Although the boil-off rate from the storage tank is quite low (see chapter 3.5), the seasonal character of the storage leads to an accumulated boil-off that is significant, 12 %. The airport will have consumption every day, and continuously at different levels for 16 hours. This difference in use pattern will directly reduce the expected share of boil-off loss from the stationary storage. Furthermore, seasonal variations in the airport's demand can be accomplished by varying the LH_2 production. There may be an energy- and economic potential within the optimization of adaptable production capacity, storage and boil-off utilization.

The filling of the NASA storage tank is done by supplying LH_2 to the tank from trailer trucks, that have transported the LH_2 from production sites far away. Thus, both the two transfer steps from production to transport tank, and from transport tank to storage tank will give opportunities for LH_2 evaporation. In addition, some LH_2 will evaporate during the transport phase. To avoid these losses (13 %), the hydrogen liquefaction can be situated at the airport or an airport forecourt (linked to the airport with an LH_2 pipeline, as described in 3.6.2).

Cooldown of ground support equipment (pipelines to the launch pad) contribute with less evaporation than the above factors. However, given the few times a year the launcher is filled, the amount per filing may be quite high. Cooldown will inevitably lead to evaporation, and it can also be a time-consuming process to reach a steady state temperature situation in the system. To mitigate these challenges, a system that can be kept cold both overnight and intra-day is proposed. This reduces the number of needed cooldowns to potential maintenance operations and will also minimize cyclic thermal stress. To keep the system cold, there may be a need for continuous recycling of LH_2 through the system.

There are also boil-off losses related to filling of the onboard tank and replenishment. These factors are highly sensitive to the onboard tank system design. Both the initial state of the tank (filling level, temperature and pressure), and the thermal ingress into the tank system will influence the expected boil-off. As aircraft will operate with fuel reserves, it is possible to assume that the onboard tank will be at all times filled with some residual LH_2 that keeps the tank cold. An initially cold tank will have a lower boil-off from filling. Improvement of tank design is outside the scope if this work, but as a starting point, we use information from open literature (see 3.7).

In summary, Section 6 analyses a system concept that is developed with the purpose of

- Minimizing evaporation from the storage tank by having nearly continuous use of LH_2 and avoiding seasonal storage.
- Avoiding the need precooling, by requiring all aircraft to have residual LH_2 that keeps aircraft cold and circulate LH_2 through the ground systems, except during maintenance.
- Defining a system with local liquefaction of hydrogen supplied through the European hydrogen backbone (relevant for AMS). Another alternative for AMS is import through LH_2 pipelines from i.e. an importing Port.

J PIPELINE TRANSPORT FROM LIQUEFACTION PLANT TO LH2 FUEL FARM

This Appendix provides details regarding the model of the LH2 pump used in Section 6.1 and more details regarding the uncertainty and sensitivity analysis conducted in Section 6.5.

J.1 Model of the LH2 pump

The pump was simulated as the 2nd order Pump in TIL's library. The capacity of the pump is specified through the parameters

- V_0^{pump} $[m^3/s]$: the volume flow when the pressure increase is zero.
- dp_0^{pump} [bar]: the pressure increase at zero volume flow
- Efficiency η^{pump} [-]: efficiency of best operating point.

Figure 41 shows the physical meaning of these parameters in the pump chart, for three different values of V_0^{pump}. In the presented system, a transport rate of 330 tons/day is specified, which corresponds to approximately 0.054 m^3/s of LH_2, which is indicated by the red dashed line.

The pressure drop in the 6'' pipe is higher than the pressure drop in the 8'' pipe, calling for a more powerful pump. Therefore, we used $dp_0^{pump} = 1.35$ bar for the 6'' pipe and $dp_0^{pump} = 0.6$ bar for the 8'' pipe. The remaining parameters V_0^{pump} and efficiency η^{pump} are considered as uncertain parameters and are given in Table 9.

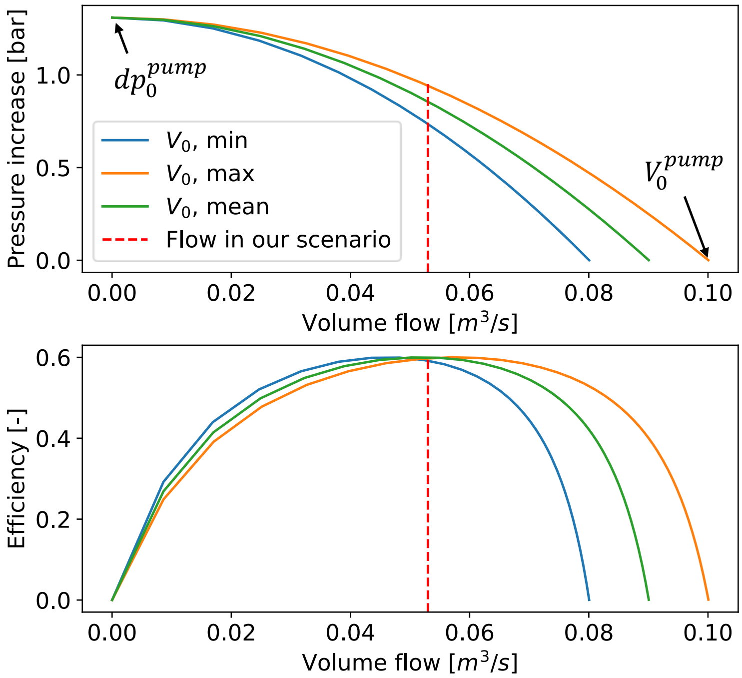

Figure 41: Pump curves with $dp_0^{pump} = 1.35 bar$, efficiency of 60%

and values of V_0^{pump} corresponding to 0.08 m^3/s, 0.09 m^3/s and 0.1 m^3/s (annotated in the chart), respectively. The flowrate corresponding to 330 tpd LH_2 are shown as the red dashed line.

J.2 Uncertainty and sensitivity analysis for the 4 km pipeline

This subsection provides additional results for the uncertainty and sensitivity analysis for the 4 km pipeline in Section 6.5.

Table 32 provides the summary statistics for the uncertainty analysis in Section 6.5.1, i.e. the statistics of the histograms in Figure 15.

Table 32: Summary statistics of uncertainty analysis for the 6'' pipe (8'' pipe).

Uncertain variable	Low bound	High bound	Mean	Standard deviation
$T_{SC}^{fuelfarm}$ [K]	0.40 (0.44)	0.68 (0.73)	0.56 (0.61)	0.05 (0.06)
Q_{ave}^{pipe} [W/m]	1.75 (2.16)	3.62 (4.58)	2.47 (3.07)	0.44 (0.56)
Q_{total}^{pipe} [kW]	7.01 (8.63)	14.47 (18.33)	9.87 (12.27)	1.74 (2.23)
P_{loss}^{pump} [kW]	1.75 (0.81)	4.98 (2.29)	3.10 (1.43)	0.77 (0.36)
P_{shaft}^{pump} [kW]	5.66 (2.61)	9.94 (4.58)	7.60 (3.51)	0.90 (0.42)

The ST indices in Figure 16 shows that the uncertainty in the vacuum layer thickness for the 8'' pipeline is to a large degree causing the uncertainty in the average heat flux through the pipeline. This can also be seen in Figure 42, where the numbers for the average heat ingress Q_{ave}^{pipe} are provided for various ambient temperatures and insulation thicknesses of the 8'' pipe.

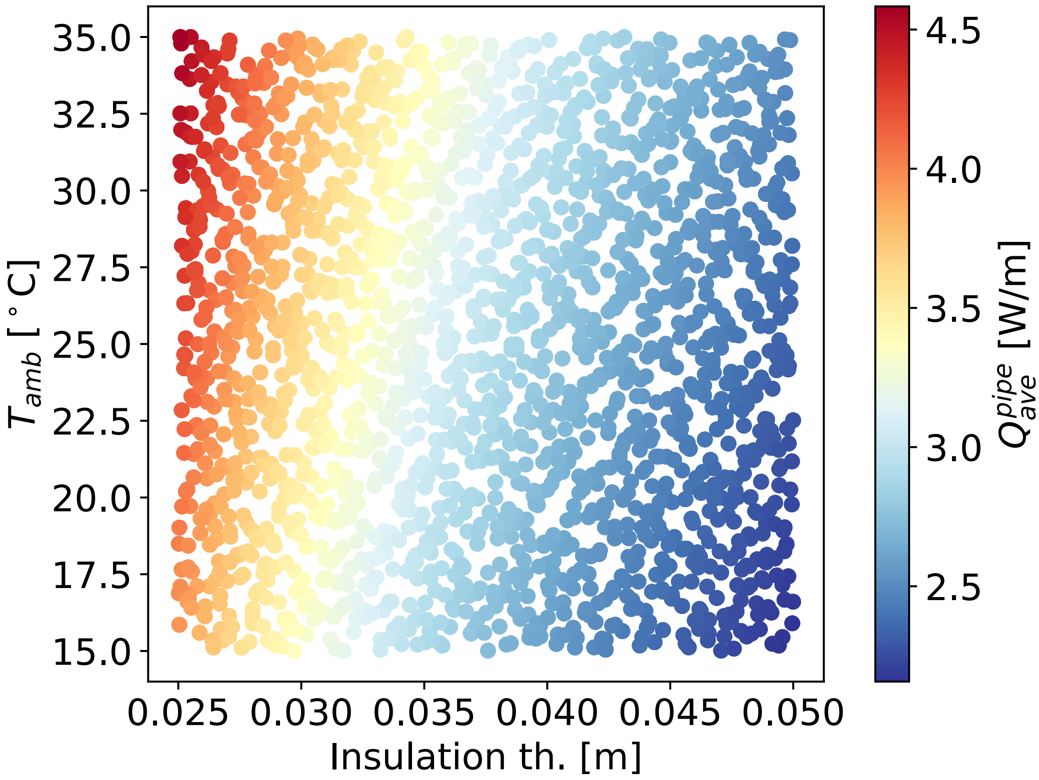

Figure 42: Average heat ingress through the 8'' pipe as a function of insulation (vacuum) thickness and ambient temperature.

K LH2 DELIVERY SYSTEM TO THE AIRCRAFT AND REFUELLING

This appendix describes in more detail how we modelled and simulated the refuelling system in Section 6.6, as well as more explanations of the results. We also discuss the validity of the vapor-liquid equilibrium assumption in the tanks.

K.1 Description of cases

We study only normal operation of the fuel farm. We consider two different timescales, which gives us two different cases, namely:

Case A – Subcooling control - timescale of hours/days: Study the supply system at the airport in the period day1-night-day2, i.e. 40 hours of operation. This window of operation allows the analysis of how the system must be controlled to maintain the subcooled state of LH_2 at all times. The pressure build-up and distribution between airplane are not of interest, allowing us to model the simplified system in Figure 43:

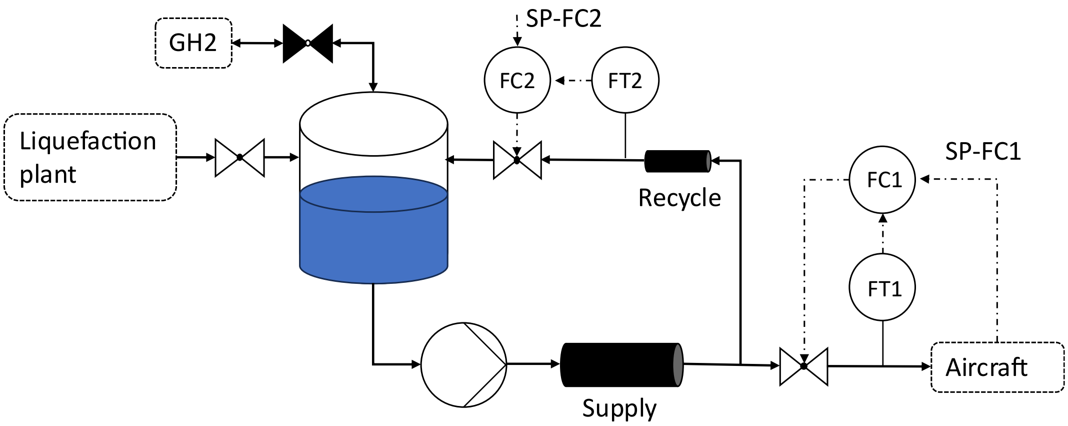

Figure 43: Modelled system for case A.

Quantities of interest are:

b. Fuel farm's storage tank, specifically its pressure variations and filling level.
c. Temperature development in the pipelines.
d. Required recycle flow to maintain subcooling overnight.

Case B – Refuelling control - Time scale of seconds/minutes: We study in detail the filling of a single aircraft and a subsequent filling of two aircrafts in parallel. This is done for i) the case of "first flight in the morning", i.e. at 06:00, where the pipes are relatively warm and we have maximum boil-off, and ii) "last flight in the evening", i.e. at 22:00, where the pipes are cold. Slow variations in the fuel farm's storage tank and recycle line are not relevant in this short time-scale, facilitating using the simplified model depicted in Figure 44.

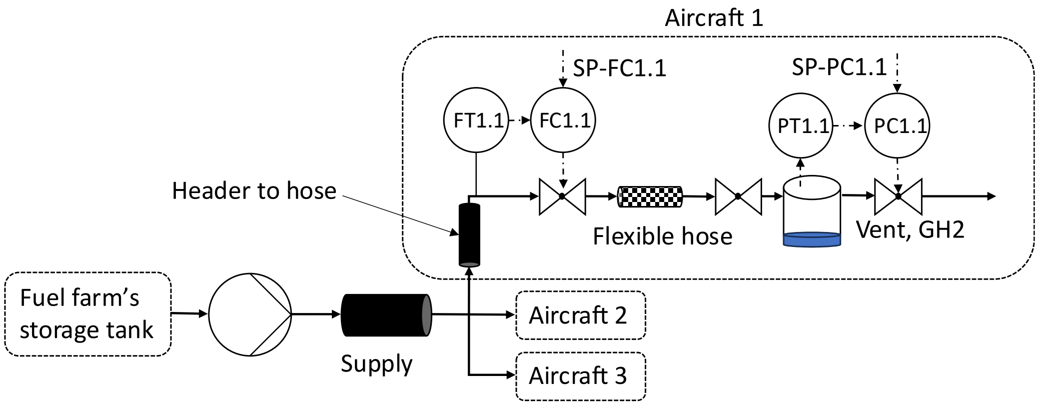

Figure 44: Modelled system for case B.

Quantities of interest are:

e. Pressure build-up in the aircraft's tank and required venting.
f. Amount of BOG (GH_2) generated.
g. Performance of the supply pump.
h. For the case of filling the aircraft at 22:00, we also estimate how much BOG is generated if the plane is left over night (i.e. it will leave the airport at 06:00).

In Section 6.6.2 we specify parameters of the equipment used in our simulations. The next subsection contains the case of 40 hours operation of the fuel farm, while the subsequent subsection contains the case of filling airplanes (time-scale of seconds/minutes). We discuss benefits and limitations of the results in Section 6.6.3.1.

K.2 Results case A: Subcooling control in the fuelling system over two days

This Section studies how operating the refuelling system in different manners over a longer time period (40 h) affects i) the pressure in the fuel farm's storage tank, and ii) temperatures in the pipelines. We consider:

- A constant supply of LH_2 to the fuel farm's storage tank of 3.8 kg/s (330 tpd), with a temperature corresponding to a sub-cooling of 0.46 K at 1.1 bara. The temperature of the received LH_2 from the liquefaction is a conservative value (i.e., "thin" insulation and inefficient pump) from the results in Section 6.5.1.
- Filling of multiple aircrafts throughout the defined daytime period (16 h). Each aircraft is filled with 6200 kg LH_2, and the total amount of LH_2 filled for all airplanes are 360 tpd (i.e, a busy day). Since the inflow to the fuel farm's storage tank is 330 tpd, its level will decrease in a 24 h period. The filling rate to each airplane is 20 kg/s, which is discussed in Appendix K.3.

The control variable, in this case, is the recycle flowrate. The recycle flowrate is operated in the following manner:

- Daytime, airplanes being filled: set-point for the recycle is 0.2 kg/s.
- Daytime, airplanes *not* being filled: set-point for recycle is 3 kg/s.

Important considerations are how should we operate the recycle during the night to:

- Keep the pipelines cold (to prevent formation of GH2) for the next day
- Filling of the first airplane after a night

We consider two different values for the recycle flowrate through the night, either a low flowrate of 2.8 kg/s or a higher flowrate of 3.8 kg/s. Figure 45 shows the mass flows effect on the fuel farm's storage liquid level and tank pressure.

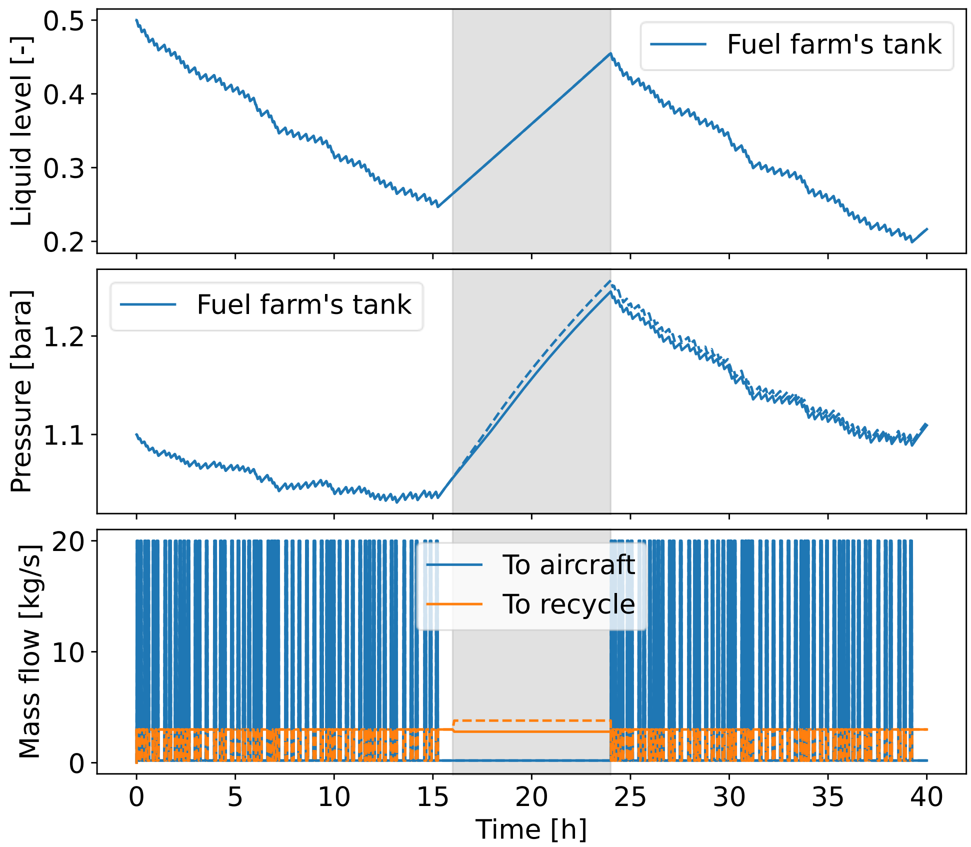

Figure 45: Mass flows to airplanes and recycle

and its effects on the fuel farm's storage tank. Grey area marks the nighttime (no filling of airplanes), solid lines are for a recycle flowrate of 2,8 kg/s through the night while dashed lines mark recycle flowrates of 3,8 kg/s through the night.

During the night, when no aircraft are filled, increasing the flowrate through the recycle line has the following effects: i) the heat input from the pump into the liquid increases, which increases the pressure in the fuel farm's storage tank, as shown in Figure 45. Furthermore, effect ii) is that the power usage by the pump increases. However, effect iii) is that the main 18'' pipe gets colder due to the increased flow, and therefore also the recycle flow gets colder, which is shown in Figure 46. Effects i) and ii) are undesired while iii) is desired.

Note that the subcooling temperature in the pipes are low at the start of day 1, shown in Figure 46 as a separate “zoomed in” plot. Specifically, the subcooling temperature at the outlet of the recycle pipe is low when the flowrate is low. There is therefore a lower limit on the recycle flow through the night to prevent two-phase formation in the pipeline.

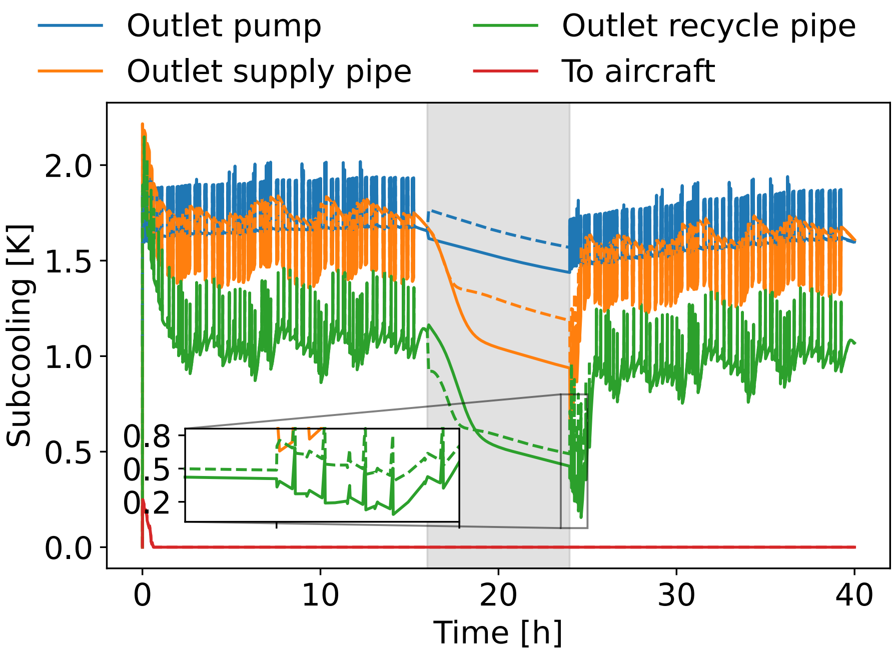

Figure 46: Degree of subcooling at various points of the refuelling system.

Grey area marks the nighttime (no filling of airplanes), solid lines are for a recycle flowrate of 2,8 kg/s through the night while dashed lines mark recycle flowrates of 3,8 kg/s through the night.

The steep changes in Figure 46 when the night start (at 16 h) is due to the change in recycle flow, from 3 kg/s for both cases to either 2.8 kg/s or 3.8 kg/s. The spiky behaviour during daytime is due to large difference in LH_2 flow through the main pipeline when planes are filled (20 kg/s) and when we only recycle (3 kg/s).

K.3 Results case B: Aircraft refuelling control

Since we consider a time-scale in seconds and minutes in this case, we assume that the suction conditions to the LH_2 distribution pump is constant (1.2 bara and 0.05K subcooling) in the time-period, which is reasonable. We simplify the system further by neglecting the recycle line. The effect of this simplification is that the LH_2 flow through the pump is slightly underestimated. However, as we saw in Appendix K.2, the required flowrate through the recycle line is significantly smaller than the flowrate used to fill the airplanes. Therefore, neglecting the recycle line in this case is reasonable. The considered system is visualized in Figure 44, and dimensions of the indicated pipes are given in Table 11.

The aircraft's tank has an initial level of 5% and an initial pressure of 1.2 bara. If the pressure increases to more than 1.7 bara, it is vented (i.e., maximum allowed pressure).

Each plane is filled with 6200 kg LH_2, and the filling rate is set to 20 kg/s. The ramp-up rate from 0 kg/s to 20 kg/s is set to 10 s. First, aircraft 1 is filled, and then aircrafts 2 and 3 are filled in parallel. For a detailed analysis of filling rates and turn-around times for refuelling, see Mangold[62].

From Figure 45, we observe that the pressure in the fuel farm's storage tank varies slowly over a period of 40 hours. The behaviour in Figure 45 is, however, dependent of our specified initial conditions at $t = 0$. In this Section, we assume that the effect of the aforementioned initial conditions are negligible after 24 h of operating the refuelling system. Therefore, we consider two different cases (or initial conditions) in this Section:

3. "Start of day", which corresponds to the first flight at 06:00 in the morning. Initial conditions for the temperatures in the pipelines and suction pressure to the pump are taken from $t = 24$ h in Figure 45 and Figure 46 for
   a. Recycle rate of 2.8 kg/s through the night
   b. Recycle rate of 3.8 kg/s through the night.
4. "End of day", which corresponds to the last flight at 22:00 in the evening. Initial conditions for the temperatures in the pipelines and suction pressure to the pump are taken from $t = 40$ h in Figure 45 and Figure 46. In this case, the pipes are colder and suction pressure to the pump is lower than in the previous case. Furthermore, the effect of recycling during nighttime has vanished after 16h of operation.

The conditions in the three fuel tanks are shown in Figure 47; since aircraft 2 and 3 are filled in parallel, their trajectories are overlapping.

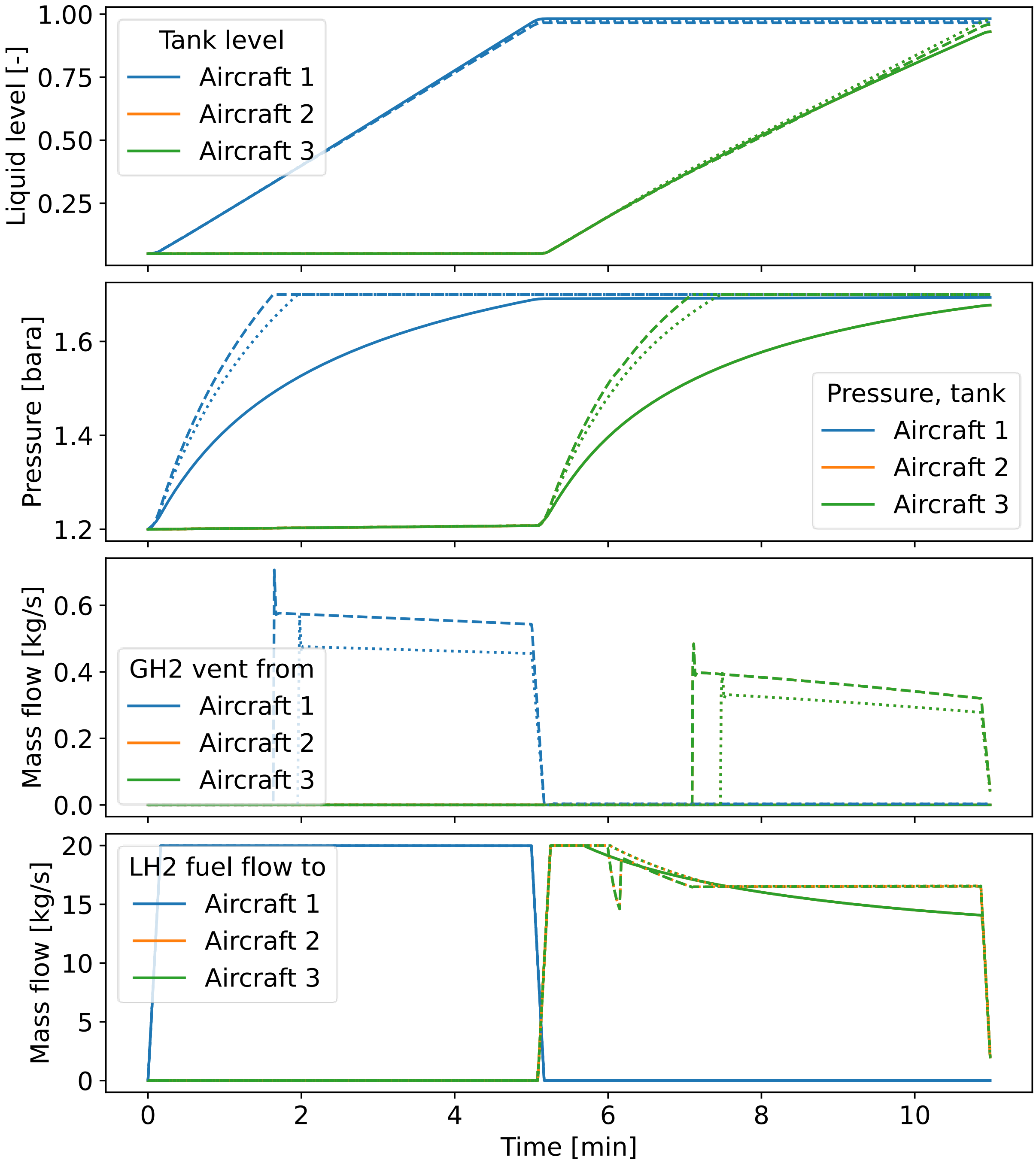

Figure 47: Development in the three aircraft tanks

for i) the filling at 06:00 with 2.8 kg/s of recycle flow through the night (dashed lines), ii) the filling at 06:00 with 3.8 kg/s of recycle flow through the night (dotted lines), and iii) the filling at 22:00 (solid lines). Aircraft 2 and 3 are filled in parallel, and their lines are therefore overlapping.

For each aircraft, Figure 47 shows that the pressure in the aircraft tank increases as the fuelling progresses. When we start with "warm" pipes (i.e., both fillings at 06:00 – dashed and dotted lines), the pressure reaches the maximum operating pressure of 1.7 bara and GH_2 is vented from the tank to a separate GH_2 system (e.g. the suction to a compressor – the vented GH2 may be compressed and utilized for ground support equipment or returned to the central storage in a gas return line). If the recycle rate is high during the night (dotted lines – 3.8 kg/s recycle rate), the pipes are colder at 06:00 and less GH_2 is vented compared to a lower recycle rate during night (dashed lines – 2.8 kg/s recycle rate).

When we start with cold pipes (plane filled at 22:00, solid lines), the pressure in the tanks reaches 1.68 barA at the end of the filling (i.e., slightly below the maximum operating pressure of 1.7 barA) and venting does not occur. However, if the plane is left overnight, BOG (GH_2) will be generated due to heat ingress in the tank. We investigate and summarize BOG (GH_2) generation during filling and overnight in Section 6.6.4.

The bottom pane in Figure 47 shows that the fuel flowrate of LH_2 drops below the desired flowrate of 20 kg/s when filling aircrafts 2 and 3 in parallel. This is due to inadequate sizing of the pump; the pump was sized for a flowrate of 40 kg/s with a pressure in the receiving aircraft tank of 1.2 bara. An appropriate sizing of the pump would consider the maximum operating pressure in the tank, 1.7 bara for the flowrate of 40 kg/s.

The drawback of a too small pump (our case) is that refuelling of two airplanes in parallel takes slightly more time than desired. The benefit is that less heat is transferred to the fluid due to inefficiencies in the pump. The pump chart is shown in Figure 48, where power readings for various flowrates are available.

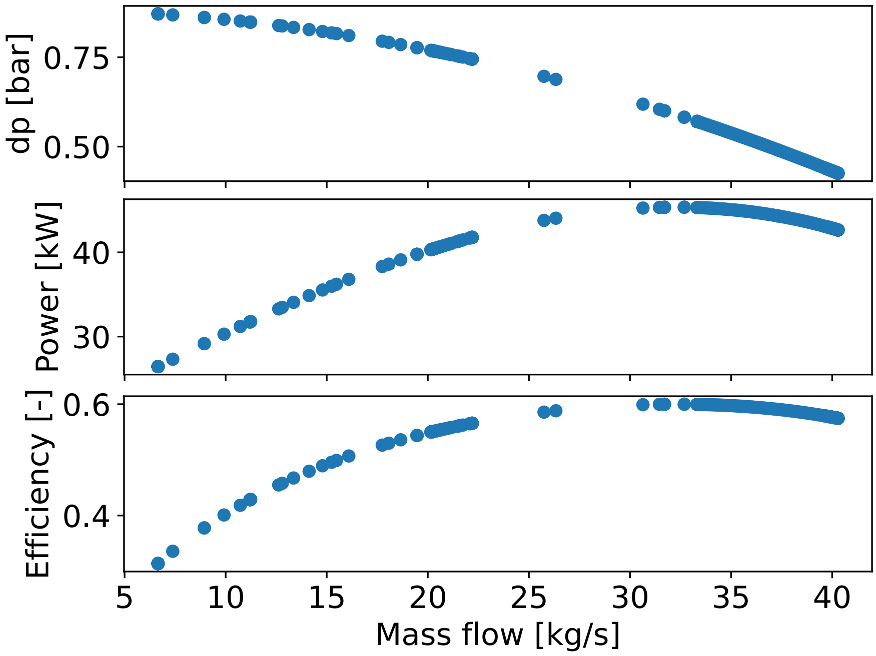

Figure 48: Pump chart showing the differential pressure increase (dp), power and efficiency of the pump for various mass flows.

Finally, the bottom pane in Figure 47 shows a dip for the mass flow rate to aircraft 2 and 3 for the case of a low nightly recirculation rate (2.8 kg/s) at around 6 minutes. This dip in the mass flow rate is due to vapor formation in the large supply pipe. This is due to that filling aircraft in parallel requires a high mass flowrate through the pump, and the pump chart in Figure 48 shows that the pressure increase over the pump *decreases* when mass flow increases. Since the boiling point of LH_2 depends on temperature *and* pressure, the sudden decrease in pressure causes some vapor formation in the pipeline. when aircraft are filled in parallel. Figure 49 shows the absolute temperature, subcooling temperature and liquid mass fraction in the main supply pipe for the cases when refuelling in the morning (warm pipes). Actually, Figure 49 shows vapor formation in the pipe before 6 minutes for the case of a low nightly recirculation rate, while the mass flow rate to the aircraft dips at approximately 6 minutes (see Figure 47); this is explained by that the control valve opens very fast and saturates at around 6 minutes (control valve plot is not shown for brevity).

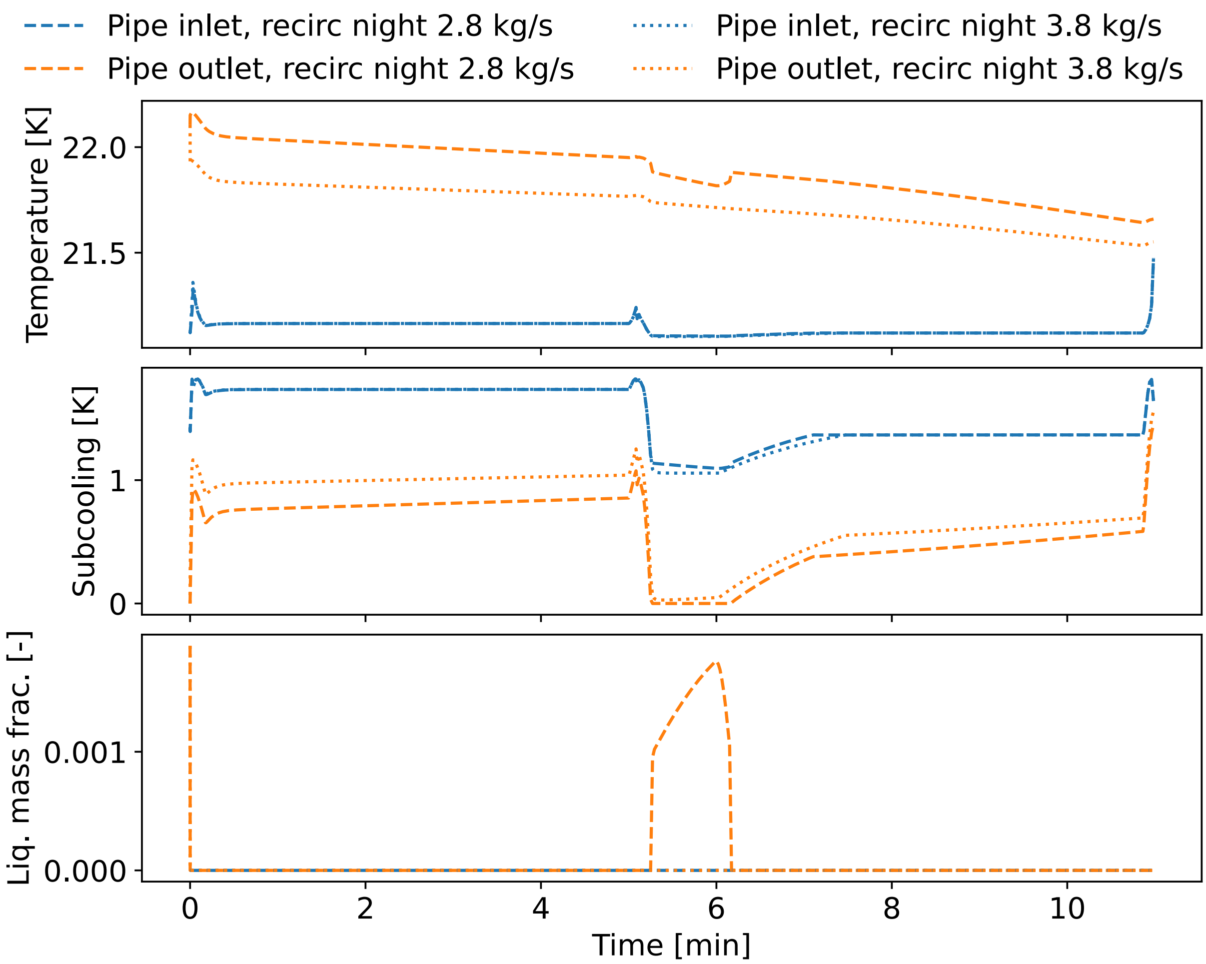

Figure 49: Vapor formation in supply pipe when filling aircraft in parallel.

K.4 Assumption of thermodynamic vapor-liquid equilibrium and its validity

We assume thermodynamic vapor-liquid equilibrium (VLE) in all storage tanks, i.e. the airport's fuel farm storage tank and all aircraft tanks. For the aircraft tanks, we assume the LH_2 is injected from the top of the tank, i.e. it is sprayed and has a large contact time with the vapor phase. Therefore, VLE is likely a reasonably valid assumption for the aircraft tanks. The validity of the VLE assumption for the fuel farm's storage tank is more questionable since i) the supplied LH_2 from the liquefaction plant *is* sub-cooled, see Section 6.5, and ii) even if there is VLE at the liquid surface, the pumped LH_2 is extracted from the bottom of the tank. The pressure of the liquid column produces a certain degree of subcooling; a 10 m LH_2 column gives approximately 0,17 K subcooling. Potential impacts of this assumption in our results are discussed in Section 6.6.3.1.

L HAZID TABLES

Table 33 HAZID table for LH_2 refuelling.

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
R.1	Overpressure due to LH2 vaporization in the aircraft tank	During the refuelling of the aircraft with LH2, the equipment temperature exceeds the normal/nominal operating temperature (the systems are "too warm"). The temperature difference with the received LH2 (cold) leads to significant evaporation and volume expansion with subsequent pressure increase in the aircraft tank and connected equipment. This situation can escalate to a dangerous state if the "vent/boil-off gas" system is not working correctly or if this is not designed for handling the amount of vapor/gas generated in due time. If LHe (liquid Helium) is used for pre-cooling of the equipment, the	The equipment on the aircraft is "too warm" to receive LH2. The pre-cooling phase was carried out not effectively or the systems did not have enough time to cool down to set the temperature. The temperature instrumentation are not functioning, or malfunctioning, and the system reads the wrong temperature. Subsequently, the pre-cooling is carried out correctly but to the	Pressure increases in the aircraft tank potentially escalating to a dangerous state. If design pressure is exceeded, the tank integrity can fail catastrophically. 2-phase release of the whole hydrogen inventory. H2 is released generating a *large* flammable cloud that can result in a fire and/or explosion, if ignited. Fragments of the tank can be shoot at distance.	The boil-off gas handling system could be designed accounting for redundancy to reduce the pressure/extract gas (not only relying on continuous mass flow). Precooling procedures and injection system from the top of the receiving tank designed to avoid excessive overpressure or LH_2 vaporization.

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
		system integrity will be *sensitive* to delays (see B.2).	wrong set temperature. The vent/boil-off gas system is not working correctly, or it is not designed for handling the amount of vapor/gas.	The event can potentially impact the airport terminal, other aircrafts, storage equipment, and people directly (public, personnel, and crews).	Mechanical extraction of H_2 gas (GH_2) from the tank to airport facilities should be considered. The use of the GH_2 at the airport shall be considered (reliquefication unit, alternative end use – such as power, fuel for GSE, etc).
R.2	Overpressure due to heat ingress in the aircraft tank and connections	Due to excessive heat ingress in not fully insulated sections (e.g., connections), the vaporization of LH2 increases and the BOG build-up, leading to increased pressure and tank damage.	Complete or partial loss of insulation of the refuelling equipment (tank, hose, movable connections) during refuelling.	The LH_2 in the tank and connections starts vaporizing if not maintained at sufficiently low temperature. The BOG builds up, the pressure increases and, finally, damage of the tank and/or connections and release.	Inherent safe design of aircraft tank and connection able to withstand increased pressure. Appropriate insulation and procedures to monitor insulation state conditions. Refuelling time calibrated on inherent

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
				GH2 is released generating a *medium-size* flammable cloud that can result in a fire and/or explosion, if ignited. The event can potentially impact the airport terminal, other aircrafts, and people directly. Likely impact on people (personnel, crews and public) also for smaller leaks due to the vicinity between the gate and the transfer terminals.	holding time of tank and connections. Pressure relief mechanisms dimensioned to handle a loss-of-vacuum situation.
R.3	Overpressure due to exceeded holding time of the aircraft tank	The aircraft is refuelling but the process is delayed due to external factors. The LH2 in the aircraft tank starts vaporizing and the pressure starts increasing.	Delays (pre-flight checks, variable weather conditions, de-icing process, busy runway). Malfunctioning of the refuelling system.	The LH2 on board in the tank starts vaporizing if not cooled down. The BOG builds up, potentially leading to damage of the tank due to overpressure and, finally, release, if the gas is not properly handled.	Procedures for emergency stop of refuelling and stop at safe conditions in stressful situations must be in place.

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
			Impossibility of completing the refuelling by the refuelling truck. Fire and/or emergency evacuation at the airport terminal.	The connections at the tank fail and a *medium size* flammable cloud of GH2 develops. This can ignite and result in a fire and/or explosion. The event can potentially impact the airport terminal, other aircrafts, and people directly. Likely impact on people (personnel, crews and public) also for smaller leaks due to the vicinity between the gate and the transfer terminals.	

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
R.4	Release of cold, flammable substance (LH_2) from the tanks or the hose connection points at the gate	Overfilling of the LH_2 receiving tank on the aircraft, rupture of the tank or disconnection of piping/valves.	Level sensors are not working as intended or are not calibrated accordingly. Refuelling procedure is not clear, not understood or the wrong refuelling procedure is used. Mechanical failure of the connection points or other equipment.	Confined or unconfined (depending on basin presence) LH_2 pool at gate. Flammable cloud from evaporating hydrogen from the pool, leading to fire and explosion, if ignited. The event can potentially impact the airport terminal, other aircrafts, and people directly. Likely impact on people (personnel, crews and public) also for smaller leaks due to the vicinity between the gate and the transfer terminals.	Dedicated procedure and personnel training for LH_2 refuelling. Ignition source control shall be implemented during transfer operations. ESD-link to stop refuelling and isolate the systems if leak is detected. PPE to avoid cold-bits and cryogenic burns for personnel handling the refuelling process.

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
				Cryogenic hazard for personnel and crew handling the refuelling hose.	
R.5	Release of cold, flammable substance (LH_2) from the hose connection point at the gate.	The refuelling system (hose or arm) is not properly coupled or decoupled from the aircraft and a LH_2 leaks occur.	Improper connection coupling/decoupling (human error/wrong procedures). Damaged connection.	Confined or unconfined (depending on basin presence) LH_2 pool at gate. Flammable cloud from evaporating hydrogen from the pool, leading to fire and explosion, if ignited. The event can potentially impact the airport terminal, other aircrafts, and people directly. Likely impact on people (personnel, crews and public) also for smaller leaks due to the vicinity between the gate and the transfer terminals.	Procedures for handling of hose/arm at gate shall be in place. A containment system (basin) at gate can avoid unconfined pool leading to larger impact areas. Ignition source control shall be implemented during transfer operations. ESD-link to stop refuelling and isolate the systems if leak is detected.

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
				Cryogenic hazard for personnel and crew handling the refuelling hose.	PPE to avoid cold-bits and cryogenic burns for personnel handling the refuelling process.
R.6	Release of cold, flammable substance (LH_2) from the hose connection point at the gate	The hose or arm used for refuelling breaks.	Dropped objects and/or impact. Mechanical integrity failure.	Confined or unconfined (depending on basin presence) LH_2 pool at gate. Flammable cloud from evaporating hydrogen from the pool, leading to fire and explosion, if ignited. The event can potentially impact the airport terminal, other aircrafts, and people directly. Likely impact on people (personnel, crews and public) also for smaller leaks due to the vicinity between the gate and the transfer terminals.	Regular (periodical) hose integrity inspection. Avoid lifting over LH_2 hose. Procedures for handling of hose/arm at gate shall be in place. A containment system (basin) at gate can avoid unconfined pool leading to larger impact areas. Ignition source control shall be implemented during transfer operations.

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
				Cryogenic hazard for personnel and crew handling the refuelling hose. Potential bigger impact than R.5 because in this case a full-bore rupture is envisioned.	ESD-link to stop refuelling and isolate the systems if leak is detected. PPE to avoid cold-bits and cryogenic burns for personnel handling the refuelling process.
R.7	Release of cold, flammable substance from the connection point with the supply truck at the gate	When loading with trucks, the amount of LH_2 supplied by one truck is not sufficient for complete filling of the aircraft tank. More than one connection/disconnection operation is needed to complete the refuelling. The disconnection and re-connection are not carried out properly, leading to a LH_2 release or air ingress in the LH_2 tank on the aircraft.	The volume of LH_2 on the truck is not enough to completely refuel the aircraft and the disconnection is not carried out properly (human error) or the technical components fail due to mechanical integrity loss, fatigue, etc.	Confined or unconfined (depending on basin presence) LH_2 pool at gate. Flammable cloud from evaporating hydrogen from the pool, leading to fire and explosion, if ignited. The event can potentially impact the airport terminal, other aircrafts, and people directly. Likely impact on people (personnel, crews	Procedures for refuelling per airplane size, initial and terminal fill-level shall be in place. Standardization of aircraft tank size and refuelling truck tank size. Procedures for emergency stop of refuelling and stop at safe conditions must be in place.

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
				and public) also for smaller leaks due to the vicinity between the gate and the transfer terminals. Cryogenic hazard for personnel and crew handling the refuelling hose. Potential air ingress and/or freeze in the aircraft tank leading to explosive atmosphere in the onboard tank (and potentially fire and/or explosion of it).	
R.8	Release of cold, flammable substance (LH_2) on board of the aircraft	LH_2 leakage during the refuelling through connections (valves, flanges, etc) installed on the aircraft. The leak is not purged through the boil-off/venting system but accumulate in the aircraft engine room.	Mechanical failure, coupling errors (during inspection, maintenance). Overpressure or increased pressure during precedent	LH_2 pool on the aircraft. Flammable cloud from evaporating hydrogen from the pool, leading to fire and explosion, if ignited, on board of the aircraft.	Leak test after inspection and maintenance of the aircraft tank. Periodic inspection of gaskets and seals. Pressure monitoring during refuelling.

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
			refuelling operations that has led to lose connections.	The event can potentially impact the airport terminal, other aircrafts, and people directly. Likely impact on people (personnel, crews and public) also for smaller leaks due to the vicinity between the gate and the transfer terminals.	Monitoring of frosting and condensation (from cold LH_2) on the equipment. Airborne design shall minimize the number of couplings.
R.9	LH_2 release from damaged LH_2 swap-tank on the aircraft.	The LH_2 swap-tank is damaged, leading to loss of vacuum or direct release of LH_2 on the aircraft. If the damage is severe, LH_2 can potentially start boiling within the tank and result in rapid expansion leading to physical failure of the tank.	Mechanical failure, impact. Ageing and thermal stress on the swapping tank.	LH_2 pool on the aircraft. Since the tank can fail catastrophically, the pool can extend to the gate area as well. Flammable cloud from evaporating hydrogen from the pool, leading to fire and explosion, if ignited, on board of the aircraft. Overpressure load from the fast physical	Ensure that swap tank isolation procedures are in place. Use impact sensor (g-sensors/accelerometer) to detect that an impact above the tolerance limit has occurred. Potentially include leak tests of swap tank and procedures for emptying before connection/disconnection.

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
				expansion of evaporating LH_2 in large amounts. Flying tank fragments impacting structures, people, other aircrafts. The event can potentially impact the airport terminal, other aircrafts, storage equipment, and people directly (public, personnel and crews). Cryogenic hazard for personnel and crew handling the refuelling hose.	Test of mechanical integrity of swapping tank. H2-flames detectors and thermal cameras. If the connection/disconnection is performed by operators, PPE against cold-bites and cryogenic burns must be used.
R.10	Release due to error in disconnection of LH_2 swap- tank.	The connection/disconnection of the swapping tank is not carried out properly or the equipment is not working as intended and a LH_2 leak	Error in connection/disconnection. Loss of material integrity of connection/disconnection equipment.	LH_2 pool on the aircraft. Flammable cloud from evaporating hydrogen from the pool, leading to fire and explosion, if	Ensure that swap tank isolation procedures are in place. Potentially include leak tests of the connection

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
		starts from the connection point.		ignited, on board of the aircraft. The event can potentially impact the airport terminal, other aircrafts, storage equipment, and people directly (public, personnel and crews). Cryogenic hazard for personnel and crew handling the refuelling hose.	with the swap tank and procedures for emptying before connection/disconnection. ESD-link to isolate the tank if the connection is leaking. H_2-flames detectors and thermal cameras. If the connection/disconnection is performed by operators, PPE against cold-bites and cryogenic burns must be used.

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
R.11	Fire and/or explosion from ignited leaks at the gate.	Undetected H_2 leak is ignited by ignition sources at the gate.	Static electricity from aircraft, passenger, trucks, buses, baggage belt, ground power unit, etc. Ignition sources at the airport.	Severe consequences for people (public, personnel, crews) as well as assets at the gate/airport terminal. Potential escalation to other areas.	Passenger/ground handling crew procedures. Establish no-go zones when refuelling. Ignition control when refuelling. Fire extinguishing procedures needs to be in place.
R.12	Uncoordinated simultaneous operations leading to a dangerous situation	While the aircraft is refuelling, the equipment handling LH_2 is hit and damaged leading to release of hydrogen.	Vehicles (bus, GHE, baggage belt, LH2 truck) on collision course towards LH_2 refuelling equipment, dropped objects.	Confined or unconfined (depending on basin presence) LH_2 pool at gate. Flammable cloud from evaporating hydrogen from the pool, leading to fire and explosion, if ignited.	Different operations should be carried out at different distances from people. Define safety zones requirements for different activities (people boarding/deboarding,

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
				The event can potentially impact the airport terminal, other aircrafts, and people directly. Likely impact on people (personnel, crews and public) also for smaller leaks due to the vicinity between the gate and the transfer terminals. Overpressure load from the fast physical expansion of evaporating LH2 in large amounts. Tank fragments. Cryogenic hazard for personnel and crew handling the refuelling hose.	baggage, catering, cleaning and hygiene).

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
R13	Ice formation on outer surfaces causing loosening of connections	Insulation is not appropriate leading to cold external surfaces where air and humidity freeze.	Partial loss of insulation.	Damage to outer layers materials potentially leading to loss or decreased mechanical integrity. Ice particles entering seal surfaces leading to unsuccessful sealing and GH2 release. Inaccessible components for maintenance and routine operations.	Monitoring and maintenance of proper insulation. Appropriate insulation and procedures to monitor insulation state conditions.
R14	Ignition in internal system due to presence of oxygen/air	Air ingress in the systems and development of a mixture in flammability range.	Air is not properly evacuated from the system after maintenance or at connection/disconnection.	Operational disruptions of the tank and connected equipment (for example, mass flow inaccurate measurements). If ignited, potential explosion of the tank and/or fire with severe impact on people,	Procedure for connection and disconnection of equipment to avoid air ingress. Procedures for start-up after maintenance or when the systems have been out of operations.

ID	Hazard	Scenario	Causes	Consequences	Risk Reducing Measures
				infrastructures and the environment.	

M FAULT TREES

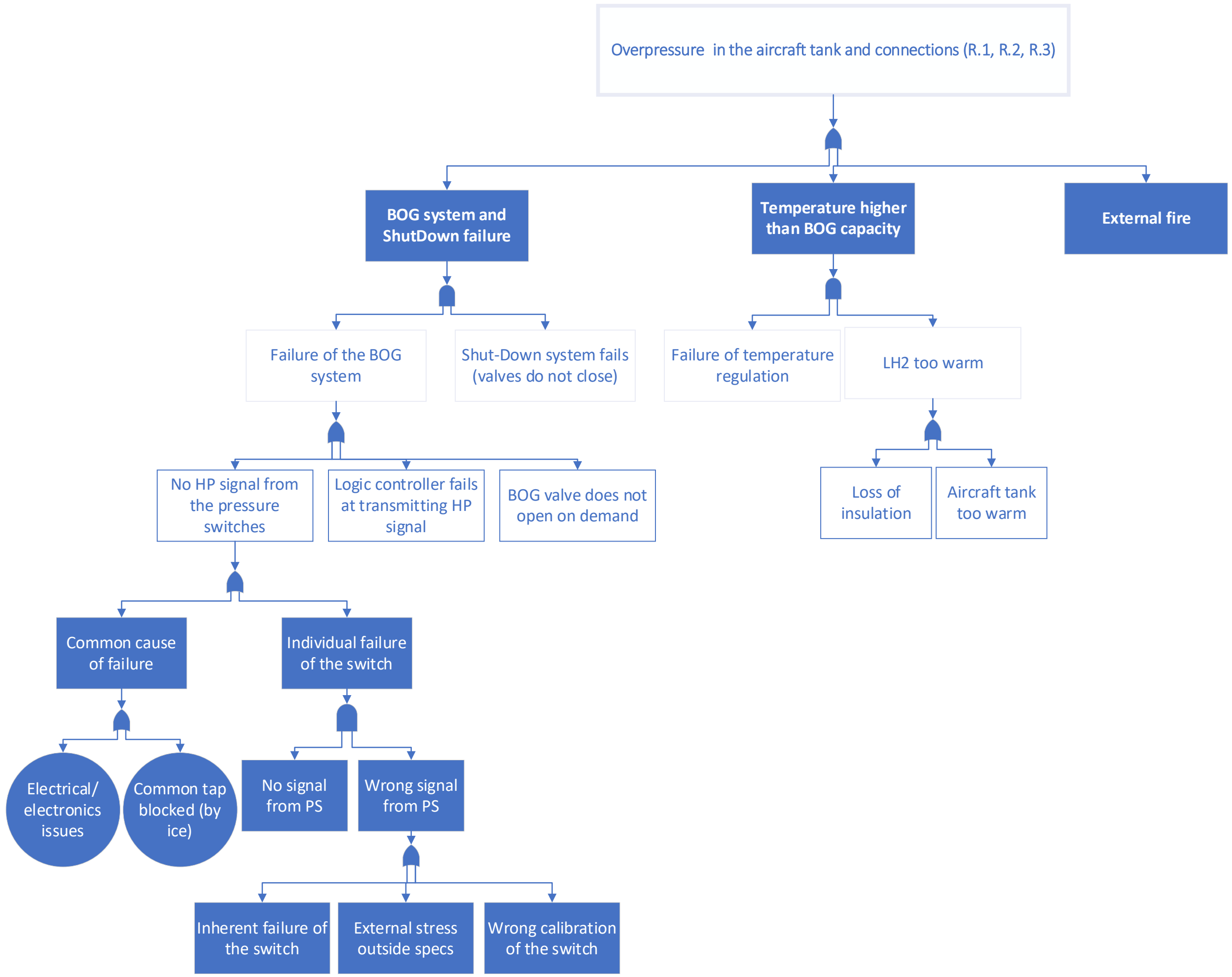

Figure 50 Fault Tree of the overpressure and increased pressure scenarios (R.1, R.2 and R.3) identified in the HAZID table (Table 33).

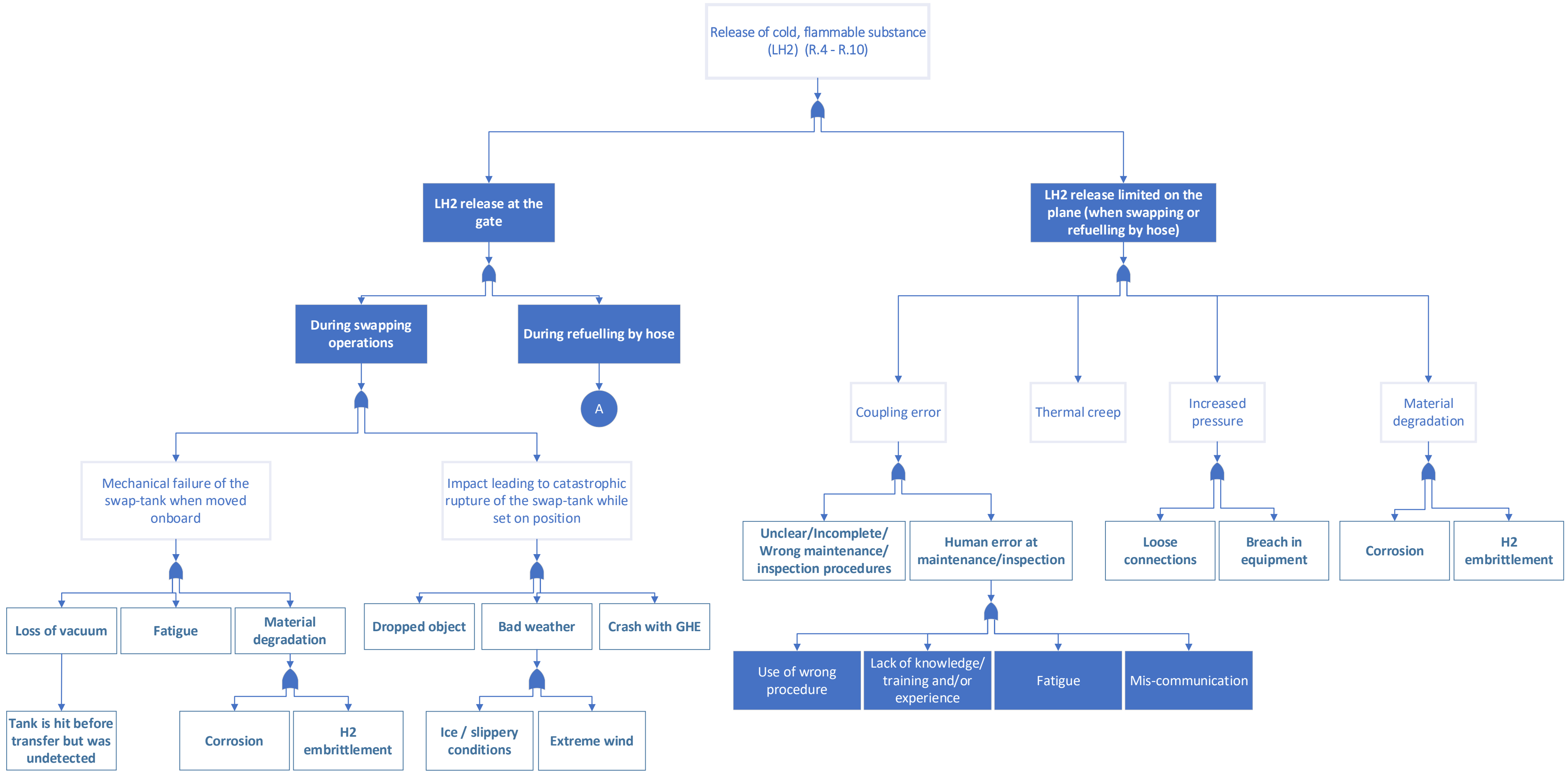

Figure 51 Fault Tree of LH2 release (part I).

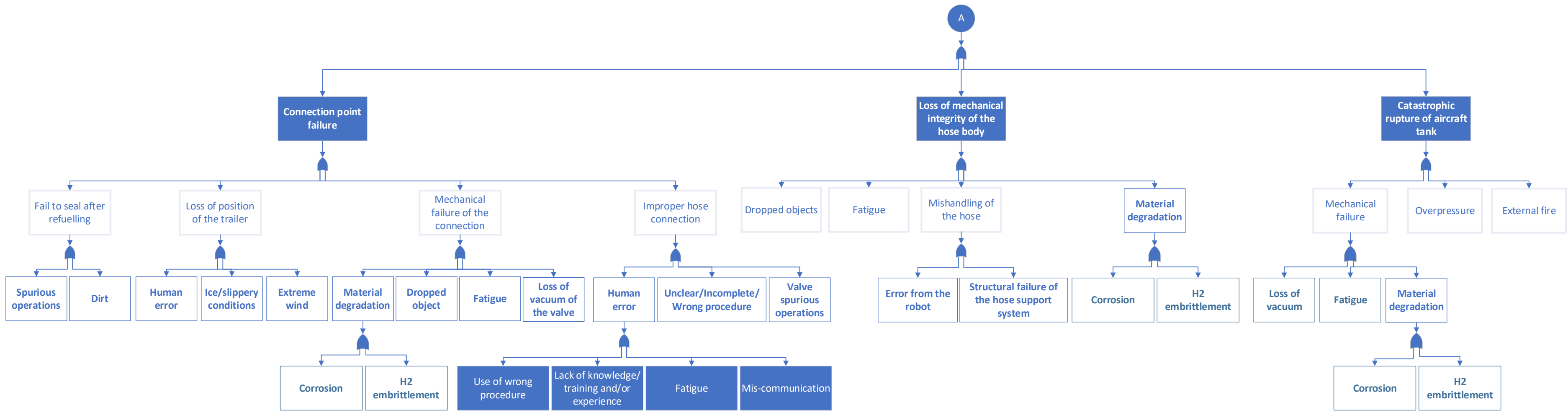

Figure 52 Fault Tree of LH2 release (part II).

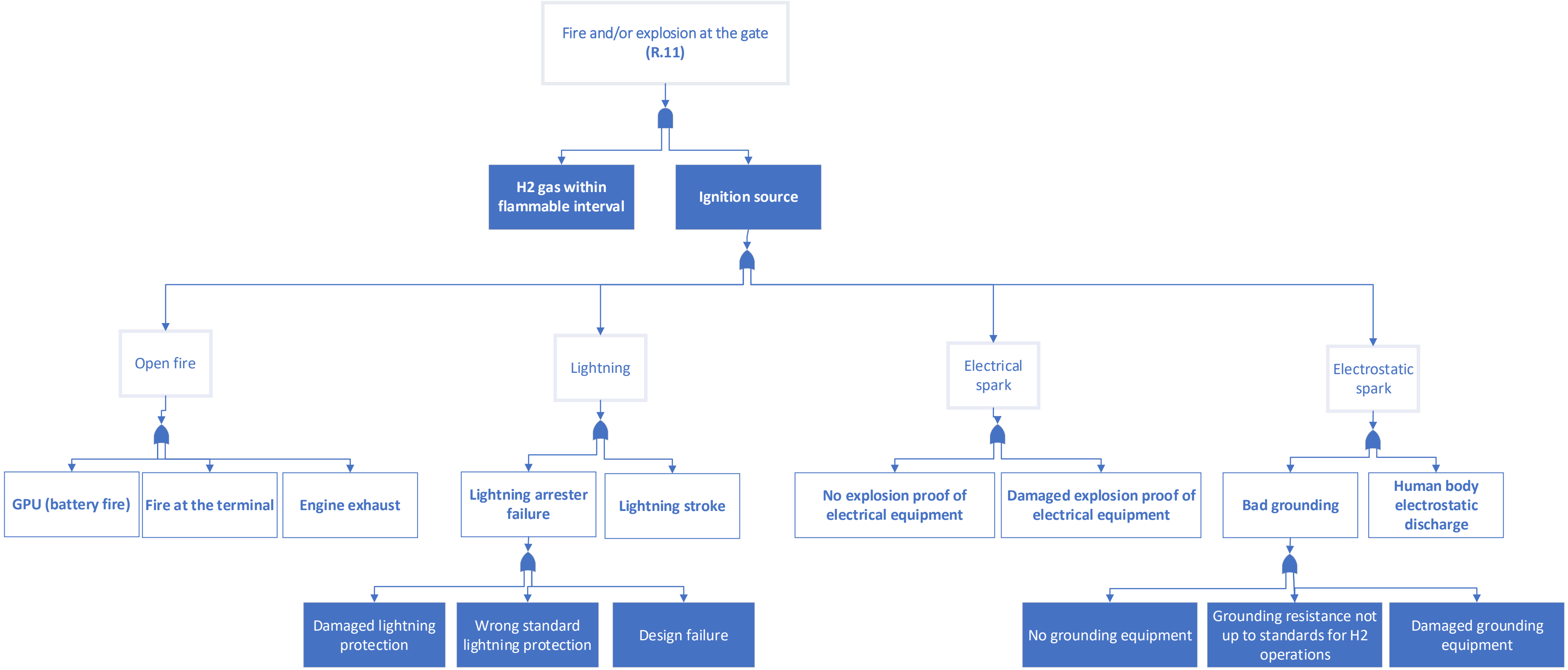

Figure 53 Fault Tree of fire and explosion at the airport.