Interreg
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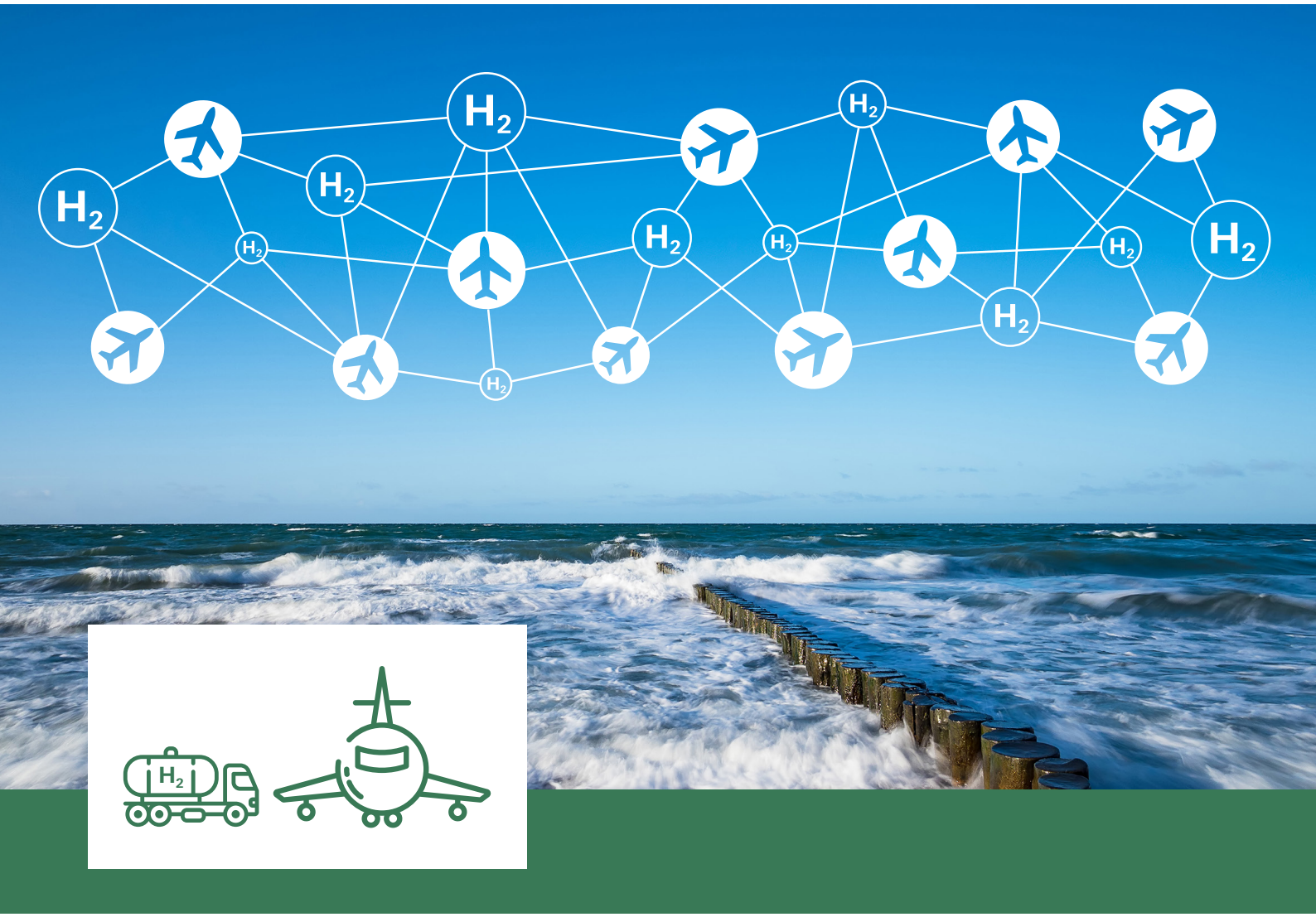
SMART GREEN MOBILITY
BSR HyAirport

Aircraft Handling



IMPLEMENTATION CONCEPT FOR AIRPORT HANDLING AND FUELLING OF HYDROGEN POWERED AIRCRAFT

CONTENT

Glossary of Abbreviations 4

1 Introduction 5
1.1 Project BSR HyAirport 5
1.2 Working Group 8

2 Regulations 9
2.1 Regulatory Mapping 9
2.2 Hydrogen-Specific Gap Analysis 9
2.3 Risk Assessment and Management of Change 10

3 Aircraft Handling Process 10
3.1 Overview and Challenges 10
3.1.1 Considered Aircraft 11
3.1.2 Challenges when using hydrogen 11
Hydrogen Properties & Related Hazards 11
Comparison With JET A-1 and AVGAS100LL 14
Hydrogen Storage Hazards 16
Conclusions 16
Liquid Hydrogen 16
3.2 Aircraft Refuelling 18
3.2.1 Hydrogen Transport on Airport 18
General 18
Airport Movements 19
Road Conditions 19
Tunnels / Underpasses 20
Storing / Parking (short term) 20
Long Term Storage 20
Maintenance 21
3.2.2 Refuelling Concepts 21
Existing Refuelling Concepts 21
Hydrogen-Specific Concepts 22
General frameworks for hydrogen refuelling 23
Analysis: Pros and Cons of Hydrogen Refuelling Concepts 24
Efficiency, Costs, Safety, and Environmental Impact 25
Conclusion 26
3.2.3 Fuel Truck Process 26
ZeroAvia truck refuelling process 26
Handling steps hydrogen vs. kerosene 27
Sampling & Hydrogen Quality 28
Refuelling nozzle 28
Fuel amount management 29
Staff and communication process 29
Venting 29
Hydrogen leaks 30
Position of truck, escape routes, safety distances, atex zones 30

3.2.4 Fuel Station Process 31
Overview of Existing Fuelling Processes 31
Future Hydrogen Refuelling Process 33
3.2.5 Defuelling and Purging 34
3.2.6 Safety Zones and Measures 35
3.2.7 Incident and Emergency Procedures for Hydrogen-Powered Aircraft 35
Incident Procedures 35
Emergency Procedures 36
3.2.9 Fire Prevention and Fire Fighting 36
3.3 Aircraft Stand Design 40
3.4 Passenger Handling 40
3.5 Other Aircraft Handling 40
3.5.1 De-icing 40
3.5.2 Ground Power (incl. earthing) & Pre-Conditioned Air (PCA) 41
Differences in procedures for handling H2 aircraft 41
H2 GPU additional safety aspects 41
3.5.3 Lavatory & Water 41
3.5.4 Baggage 42
3.5.5 Other (Cleaning, Catering) 42
3.5.6 Summary 43
3.6 Aircraft Movement on Airport 43
3.6.1 General - Pushback and Taxi 43
3.6.2 Water as by-product 43
3.7 Take-Off and Landing 44
3.8 Conclusion of handling process 44
3.9 Night-Stop (outdoors/indoors) 45
3.10 Conditions for Hangar use & Maintenance (line&base) 46
3.10.1 Hydrogen Hazards and Safety Objectives in Hangars 46
3.10.2 Evolving Regulations, Codes, and Standards for Hydrogen in Hangars 47
3.10.3 Ventilation and Gas Detection in Hydrogen Hangars 48
3.10.4 Hazardous Area Classification and Ignition Source Control 50
3.10.5 Hangar Operational Procedures for Hydrogen-Fuelled Aircraft 51
3.10.6 Parallels with Hydrogen Bus/Truck Maintenance Facilities 53

4 Piloting Activities 55
4.1 Proof of concept with BeyondAero 55
4.2 Taxi Test at Rotterdam De Hague Airport 55
4.2.1 Overview of the Test 56
4.2.2 Safety aspects and permitting process 56
4.2.3 Test activities 57
Hydrogen Refuelling 57
Taxi test 59
4.2.4 Findings and conclusion 59

5 Conclusion and Outlook 60
5.1 Conclusion 60
5.2 Liquid Hydrogen 61
Liquid Hydrogen: Differences, Focus, and Challenges 61
5.3 Further Topics to consider in the Future 62

GLOSSARY OF ABBREVIATIONS

Abbreviation	Meaning / Context
AIP	Aeronautical Information Publication
ATEX	Atmosphères Explosibles – zones where explosive atmospheres may occur
BSR	Baltic Sea Region
GH_2	Compressed Gaseous Hydrogen
LH_2	Liquid Hydrogen
DMS	Dead Man Switch
SOC	State of Charge (percentage fill level of hydrogen tank)
TPRD	Thermally Activated Pressure Relief Device
SAE	Society of Automotive Engineers
ISO	International Organization for Standardization
JET A-1	Conventional aviation fuel
AVGAS100LL	Conventional aviation fuel
OEW	Operating Empty Weight
MTOW	Maximum Take-Off Weight
GPU	Ground Power Unit
PPE	Personal Protective Equipment
IGOM	IATA Ground Operations Manual
AHM	Airport Handling Manual
SEVESO	EU Directive on the control of major-accident hazards
TKO	Take-Off
UFL	Upper Flammability Limit
LFL	Lower Flammability Limit
HAM	Hamburg Airport
RIX	Riga International Airport
VXO	Växjö Smaland Airport
WP	Work Package
TULIPS	EU research project in sustainable aviation
GOLIAT	EU research project in sustainable aviation
HORIZON	EU research program
CORDIS	EU research results database
RISE	Research Institutes of Sweden
HPC	Hydrogen Powered Concept (likely project-specific)

1 INTRODUCTION

The following section provides an overview of the BSR HyAirport project as well as the objectives of the work package (WP) 1.3 Aircraft Handling.

1.1 PROJECT BSR HYAIRPORT

BSR Hydrogen Air Transport – Preparation of Baltic Sea Region Airports for Green Hydrogen

The project "BSR Hydrogen Air Transport – Preparation of Baltic Sea Region Airports for Green Hydrogen," in short referred to as "BSR HyAirport," is a transnational cooperation in the framework of the Interreg Baltic Sea Region Programme aimed at promoting the use of hydrogen in the aviation sector. It seeks to facilitate the early adoption of hydrogen-powered aircraft by preparing airports for storing, handling, and delivering green hydrogen as a future energy source in aviation.

The integration of (gaseous) hydrogen as an energy source in aviation presents a transformative opportunity to reduce the carbon footprint of air travel. As climate change pressures industries to adopt cleaner technologies, initiatives like the BSR HyAirport project are crucial. By preparing airports for hydrogen-powered aircraft, the BSR HyAirport project aims to establish a framework that promotes sustainable aviation and aligns with broader environmental goals in the Baltic Sea Region (BSR). The project focuses on facilitating the adoption of hydrogen technology by creating the necessary infrastructure for storing, handling, and delivering green hydrogen. It fosters regional cooperation among partners from multiple countries, develops practical solutions for hydrogen usage in aviation, and tests and pilots these solutions to ensure their operational suitability, ultimately supporting the aviation sector's transition to more sustainable practices.

BSR HyAirport is an initiative of the Lead Partner, Hamburg Airport. Hamburg Airport developed the project and applied for co-funding by the Interreg Baltic Sea Region Programme in March 2023. The Interreg Baltic Sea Region Programme is a cooperation and funding instrument designed by the European Union to promote cross-border regional development and enhance collaboration among countries in the Baltic Sea Region area. As part of the European Union's Interreg initiative it focuses on addressing common challenges faced by the region, such as environmental sustainability, economic growth, and social inclusion and fosters collaboration across borders. Key areas of focus include promoting innovation, sustainable development, climate change adaptation, and improving accessibility within the region. By facilitating cooperation and sharing best practices, the Interreg Baltic Sea Region Programme aims to create a competitive, environmentally friendly, and inclusive region.

The BSR HyAirport project features transnational cooperation across seven countries in the Baltic Sea Region, including Germany, Poland, Lithuania, Latvia, Estonia, Finland, and Sweden. It benefits from a broad partnership comprising 16 project partners and 24 associated organizations across the aviation value chain, including airports, airlines, industry partners, aviation suppliers, public authorities, research and education institutions, and NGOs.

Hamburg Airport operates as the lead partner, with the other project partners being:
Poznan Airport, Poland
State company Lithuanian Airports, Lithuania
SJSC Riga International Airport, Latvia
Tallinn Airport, Estonia
Finavia Cooperation, Finland
Swedavia AB, Sweden
Växjö Småland Airport AB, Sweden
Latvian Hydrogen Association, Latvia
Sylt Airport, Germany
Sylt Air, Germany
Lübeck Airport, Germany
SIA Gulfstream Oil, Latvia
Latvia University of Life Sciences and Technologies, Latvia
RISE Research Institutes of Sweden, Sweden

FIGURE 1:
Project Partners



FIGURE 2:
Map of project partner locations

The project partnership represents a very high percentage of airports in the Baltic Sea Region as project partners Finavia, Lithuanian Airport and Swedavia operate between 3 and 20 airports in their home countries.

The project creates a unique platform for the joint development, implementation, and testing of practical solutions addressing the common challenges and specific needs related to hydrogen usage. With a total duration of 36 months, the project commenced in November 2023 and will conclude in October 2026.

The BSR HyAirport project is divided into three work packages: WP 1 – Preparing Solutions; WP 2 – Piloting and Evaluating Solutions; and WP 3 – Transferring Solutions.



FIGURE 3:
Working Packages of BSR HyAirport

The project focuses on applications using gaseous hydrogen as proposed smaller aircraft will use gaseous hydrogen and will be ready for production and operation much earlier compared to larger aircraft. First scheduled flights with gaseous hydrogen-powered aircraft could already operate at the end of the decade. Larger aircraft, e.g. the Airbus A320 family and Boeing 737 family that currently dominate intra-European air transport, will most likely use liquid hydrogen and not enter scheduled operations before 2035.

In Work Package 1.3 an implementation concept for the airport handling and fuelling of hydrogen-powered aircraft, with the goal of preparing airports for these operations, was developed. The output from this work package is this report, which served as a prerequisite for the piloting activities and contributes to the results of Output O.2.4 “Tested airport operations with hydrogen-powered aircraft”. These results can also be found in this report in chapter 4 “Piloting Activities”. In particular, the solutions developed for aircraft handling form a central basis for pilot or demonstration projects and will undergo testing to ensure their practical suitability.

Within the framework of this work package, project efforts concentrate on creating concepts and solutions for the future handling of aircraft powered by green hydrogen at airports in the BSR. This includes logistics for transporting hydrogen from the fuel storage depot to the aircraft and the actual fuelling processes. To achieve efficient and competitive aircraft operations, it is essential to minimize handling and turnaround times while ensuring that handling and fuelling processes remain safe and reliable.

As part of the solution development process, a series of working group meetings took place, involving project partners and external participants and experts. These sessions addressed various aspects of the handling process and built upon each other to enhance the depth of the discussions. The project partnership's broad interdisciplinary composition brings together organizations from various countries and areas of the aviation sector, creating an extensive pool of practical experience and operational know-how. Leveraging these unique experiences, along with specialized external support, provides an optimal platform for the joint development of effective solutions for handling and fuelling hydrogen-powered aircraft at airports throughout the BSR and beyond.

The results will be documented and shared with target groups and the interested professional community. Airports outside the partnership, airlines, regional and national authorities, technology and energy providers as well as interest groups belong to the target groups of the BSR HyAirport project. The project partnership is ready to share project results as regular / scheduled flights won't operate in larger networks if a large number of airports are not prepared for handling of GH2-powered aircraft.

Key deliverables include a standardized concept for handling and fuelling aircraft powered by gaseous hydrogen, aimed at preparing airports for future hydrogen aircraft operations. The initial focus is on smaller, regional aircraft, which are expected to begin operating in this decade, while larger models are anticipated to enter service in the next decade. The concept integrates specific regulations regarding aircraft handling, such as hydrogen delivery and refuelling as well as parking, boarding, disembarking passengers, and loading and unloading baggage and freight.

1.2 WORKING GROUP

As mentioned above, the initial project focus is on smaller, regional aircraft, as these will probably be powered by gaseous hydrogen corresponding to its properties. This size corresponds to ICAO code letter A and B and includes also smaller code letter C aircraft. The manufacturing company ZeroAvia for example is retrofitting a Cessna Gran Caravan for the use of gaseous hydrogen.

Smaller aircraft are usually associated with shorter ranges. This reflects the structure of the BSR HyAirport project and especially the working group "Aircraft Handling". It consists of the following project partners:

Hamburg Airport, Germany
SJSC Riga International Airport, Latvia
Tallinn Airport, Estonia
Swedavia AB, Sweden
Växjö Smaland Airport AB, Sweden
Latvian Hydrogen Association, Latvia
Sylt Airport, Germany
Sylt Air, Germany
Lübeck Airport, Germany
RISE Research Institutes of Sweden, Sweden

The participating airports can be described as small to mid-size, their key business being short to mid-range routes between cities or in rural areas around the Baltic Sea. This concept document mostly consists of knowledge and experience from these kinds of airports but still claims to offer guidance for any airport preparing itself for handling hydrogen powered aircraft.

This concept document was produced by the participating project partners. Collaboration occurred through monthly online working group meetings and additional meetings focused on specific topics. Information was gathered through broad industrial research, which also included exchanges with companies and projects such as ZeroAvia, BeyondAero, Apus, H2Fly, AeroDelft. Following the writing phase, an intensive review phase involving all project partners finalized the existing document.

2 REGULATIONS

Establishing hydrogen aviation at airports requires, first and foremost, a clear understanding of the applicable regulatory requirements.

Regulatory frameworks governing hydrogen operations at airports are predominantly established at the national level, leading to notable differences between countries, even within the European Union. Furthermore, standards and codes of best practice play a crucial role in ensuring safety, consistency, and effective implementation—both in current operations and as the sector evolves. These topics were assessed for the project by an external service provider in 3 phases and the results, separated in 2 reports, can be found in appendix A & B.

2.1 REGULATORY MAPPING

Compilation of a regulatory register for aircraft ground handling processes, covering international, European, and national requirements as well as industry standards relevant from aircraft arrival to departure. Identification of applicable EASA, ICAO, SAE, JIG, national rules as well as IS-BAH and ISAGO requirements.

2.2 HYDROGEN-SPECIFIC GAP ANALYSIS

Review of the identified regulations and industry standards during Phase 1 addressing airport ground handling activities for aircraft turn-around management from the time they enter the airport's airspace until they leave it again, including emergency response planning. The review has the objective to determine the extent of the applicability of the existing legal frameworks for gaseous hydrogen powered aircraft and to identify gaps as well as potential hazards, which are not covered by the existing rules, regulations and/ or industry standards for gaseous hydrogen powered aircraft operations. These gaps and potential hazards are considered significant changes compared to conventional aircraft ground handling operations.

2.3 RISK ASSESSMENT AND MANAGEMENT OF CHANGE

Based on Phase 2 results, the significant changes between conventional aircraft ground handling and gaseous hydrogen powered aircraft ground handling operations are risk-assessed within a Management of Change process. A hazard log and risk register is developed for gaseous hydrogen powered aircraft ground handling operations for a basis to conduct an operational risk evaluation for the gaps and hazards identified. The risks for the hazards are categorized into low, medium and/ or high. For the risk classification (severity vs. probability) a group of relevant subject matter experts are involved to generate an objective output for the risk classification. The integration of hydrogen-related risk into preliminary Management of Change documentation and safety risk registers includes coordination with known hydrogen aircraft developers and initial scenario-based analysis as well as further project group coordination.

3 AIRCRAFT HANDLING PROCESS

In the transition towards hydrogen-powered aviation, the safe and efficient handling of aircraft on the ground is of paramount importance. This chapter outlines the processes and challenges associated with managing hydrogen-powered aircraft at airports, with a focus on the technical specifications, handling procedures, and unique safety considerations posed by hydrogen. By examining both the physical properties of hydrogen and the operational environment, the following sections aim to provide a comprehensive understanding of the requirements and risks inherent to the adoption of hydrogen as an aviation fuel.

3.1 OVERVIEW AND CHALLENGES

The transition to hydrogen-powered aviation presents a set of unique challenges and opportunities, both technical and operational, for ground handling at airports. As outlined in the following sections, the safe management of hydrogen aircraft depends on several critical factors: the specific design and configuration of future hydrogen aircraft, including the location of fuel tanks, refuelling points, and pressure relief device vents, and the distinct physical and chemical properties of hydrogen itself. These elements not only influence the technical requirements for refuelling and maintenance but also shape the safety zones and operational procedures required to mitigate risks associated with hydrogen's extreme flammability and other hazards. Moreover, the differences in hazard profiles between hydrogen and conventional fuels demand innovative detection technologies and robust organizational measures to ensure the safety of airport personnel. Together, these complexities underscore the need for comprehensive planning, adaptable safety protocols, and ongoing collaboration between manufacturers, regulatory bodies, and airport operators as hydrogen aviation becomes an integrated reality.

For the purposes of this document, the term “conventional aircraft” will be used to refer to aircraft powered by kerosene or aviation gasoline (avgas), in order to ensure clarity and consistency throughout the discussion.

3.1.1 CONSIDERED AIRCRAFT

The specifications of future hydrogen powered aircraft are highly dependent on the respective manufacturer and will vary, depending on whether the aircraft is retrofitted or newly designed. For a safe and dependable handling process of the aircraft though, especially two characteristics – next to the overall size of the aircraft - will be crucial: the location of the aircraft tanks, kind and number of refuelling connection(s), position and direction of the pressure relief device vents of the hydrogen system. The refuelling point defines the position of the refuelling equipment and therefore the space for the remaining handling processes. Among other aspects, this, together with the position of the pressure relief device vents, defines the position of the necessary safety zones. And these in turn will affect, if and which of these handling processes can take place in parallel with refuelling. If parallel refuelling is not possible because of extended safety zones, this will result in longer overall turnaround times.

3.1.2 CHALLENGES WHEN USING HYDROGEN

HYDROGEN PROPERTIES & RELATED HAZARDS

Hydrogen is hazardous and extremely flammable. Conventional aviation fuels such as Jet-A1 and energy carriers such as Li-ion batteries are also hazardous. The key point is to understand the difference between the hazards of hydrogen and those of conventional fuels and energy carriers, and to mitigate the risks by developing appropriate technical and organisational solutions. As this study is focussed on airports rather than aircraft in flight, the hydrogen properties are based on typical ambient conditions at ground level, i.e. standard atmospheric pressure and 20°C. When considering aircraft in flight the effect of altitude (decreased ambient pressure) on safety-related properties must be considered, e.g. changes in flammability limits.

The paragraphs below are based on a range of sources including ISO TS15916: 2026 “Basic considerations for the safety of hydrogen systems” and typical Material Safety Data Sheets.

Hydrogen is a colourless (invisible), odourless and tasteless, non-toxic, non-carcinogenic, non-ecotoxic, non-corrosive, buoyant and extremely flammable gas. Although non-toxic, in sufficient concentration in a poorly ventilated enclosure, hydrogen can displace oxygen and act as a simple asphyxiant. As hydrogen is odourless, colourless and tasteless, it is undetectable with human senses and is an important hazard for all people working with hydrogen systems. Technical solutions such as hydrogen sensors are needed to detect the presence of hydrogen.

The ductility and fatigue life of many common metals is reduced when exposed to hydrogen at pressures above ambient or at high temperatures (hydrogen embrittlement and hydrogen attack respectively). This is of importance to the designers of hydrogen systems but does not directly affect airport operations.

Due to hydrogen's small molecular size and low viscosity, it is difficult to contain. Leak pathways exist through which hydrogen may leak but other gaseous fuels or fuels vapours would not. Hydrogen systems can only be adequately leak tested with hydrogen, helium, or preferably an inert trace gas containing 5% hydrogen. Hydrogen permeates through all materials to a greater or lesser degree, and especially through polymers when there is high driving pressure or elevated temperature.

At ambient temperatures, hydrogen has strong buoyancy and dispersion characteristics which is very positive in open locations such as the airport apron but can be negative in enclosures such as vehicle compartments or airport buildings as a flammable mixture will form more quickly than with conventional fuels.

Hydrogen is extremely flammable when mixed with air, with very wide limits of flammability (4 – 75% by volume in air) and detonation that are much wider than those of conventional fuels. However, the lower flammability limit is similar to, or higher than conventional fuels. Flammable hydrogen/air mixtures are easily ignited with the minimum ignition energy being lower than that of other fuels, however, the autoignition or hot surface ignition temperature is significantly higher than conventional fuels.

Pure hydrogen burns with a very pale blue flame which can be very difficult to see in bright light (both outdoors and indoors) and is an important hazard for people working with hydrogen systems and especially emergency services. Impurities in the air such as dust may increase the visibility of a hydrogen flame, but this cannot be relied upon. Hydrogen flames radiate much less heat than hydrocarbon flames which reduces the risk of igniting nearby materials and makes the area of a fire more accessible, but this also means that a person can approach much closer to the flames before warning pain is felt (another hazard important for people working with hydrogen systems and especially emergency services). Hydrogen flames are slightly hotter than hydrocarbon fuels.
The primary combustion product is steam.

Hydrogen combustion hazards include standing flames, jet fires, and explosions. Hydrogen/air mixtures may explode, typically as a deflagration in the open following delayed ignition of a hydrogen release. Some conditions, e.g. a degree of enclosure and congestion in the enclosure, can cause turbulence and flame acceleration in the burning mixture which leads to high overpressures and detonations are possible.

Key safety related properties of hydrogen are summarised in Table 1below together with those of JET-A1 and AVGAS100LL.

Property	Unit	HYDROGEN	JET-A1 (kerosene)	AVGAS100LL (petrol)
Colour	-	None	Clear/yellow	Blue
Odour	-	None	Hydrocarbon/ almost diesel	Petrol
Boiling point	^{0}C	-252.9	150 to 300	40 to 170
Vapour density at NTP (Air 1.23)	kg/m^3	0.08	>3	3 - 4
Liquid density at 15^{0}C	kg/m^3	Not applicable	780 - 840	710
Toxicity	-	Non-toxic	Harmful/ irritant	Harmful/ irritant
Flammability limits (air by vol.)	%	4 - 75	0.6 – 6.0	1.4 – 7.6
Flash point	%	-	≥ 40	< -40
Minimum ignition energy in air	mJ	0.017	0.3	0.8
Autoignition temperature	°C	585	207 - 250	280 to 470
Flame visibility in air (daylight)	-	Practically invisible (very pale blue in low light)	Yellow	Yellow
Flame temperature in air	°C	2045	2000	2000
Percentage of thermal energy radiated from flame to surroundings	%	ca5 – 10	30-40	Not available
Burning velocity in NTP air	m/s	2.65 – 3.25	ca0.2	ca0.35-0.5
Note: NTP = Normal temperature and pressure = 1 atm (1.013bar), 20°C (293.15K)				

TABLE 1:
Properties of aircraft fuels

COMPARISON WITH JET A-1 AND AVGAS100LL

In this section, the hazards of hydrogen are compared with Jet A-1 and AVGAS100LL based on material taken from typical Material Safety Data Sheets.

Physiological Hazards

Hydrocarbon fuels such as Jet A-1 and AVGAS100LL are generally not considered highly toxic, and for normal situations periodic medical surveillance is not required. Nonetheless, these fuels should be handled with care as they can act as irritants and over-exposure can lead to harmful effects including neurological effects. In comparison, hydrogen is a non-toxic, non-carcinogenic, non-corrosive gas, however, in sufficient concentration in a poorly ventilated enclosure for example, hydrogen can displace oxygen and act as a simple asphyxiant.

Environmental Hazards

Spillages of both Jet A-1 and AVGAS100LL can contaminate ground water, and both fuels are toxic to aquatic life, but expected to be biodegradable and non-persistent. Hydrogen in contrast is non-ecotoxic. Hydrogen has an indirect greenhouse effect on the climate when released into the atmosphere, e.g. through leakages, venting or purging. Hydrogen is not directly a greenhouse gas, but its oxidation reactions when released into the atmosphere can increase the lifetime of methane in the atmosphere due to reduced atmospheric hydroxyl, increased ozone, and increased stratospheric water vapor, as well as aerosols ， . A detailed comparison of the greenhouse effects of hydrogen with those of conventional aviation fuels is beyond the scope of the current report.

Release & Dispersion

At ambient temperatures, hydrogen is a buoyant gas with strong diffusion characteristics which is a very positive characteristic for releases in the open as the hydrogen will rise and disperse quickly. In an enclosure it may mean that a release would quickly generate a flammable mixture. Its subsequent dispersion is very much dependent on the particular scenario and the size of the release.

Jet A-1 and AVGAS100LL are both liquids under normal conditions, and the vapours of both fuels are 3-4 times heavier than air. This means that the fuel from leaks or spillages may remain for some time after the release, and vapours will linger around the spill or in low lying areas, e.g. drains. Hydrogen (H2) is the smallest molecule with a low viscosity which means that it has a propensity to leak when other fuel vapours would not. The leak testing of hydrogen systems must follow stringent procedures using specific hydrogen leak test gases, and not nitrogen or air.

Detection

Jet A-1 and AVGAS100LL spillages are readily detectable due to the colour of the liquids and their characteristic hydrocarbon odours. Hydrogen is colourless, odourless and tasteless, which means that a leak is impossible to detect with human senses (a high-pressure leak may be felt or heard but this cannot be relied upon in noisy environments such the airport apron). A wide range of hydrogen detection technologies are available.

Ignition

Flammable hydrogen/air mixtures are easily ignited with the minimum ignition energy being 0.017mJ at the stoichiometric concentration, which is more than an order of magnitude lower than that of Jet A-1 (0.3 mJ) and AVGAS100LL at (0.8 mJ). In other words, a weaker spark is required to ignite hydrogen/air mixtures. At the lower flammability limit the minimum ignition energy for hydrogen/air mixtures is closer to that of the hydrocarbon fuels.
The high autoignition temperature of hydrogen (585°C) is an advantage, as it is significantly higher than Jet A-1 (207-250°C), and higher than AVGAS100LL (280-470°C).

Combustion
AVGAS100LL is classed as being a highly flammable liquid and vapour, while Jet A-1 is classed as being a flammable liquid and vapour. Hydrogen is classed as being an extremely flammable gas. While the lower flammability limit (LFL) of Jet A-1 (0.6% by volume in air) is lower than AVGAS-100LL (1.4%), the flash point of Jet A-1 is ≥ 40°C which is higher than ambient conditions in most parts of the world whereas for AVGAS100LL it is < -40°C which is lower than ambient conditions except in extreme weather conditions. In contrast hydrogen has a LFL of 4% meaning that a higher concentration is needed before it becomes flammable.

Hydrogen has extremely wide limits of flammability in air (4 to 75% by volume in air). Below those limits the mixture is too lean to burn, i.e. insufficient hydrogen. In contrast the flammability limits of Jet A-1 (0.6 to 6.0%) and AVGAS100LL (1.4 to 7.6%) are much narrower. While this means that for a given release a greater quantity of hydrogen may be within flammable limits, this is offset to some degree by the much stronger diffusion and dispersion characteristics of hydrogen in many situations.

Hydrogen is very energetic in terms of combustion due to its wide limits of flammability and high burning velocity which for hydrogen (2.65-3.25m/s) is an order of magnitude faster than Jet A-1 (approx. 0.2m/s) and AVGAS100LL (approx. 0.35-0.5m/s). Hydrogen/ air mixtures can explode as a deflagration which is typical of fuel/air mixtures in the open, and in the presence of certain conditions more severe detonations can occur.

Both Jet A-1 and AVGAS100LL burn with visible flames and as with other hydrocarbons, the flames radiate significant heat which can trigger secondary fires but also provides a warning to emergency responders. In contrast pure hydrogen burns with an almost invisible very pale blue flame in ambient lighting. Some photographs or videos of hydrogen burning show a pale-yellow flame, but this is due to impurities in the air burning such as dust. It should be assumed that a hydrogen flame is invisible without thermal imaging equipment. Hydrogen flames also radiate much less heat than hydrocarbon fires. Depending on the particular situation this may mean fewer secondary fires, but it also means that less warning is provided to emergency responders which is especially hazardous in combination with the very poor flame visibility.

Because of the ease of ignition of hydrogen/air mixtures, the probability of a fire is extremely high if the concentration of hydrogen is within the flammability limits. Unprotected flames or sparks should be avoided in the vicinity of hydrogen storage, or handling equipment or vehicles. Given hydrogen's propensity to leak, special consideration is needed when, for example, leak testing equipment or responding to an emergency, and especially in enclosures or other situations where the hydrogen can be contained and is not able to disperse freely into the atmosphere. Existing airport firefighting tactics need to be adapted to address the specific hazards of a high-pressure hydrogen release at an airport based on the experience from other industries.

Material Compatibility
Both Jet A-1 and AVGAS100LL are incompatible with some materials. For hydrogen there are special incompatibility issues with a number of common metals at elevated pressures or temperatures. Material compatibility is a system design issue and if this has been correctly considered in design and system specification there should be no hazards specific to the airport operations beyond those associated with a release or leak of hydrogen.

HYDROGEN STORAGE HAZARDS

Storage of hydrogen as a compressed gas is typically at nominal working pressures of 35 or 70MPa on-board land vehicles, and higher at the refuelling station. Transient pressures immediately following fast refuelling are significantly higher on board the vehicle than the nominal system rated pressure (+25% for 70MPa systems), and this would also be the case for ground handling equipment or aircraft if fast refuelling is used.

There are different forms of construction for cylinders/tanks/containers used for the storage of (compressed) gaseous hydrogen. While all-metal cylinders are commonly used for transportable industrial gas bottles, they are too heavy for typical land vehicles and aircraft. For land vehicle use hydrogen fuel cell vehicles typically use “Type 3” or “Type 4” containers which are constructed from a structural fibre/resin composite overwrap around a thin metal or polymer liner (Type 3 and Type 4 respectively). This type of technology can also be used for the transport of hydrogen. For land vehicle systems the containers incorporate on-tank valves to secure hydrogen in the tanks in the event of a system leak and a thermally activated (temperature triggered) pressure relief device (TPRD). The TPRD is a key safety component as it prevents excessive pressure rise due to heat.

While high pressure leaks may be audible and can be sufficiently loud enough to cause ear damage, being able to hear a leak cannot be relied upon in a noisy environment such an airport stand where personnel may also be using ear protection. The actual outcome of a hydrogen leak or release from a (compressed) gaseous hydrogen system is dependent on a range of factors. High-pressure hydrogen systems can result in standing flames or micro flames, jet releases or jet fires, for example, due to pipe breaks or connection leaks. If there is a delay between the start of the release and ignition, an explosion may occur. The worst-case scenario is a high-pressure hydrogen container rupture causing an explosive release of compression energy and fragmentation damage with the potential for subsequent ignition of the resulting hydrogen/air mixture.

CONCLUSIONS

While the hazards associated with hydrogen are different from those of conventional aviation fuels, the risks associated with those hazards have been understood and managed for many years in several industries. In the aviation industry these risks can be managed safely provided that the components and systems are designed, specified, integrated, operated and maintained for hydrogen rather than conventional or similar fuels. This can be achieved by using existing knowledge from other industries and hydrogen applications, safety principles and procedures and adapting them to the specific airport and aircraft environment. Similarly, airport procedures and training need to be adapted to the specific hazards of hydrogen and hydrogen systems.

LIQUID HYDROGEN

The focus of HyAirport is on compressed gaseous hydrogen, however, larger commercial aircraft may require liquid hydrogen storage in the future, therefore a short overview about the topic is given in the following.

Liquid hydrogen has been used as a rocket fuel, for example, Ariane, Apollo and US Space Shuttle, and also as an automotive fuel, e.g. the small-series BMW Hydrogen 7 in 2005-7 [https://en.wikipedia.org/wiki/BMW_Hydrogen_7].
The paragraphs below are based on a range of sources including ISO TS15916: 2026 “Basic considerations for the safety of hydrogen systems”, and deliverable of European projects such as PresLhy [https://preslhy.eu/].

Hydrogen can be stored as a cryogenic liquid around -253°C at low pressures typically 0.5-1.0MPa or up to 1.6MPa depending on the specific type of storage. The extreme cryogenic temperatures associated with liquid hydrogen storage (approximately 90°C colder than liquified natural gas or LNG) introduce additional hazards compared to hydrogen at ambient temperatures or when stored as a compressed gas. The additional hazards of liquid hydrogen include cold embrittlement of storage materials, significant thermal stresses/stress gradients, the possibility of cryo-burns and related cryogenic injuries, rapid volumetric expansion of the released fluid including phase change, localised oxygen enrichment on uninsulated cryogenic components, material compatibility, slower dispersion in the atmosphere, changes to flammability properties, and boil-off.

Thermal energy is always being transferred to the inner tank and to the hydrogen that it contains at the normal operating temperature of a liquid hydrogen system. As heat is transferred, the liquid expands, increasing the pressure in the tank and some of the liquid hydrogen is vaporised further increasing the pressure in the tank. The pressure is controlled when the hydrogen is drawn off for use, however, otherwise the pressure in the tank increases, e.g. when the hydrogen is not being consumed. In this latter case the “boil-off” and resulting gas pressure needs to be safely managed, otherwise the tank can rupture.

Effects on the skin similar to a thermal burn, known as cryo burns due to extremely low temperatures, can be produced by contact with LH2, cryogenic hydrogen gas, or uninsulated components (or those with damaged insulation) cooled by the cryogenic hydrogen. Delicate tissues such as the eyes and lungs are more susceptible to extreme cold than the skin. Prolonged inhalation of extremely cold air or vapours may cause serious lung damage or trigger asthma in susceptible people. Prolonged exposure of the skin to cryogenic gases or contact with cryogens or cold surfaces can cause frostbite. Unprotected skin can stick to surfaces at cryogenic temperatures, and the skin may tear away if attempts are made to pull away. Prolonged exposure to low air temperatures can lower the body temperature causing hypothermia.

Personal protective equipment (PPE) such as cryogenic gloves and goggles should be worn where there is a risk of contact with the cryogenic liquid or gas, or equipment surfaces at very low temperatures. Adequate training in emergency procedures for handling cryo-injuries or hyperthermia is necessary.

At ambient temperatures, hydrogen is a buoyant gas with strong diffusion characteristics which is a very positive characteristic for releases in the open as the hydrogen will rise and disperse quickly. In an enclosure it may mean that a release would quickly generate a flammable mixture. Its subsequent dispersion is very much dependent on the particular scenario and the size of the release. In contrast liquid hydrogen or cryogenic hydrogen gas releases are much denser, with cryogenic hydrogen gas just above boiling point being heavier than air. In practice this means that initially a cryogenic release will behave differently to an ambient temperature gaseous hydrogen release. If the cryogenic hydrogen release is small, heat from the atmosphere will quickly warm up the hydrogen and it will behave similar to an ambient temperature hydrogen release very quickly. If the release is larger, the gas will remain denser for some time and may linger or even sink until the atmosphere heats up the gas sufficiently for its density to decrease and gain buoyancy. However, regardless of the release scenario, for an initial period which may be of longer or shorter duration, the release and dispersion of LH2 will be very different to a comparable CGH2 release.

For cryogenic hydrogen just above its boiling point, the Lower Flammability Limit (LFL) increases to approximately 7.5% from 4% at ambient temperature, while the Upper Flammability Limit (UFL) decreases from 75% to 67%. While the increase in LFL is notable, the flammability range is still ex-

tremely wide compared to other fuels and the LFL will rapidly decrease as the hydrogen warms up. For small releases the LFL would effectively remain at 4%. Other differences in the combustion behaviour of cryogenic hydrogen in comparison to ambient temperature gaseous hydrogen include:

- Ignition, no practical change
- Flame temperature, no practical change
- Thermal radiation higher
- Jet fire, increased flame length
- Deflagration, no practical change but should be investigated further
- Detonation and deflagration to detonation transition (DDT) should be investigated further

3.2 AIRCRAFT REFUELLING

As aviation seeks to transition from conventional fossil fuels to more sustainable alternatives, refuelling procedures must evolve to address the specific requirements of future energy carriers. Section 3.2 explores the refuelling of aircraft, beginning with an analysis of established concepts for kerosene-powered planes. By examining current practices and the adaptations necessary for hydrogen, this chapter sets the foundation for understanding the operational, safety, and technical criteria that will shape the next generation of refuelling systems.

3.2.2 HYDROGEN TRANSPORT ON AIRPORT

GENERAL

If gaseous hydrogen is to be used as an aviation fuel, it will have to be transported around the airport. Depending on the demand hydrogen may be transported by pipeline or fuel bowser. Given that the volume of hydrogen to be moved may be much larger than for JET-A1 for a similar flight profile, it may mean additional fuel bowser movements depending on the particular flight requirements. The potential increase in fuel bowser movements may bring its own risks and may lower the investment threshold for pipeline/hydrant distribution at airports. In the sections below, only transport of hydrogen by fuel bowser is considered on the airside of the airport for demonstrations and early commercial operation.

Hydrogen is a significantly more energetic fuel, in terms of its much wider flammability limits and significantly higher burning velocity than hydrocarbon fuels such as JET-A1]. Along with other specific hydrogen hazards described in Section 3.1.2, hydrogen bowsers may need different risk mitigation measures to conventional JET-A1 bowsers. It may be advisable to apply tighter restrictions to hydrogen transport for demonstrations than for JET-A1 until sufficient field experience has been gained in handling hydrogen airside. These restrictions may be changed (relaxed, or if necessary increased) for commercial operation based on more detailed risk assessments including the knowledge and experience gained from demonstration projects such as BSR HyAirport.

Hydrogen transportation on the airport must fulfil relevant European and national legal requirements (e.g. ADR). On a system level, a gaseous hydrogen fuel bowser will need to be equipped with pressure relief devices of some type to avoid rupture of the storage system due to excessive pressure. These devices may take a variety of forms depending on the particular storage system, hydrogen refilling and dispensing systems, and the probable causes of over-pressurisation. For example, for road vehicle on-board hydrogen storage (for use of the fuel by the vehicle, not transport of bulk hydrogen), the only causes of over-pressurisation are due to a failure of the refilling station (which is mitigated by the refilling station systems and storage system certification requirements)

or by exposure to excessive temperature, i.e. fire (which is mitigated by TPRD (thermally activated pressure relief devices)). It is important to know the triggering mechanism and type of pressure relief devices installed on the hydrogen bowsers, and how, where, and in which orientation the hydrogen is vented to atmosphere (these may be different for different hydrogen bowsers). For road vehicles the location and direction of these vents is open to the OEM, and at present this is the case for airside machinery/vehicles, but is important for both operators and fire and rescue services in the event of an incident. It may be considered in future standardisation activities.

The following sections are a high-level review for the transport of gaseous hydrogen around on the airport, and detailed recommendations should be based on the specific equipment and systems to be used with a detailed a risk analysis for each airport.

AIRPORT MOVEMENTS

In the event that a hydrogen fuel bowser was involved in an accident, e.g. with other airport vehicles or a fire, the potential outcomes may be different to those of a conventional JET-A1 fuel bowser. As noted in the previous section, gaseous hydrogen fuel bowsers would need pressure relief vents, and the position, direction, flow rates, etc may vary between different bowsers designs.

For early knowledge building demonstrations, it may be appropriate to restrict hydrogen transport to specific parts of the airport, e.g. to operate in more open areas away from the airport terminal or other sensitive infrastructure, or away from areas where groups of people may be found. Enclosure of a flammable hydrogen/air mixture is one of the contributing factors to higher, more destructive overpressures in the event of an explosion. Such enclosures may be formed by the airport terminal buildings, piers, air bridges or hangers, or roads beneath terminal buildings. The position of building air intakes should be considered in the context of potential hydrogen releases, so that any released hydrogen is not pulled into a building via the ventilation system. It is important to take possible ignition sources into consideration.

Agreed routes for hydrogen vehicles, driver/operator training in the risks and hydrogen systems, including vehicle warning, and emergency response. For emergency response purposes, the hydrogen fuel bowser should be easy to visually differentiate from conventional fuel bowsers.

ROAD CONDITIONS

The fuel bowser components and systems should be compatible with all aircraft or runway de-icing fluids used at the airport, other automotive fluids, e.g. windscreen washer fluid, and road salt if they may be exposed landside. The hydrogen bowsers should be operated on roads for which they are designed, and not for example, along airside construction haulage routes where vibrations/ shocks/ dust may be more severe.

TUNNELS / UNDERPASSES

Fully or partially enclosed environments can lead to increased explosion overpressures in the event that ignition of a hydrogen air mixture is delayed. Airside roads may pass through a variety of enclosures including tunnels, underpasses beneath runways, taxiways or buildings, or partially enclosed roads beneath/alongside terminal buildings, etc.

If JET-A1 fuel bowsers are prohibited from any of the above enclosures, then hydrogen fuel bowsers should also be prohibited in the absence of further in-depth risk analyses. Compliance with appropriate national legal requirements is necessary.

While it may be acceptable for a hydrogen powered vehicle such as an airport bus to traffic the above areas, it should be understood that the risk may be very different for a hydrogen fuel bowser intended for the bulk transport of hydrogen. A hydrogen powered airport vehicle would have ca 5 - 100kg of hydrogen on-board depending on the type of vehicle. A fuel bowser would have a maximum of ca 1000kg on a truck, or perhaps ca 2000kg if a truck and trailer combination was used. The increased quantity of hydrogen stored on the fuel bowser increases potential consequences compared to if hydrogen was used as a fuel for an airside vehicle.

As noted in earlier sections, the pressure relief vent locations and orientations need to be identified and considered in risk analyses, to determine appropriate risk mitigation measures including access restrictions.

STORING / PARKING (SHORT TERM)

Typically, short-term parking or storage of hydrogen bowsers should be in a secure location in the open, or beneath a single sloped roof or V-shaped roof so hydrogen can easily disperse to atmosphere and not be trapped beneath the structure by sides beams, for example. A risk analysis should be undertaken for the specific vehicles/machines and parking location(s).

LONG TERM STORAGE

Long-term parking or storage of hydrogen bowsers should be in a secure location in the open, or beneath a single sloped roof or V-shaped roof so hydrogen can easily disperse to atmosphere and not be trapped beneath the structure by sides beams, for example. Furthermore, depending on the particular circumstances for long-term storage it may be appropriate to defuel the system to close to the minimum pressure/SoC recommended by the hydrogen system manufacturer. Alternatively, the system may be purged of hydrogen with an inert gas such as nitrogen if the vehicle is to be out of use for extended periods, e.g. end of demonstration project or end of operational life. A risk analysis should be undertaken for the specific parking or storage location(s) and operational needs.

MAINTENANCE

Maintenance workshops should, as a minimum, comply with appropriate national legal requirements. However, in many cases national legal requirements may not take into account the specific hazards related to hydrogen.

Maintenance activities will require the introduction of specific measures to handle hydrogen vehicles. A full risk analysis should be undertaken for the specific workshop considering, for example, ventilation, hydrogen gas and flame detection systems including any automatic response systems, any maintenance bay specific measures such as hoods and extra ventilation, proximity to hot work, any specific tools, e.g. non-sparking, staff personal protective equipment (PPE), role specific training, outside quarantine area for damaged hydrogen vehicles, and safe maintenance and emergency procedures. Safe venting locations and procedures are necessary, which may involve the release of hydrogen from a vent mast to open atmosphere, to a flare mast, or even into a specific hydrogen storage unit.

3.2.2 REFUELLING CONCEPTS

EXISTING REFUELLING CONCEPTS

Hydrogen-powered aircraft require innovative refuelling strategies to ensure operational safety, efficiency, and environmental sustainability. To develop future hydrogen refuelling processes, it is essential to analyse existing refuelling concepts for both conventional and hydrogen-based aviation.

In conventional aviation, sever
al refuelling concepts are already established and widely used depending on the size and operational structure of the airport. At smaller airfields, self-service refuelling stations are common. These stations allow pilots to refuel their aircraft independently using automated systems for payment and fuel delivery. While this approach offers a high degree of flexibility and reduces the need for ground personnel, it also requires strict safety standards due to the flammable nature of kerosene.

At larger airports, mobile refuelling units in the form of fuel trucks are frequently used. These trucks transport fuel directly to the aircraft and provide a high level of mobility and operational flexibility. Because they can carry large quantities of fuel, they are particularly suitable for commercial operations and busy airport environments. However, their use requires trained personnel and strict operational procedures to minimize risks such as fuel spills or fire hazards during the refuelling process.

Another common solution at major airports is the hydrant refuelling system. In this approach, fuel is delivered to aircraft through underground pipelines connected to refuelling pits located near the parking positions. This system significantly reduces the need for fuel truck movements on the apron, increases operational efficiency, and lowers potential safety and environmental risks associated with transporting fuel across the airport.

HYDROGEN-SPECIFIC CONCEPTS

Future hydrogen refuelling concepts are likely to build on these established approaches but must account for the specific physical and chemical properties of hydrogen. Compared to conventional jet fuel, hydrogen has a much lower density, is typically stored at high pressures, and is highly flammable. These characteristics require adapted infrastructure, enhanced safety measures, and specialised refuelling technologies.

One possible solution is the use of mobile refuelling units transporting gaseous hydrogen in high-pressure tanks. These hydrogen fuel trucks would operate similarly to conventional fuel trucks but would require reinforced containment systems capable of handling pressures typically ranging from 350 to 700 bar or even higher, see chapter 3.1.2.3. To ensure safe operation, additional safety technologies such as hydrogen leak detection systems, overpressure protection, and dedicated hydrogen sensors would be necessary. During the refuelling process, cascade refuelling could be applied, and compressors might be required to match the pressure levels between the storage tanks and the aircraft tanks. In this report, the focus lies on gaseous hydrogen, while liquid hydrogen is not further examined.

Another approach involves the on-site production of hydrogen at airports, for example through electrolysis powered by renewable energy sources. Producing hydrogen directly at the airport could reduce transportation risks and contribute to broader sustainability goals within the aviation sector. In such scenarios, aircraft could be refuelled with gaseous hydrogen either through stationary dispensers, conceptually similar to self-service refuelling stations, or through mobile fuel trucks or bowsers. Naturally, this concept would require further technological development, particularly in the areas of scaling and cost-efficient hydrogen compression, storage and dispensing.

Another approach involves the on-site production of hydrogen at airports, for example through electrolysis powered by renewable energy sources. Producing hydrogen directly at the airport could reduce transportation risks and contribute to broader sustainability goals within the aviation sector. In such scenarios, aircrafts could be refuelled with gaseous hydrogen either through stationary dispensers, conceptually similar to self-service refuelling stations, or through mobile fuel trucks or bowsers. Naturally, this concept would require further technological development, particularly in the areas of scaling and cost-efficient hydrogen compression, storage and dispensing.

It should also be noted that hydrogen refuelling stations without on-site production represent a valid alternative. In these cases, gaseous hydrogen could be supplied to airports via GH_2 tanker deliveries and subsequently stored and distributed on-site for aircraft refuelling.

By integrating these concepts, future hydrogen refuelling systems can blend the efficiency of hydrant systems with the flexibility of mobile refuelling trucks and the sustainability of on-site production. Emphasising safety, technological advancement, and environmental responsibility will be key to enabling hydrogen as a cornerstone of aviation’s green transition.

GENERAL FRAMEWORKS FOR HYDROGEN REFUELLING

To ensure safe and standardised handling during aircraft turnaround, hydrogen refuelling procedures must be integrated with flight crew coordination and ground handling processes.
An important element of this integration is the definition of refuelling levels, which clarify the degree of supervision and cockpit involvement during the process. Additional frameworks are also specified in this chapter.

REFUELLING LEVELS

Level 1 – Unattended or Semi-Attended Refuelling

- The cockpit is unoccupied, or the crew is not actively monitoring.
- Only allowed under strict safety conditions.
- Emergency shut-off systems must be accessible.
- Used during early turnaround or when crew is not yet onboard.

Level 2 – Attended Refuelling

- The flight crew is present and actively monitoring the process.
- Enables real-time adjustments and immediate response to issues.
- Continuous communication between the cockpit and fuelling operator is required.

REFUELLING PANEL SETTINGS

Located under the wing or fuselage, the **refuelling panel** includes:

- **Fuel Quantity Selectors:** Set the desired amount per tank.
- **Tank Selection Switches:** Choose which tanks to fill (e.g., left wing, centre).
- **Pressure Gauges:** Monitor fuel pressure during delivery.
- **Flowmeters:** Track the exact amount of fuel delivered (e.g. mass capacity method).
- **Emergency Shutoff:** Instantly halts fuelling if needed.
- **Interphone Jack:** Connects to the cockpit for coordination.

STAFF COORDINATION

Before Fuelling:

- The fuelling operator verifies the aircraft and fuel order.
- The fuelling operator inputs the required fuel quantity and tank configuration.
- The fuelling operator confirms settings with the cockpit before starting fuelling.
- The captain confirms total fuel requirements, including reserves and alternate fuel.
- Any special instructions are communicated to the fuelling team.

During Fuelling:

- The cockpit monitors fuel gauges and tank levels.
- Adjustments can be made based on balance or performance needs.
- Any anomalies are reported and addressed immediately.

After Fuelling:

- The pilot signs off on the fuel receipt.
- Final fuel data is entered into the flight management system (FMS).
- The aircraft is cleared for further ground operations.

ANALYSIS: PROS AND CONS OF HYDROGEN REFUELLING CONCEPTS

Hydrogen refuelling concepts for aircraft vary significantly in terms of efficiency, costs, safety, and environmental impact. The choice of system will depend largely on the airport's size and operational requirements. Below is an evaluation of the primary refuelling methods, considering these factors.

Compressed Gas Fuel Trucks (used as mobile or stationary fuel solutions)

Advantages	Disadvantages
Flexibility: Trucks can be deployed at various locations, making them ideal for small regional airports or situations where fixed infrastructure is unavailable.	**Limited Efficiency:** Refuelling times may be slower compared to fixed systems, especially for high-traffic airports.
Lower Initial Costs: Compared to hydrant systems, fuel trucks require less upfront investment.	**Operating Costs:** Maintenance of high-pressure systems and training staff increases operational expenses.
Scalability: Fleets can be scaled according to airport demand, providing adaptability for fluctuating traffic.	**Safety Risks:** Mobile operations pose a higher risk of leaks during transportation, connection and transfer.
Limited airport infrastructure adaptions, both for the airport operator and for the aircraft operator with limited impact on current airport operations.	**Space requirements**: For increased traffic the space requirements for truck positioning will be of need for space accordingly.

TABLE 2:
Pros and Cons of Fuelling Trucks

Best Fit: Small to medium-sized airports with moderate traffic.

Hydrogen Hydrant Systems

Advantages	Disadvantages
High Efficiency: Underground pipelines enable rapid and continuous fuel delivery, reducing aircraft turnaround times.	**High Upfront Costs:** Installation requires significant investment and impact in infrastructure and materials resistant to hydrogen embrittlement
Reduced Transportation Risks: Hydrogen is stored and transported underground, minimizing safety hazards.	**Complex Maintenance:** Pipelines and hydrant systems require advanced monitoring and specialized repairs.
	Limited Flexibility: The system is stationary, making it unsuitable for small airports or those with sporadic traffic.

TABLE 3:
Pros and Cons of Hydrant Systems

Best Fit: Large international airports with high operational demands and long-term hydrogen adoption plans.

Comparison by Airport Size

Factor	Small Regional Airports	Large International Airports
Compressed Gas Trucks	Suitable for flexibility and lower traffic demands	May struggle with high traffic and efficiency needs
Hydrant Systems	Impractical due to high costs and low utilization	Ideal for high-traffic operations and long-term use
On-site Production	Feasible if renewable energy is available locally	Highly beneficial for sustainability and efficiency

EFFICIENCY, COSTS, SAFETY, AND ENVIRONMENTAL IMPACT

Efficiency: Hydrant systems are the most efficient for high-traffic airports, while trucks and on-site stations provide more flexibility for smaller locations.

Costs: Compressed gas trucks have lower upfront costs but higher operational expenses. Hydrant systems require substantial investments but offer long-term savings for large airports.

Safety: Hydrant systems and on-site production change transportation-related risks, though trucks, as any hydrogen system, require rigorous safety measures to handle high-pressure hydrogen.

Environmental Impact: On-site production powered by renewables is the most environmentally friendly solution, while hydrant systems also reduce emissions associated with fuel transport.

CONCLUSION

The choice of the hydrogen refuelling concept should align with airport size and traffic levels. Smaller airports may prioritize flexibility and cost-effectiveness, favouring compressed gas trucks or compact on-site systems. Larger hubs, however, benefit most from hydrant systems and large-scale hydrogen production, enabling efficient, high-volume operations while supporting global sustainability goals.

3.2.3 FUEL TRUCK PROCESS

To understand the refuelling process by truck it helps to use a concept written by ZeroAvia as a basis. This is done in chapter 3.2.3.1. All marked information in that chapter is taken from the feasibility study “Hydrogen demonstration flight between Rotterdam The Hague Airport and Hamburg Airport with ZeroAvia” (2025), it was supplemented by information gained in personal conversations with ZeroAvia. In the chapters following the ZeroAvia concept, all important aspects of hydrogen aircraft refuelling by truck are stated and described.

ZEROAVIA TRUCK REFUELLING PROCESS

The truck used by ZeroAvia is a standard 40ft trailer, the general characteristics can be found in table 1. It operates using cascade refuel architecture, filling the aircraft from six-cylinder banks with different initial pressure. Another variant for the refuelling technology is a compressor to reach the target pressure of the aircraft hydrogen system (usually 350 or 700 bars).

To start the cascade refuelling process, which follows the fuel protocol specified by SAE J2601, “the initial pressure of the aircraft's hydrogen storage tanks is recorded”, if it can be found for example on an outside panel on the aircraft. Otherwise, it must be captured by the fuelling hose/adapter. Additionally, the ambient temperature is recorded.

“Once the refueller completes its automated pre-checks — which include system communication, pressure hold, leak checks, and hydrogen detection system checks — and raises the deployable vent stack, the operator will connect a bonding wire to the aircraft to equalize the electrical potential (as done today as well for conventional fuels) and then connect the refuelling hose to the aircraft. The integrated infrared communications refuelling nozzle will read the signal provided by the aircraft to ensure compatibility, check aircraft tank pressure, do a pressure system check for leakages and monitor tank temperatures. Once the operator confirms that this information aligns with earlier checks, they will select a State of Charge (SOC) percentage to which they want to fill the aircraft.” This choice also allows for a partial refuelling for example for test flights.

“If the aircraft health signal remains positive, refuelling will begin by opening the lowest available cylinder bank (the one with the lowest pressure that still provides a sufficient pressure differential, or Delta P, to the aircraft). […] Once the pressure between the aircraft and […] [that bank] equalizes, the next lowest available bank […] would open, and so on, until the aircraft reaches the desired SOC. This example demonstrates a cascade fill architecture.

While the lowest available cylinder bank is open, the system will monitor flow rates, pressures, temperatures, and average pressure ramp rates (the rate at which the aircraft pressure is increasing). It will use flow control to ensure all parameters stay within limits and that the average pressure ramp rate remains within the acceptable corridor (in accordance with J2601)." It should be noted that the available documentation does not specify whether the SAE J2601 fuelling control is based on lookup tables or the MC Method.

"Once the aircraft has reached the desired SOC, the cylinder banks are closed, and the refuelling hose is disconnected. The bonding lead can then be disconnected also. The refuelling system will then vent any remaining hydrogen in the manifolds (and in the hose), lower the vent stack, and prepare for transport. The final pressure and SOC are recorded on the aircraft, completing the refuelling process."

For safety reasons, the refuelling process designed by ZeroAvia provides the mandatory emergency button to stop the flow of hydrogen if a problem arises, but their refuelling process doesn't involve the use of a dead man switch (DMS).

HANDLING STEPS HYDROGEN VS. KEROSENE

In **Table 4**, the basic steps of refuelling a hydrogen aircraft are listed and compared to those of refuelling a conventional aircraft powered by kerosene or avgas.

hydrogen	conventional
record aircraft tank pressure	
record ambient temperature	
refueller pre-checks	
raising of refueller vent stack	
connect bonding wire	connect bonding wire
connect integrated refuelling hose	connect refuelling hose
select planned State of Charge	check/select fuel amount at aircraft panel
hydrogen sample (if necessary)	liquid sample (in certain turn arounds)
fuelling (automatically monitored and controlled; use of DMS → JIG 7.2.5)	fuelling (using DMS)
disconnect refuelling hose	disconnect refuelling hose
disconnect bonding wire	disconnect bonding wire
vent hose & manifolds	
lower vent stack	
record pressure & SOC on aircraft	

TABLE 4:
Differences of conventional JETA1 and hydrogen refuelling

SAMPLING & HYDROGEN QUALITY

Refuelling a conventional aircraft usually requires taking a fuel sample before certain fuelling processes, typically before the first fuelling event of the day or after refilling the refueller's fuel tank. It still has to be determined whether it will be necessary to take hydrogen samples before the refuelling process. This will, among other things, depend on the particular refuelling concept. Arguments against it are the storage of the gas in a closed system, whose internal pressure is much higher than the ambient pressure, making it impossible for contamination to get in. If sampling should still prove to be necessary, as contaminated hydrogen may result in a loss of propulsion power, it could be done via gas analyses at the airport. In a newly purged system, e.g. after maintenance on a defuelled system, some form of check will be needed anyway to ensure that the hydrogen concentration in the aircraft tanks is sufficiently high.

The required hydrogen quality/purity is dependent on the aircraft manufacturer, who refer to industry standards. These are:

IAW SAE J2719
ISO 14687

REFUELLING NOZZLE

The following standards and specifications are stated by the aircraft manufacturers for the connection between aircraft refuelling point and the refuelling hose:

- H35 refuelling nozzle (WeH TK16, ZeroAvia)
- H70 refueling nozzle (WeH TK20, BeyondAero)
- H70 refuelling nozzle (WeH TK20, BeyondAero)
- connection Type A (SAE J2600, Apus – 2025 – not existing anymore in 2026)

Apart from that, all manufacturers state the objective to standardize the requirements as far as possible and to adapt current and future industry standards for their products. This is also partly justified by the need to avoid cross-compatibility, it should for example not be possible to refuel a 350 bar system with a 700 bar refuelling system. However, a 700 bar aircraft system may potentially be refuelled from a 350 bar source, resulting only in a partial fill depending on the system pressure and refuelling architecture.

Relevant standards based on automotive practice include:

- ISO 17268-1:2025 Gaseous hydrogen land vehicle refuelling connection devices
  - Part 1: Flow capacities up to and including 120 g/s [specifies H35, H70, etc]
- SAE J2601.2 (350 bar systems)
- SAE J2601.5 (700 bar systems)

In the future:

- ISO/CD 17268-2.2 Gaseous hydrogen land vehicle refuelling connection devices
  - Part 2: Flow capacities greater than 120 g/s
- The SAE AE 5CH working group has been working on hydrogen aircraft refuelling protocols for both gaseous and liquid hydrogen. New and adapted protocols are to be expected in the future.

FUEL AMOUNT MANAGEMENT

Instead of requesting the required additional number of litres of kerosene, as it is done by operators of conventional aircraft, the process of establishing the required fuel amount for hydrogen powered aircraft can be done in two different ways.

One uses the State of Charge (in percent) of the aircraft, corresponding to the desired tank pressure. First, the initial pressure of the aircraft's hydrogen tank is recorded, either from the corresponding aircraft display or outside panel or by an integrated refuelling nozzle connected to the refuelling hose. This is equivalent to ascertaining the current fuel level of a conventional aircraft. Next, instead of choosing the needed amount of additional hydrogen, the required State of Charge (in percent) of the hydrogen tanks is selected, and the aircraft is refilled accordingly.

Another method could be a flow rate detector to establish the amount of hydrogen which is transferred to the aircraft. A flowmeter will also be necessary independent from the method for accounting reasons.

The process again will depend on the specific refuelling requirements of the aircraft manufacturer.

STAFF AND COMMUNICATION PROCESS

During the first handlings of hydrogen powered aircraft, the processes will presumably be accompanied very closely by the aircraft manufacturers. In most cases those will even do the refuelling themselves, resulting in customized staff and communication processes. Afterwards, as the concept of hydrogen aircraft is established at airports, there is no reason not to keep the current processes as seen from today. This could mean one of the following examples of staff and communication scenarios:

1. Operator (pilot/airline) refuels their aircraft by themselves, e.g. at a fuel station
2. refuelling operator keeps in constant exchange with aircraft operator while refuelling
3. ramp agent keeps in constant exchange with aircraft crew via radio while keeping eye contact with refuelling operator

VENTING

As stated in chapter 3.1.2, hydrogen is 14x lighter than air and therefore rises quickly when released. This behaviour leads to the need for venting zones opening upwards on top of the hydrogen tanks of the aircraft, compared to the venting zones under the wings of conventional aircraft. Additionally, hydrogen trucks need venting as well as kerosene trucks. In all operations, normal and emergency, the mobile storage and dispensing unit designed by ZeroAvia uses a retractable vent stack with a height of approximately 1,8m above the unit top when deployed.

Venting upwards means that the ATEX-zones, that are usually located near the ground and under the wings of the aircraft, relocate to the area above the aircraft when refuelling with hydrogen, influencing mostly the possible stand position in relation to light posts, obstacle marking lights and other ignition sources in certain heights on the apron. Nevertheless, while connecting and disconnecting the fuelling hose, the ATEX-zones expand around the refuelling truck and the aircraft. The corresponding ATEX-zones for hydrogen aircraft are described in chapter 3.2.3.9.

HYDROGEN LEAKS

Hydrogen leaks can be viewed and handled differently from kerosene spills. Gaseous hydrogen is 14 times lighter than air and therefore rises and disperses. When released in small amounts and outside, the potential for danger is usually comparatively small, but when a crucial mix of the factors Ignition Source and flammable mixture of hydrogen and air (oxygen) within a specific concentration range is given, it can cause combustion or even explosion.

As these factors cannot always be excluded completely during the refuelling process of an aircraft, hydrogen releases must be prevented as much as possible. See chapter 3.1.2 for further information.

As hydrogen is odourless, colourless and tasteless, special sensors must be used to detect any hydrogen leaks at the fuel truck, the hose or nozzle or in the aircraft. Most sensors detect the presence of hydrogen, and ultrasound sensors can be used to detect the sound of gas escaping or special tapes changing their colour with contact to hydrogen are worth considering.

Also, visual alerts in the interior and exterior of the aircraft, when a drop in pressure is detected, may be used to signal to the flight crew and ground personnel that a potential hazardous leakage of hydrogen has occurred. (ZeroAvia Conops)

POSITION OF TRUCK, ESCAPE ROUTES, SAFETY DISTANCES, ATEX ZONES

The position of the refuelling truck depends on the location of the aircraft tanks and their specific refuelling points which are defined by the aircraft manufacturer. For airport operations, the established position on the opposite side of the aircraft from the passenger door would be desirable to maintain, as this would influence airport layout as few as possible. Aircraft manufacturers as e.g. BeyondAero have confirmed to plan to place the refuelling point accordingly.

Possible other positions of the refuelling truck are directly in front or behind the aircraft, respectively in a 90° angle to the aircraft longitudinal axis (picture 1). This has a direct impact on the aircraft stand layout, as an aircraft, which e.g. must be refuelled from the front, nose-in positioning directly in front of a building may be restricted by explosion safety zone regulations. Additionally, the aircraft must be safely secured so that it can't collide with the refuelling truck. A refuelling position directly behind the aircraft may influence or even restrict the moving areas of other aircraft handling processes. The safety distance between truck and aircraft will still need to be determined (ZeroAvia Conops). In any case, the escape route for the refuelling truck must be always kept clear of obstacles.

The safety zones around the aircraft and the refuelling truck are still to be established. This will be done by the manufacturers building on regulatory frameworks. The safety zones determine the areas which must be free of any possible ignition source during the refuelling of the aircraft.
For small hydrogen aircraft, it may be likely that no other activity can take place within the refuelling safety perimeter during refuelling. For business aviation, however, this may not necessarily be a major operational issue, as many other turnaround activities are relatively short. The hydrogen refuelling time itself may therefore remain the main driver of the total turnaround time. (Beyond Aero)

In their first concept, ZeroAvia defines a safety distance of approximately 2 m left and right and 1 m in front of the refueler. Additionally, a 2.6m Radius is drawn on top of it and a 2.3m Radius around the back of the refueler, where the system is controlled from. These areas are classified as ATEX 2 zones, where “an explosive atmosphere consisting of a mixture with air or flammable substances in the form of gas, vapour or mist is not likely to occur in normal operation but, if it does occur, persists for a short period only.” (IEC 60079-10-1 Area Classification) As ATEX 1 zone (“a place in which an explosive atmosphere consisting of a mixture with air or flammable substances in the form of gas, vapour or mist is likely to occur in normal operation “), only the conical area above the vent stack is classified.

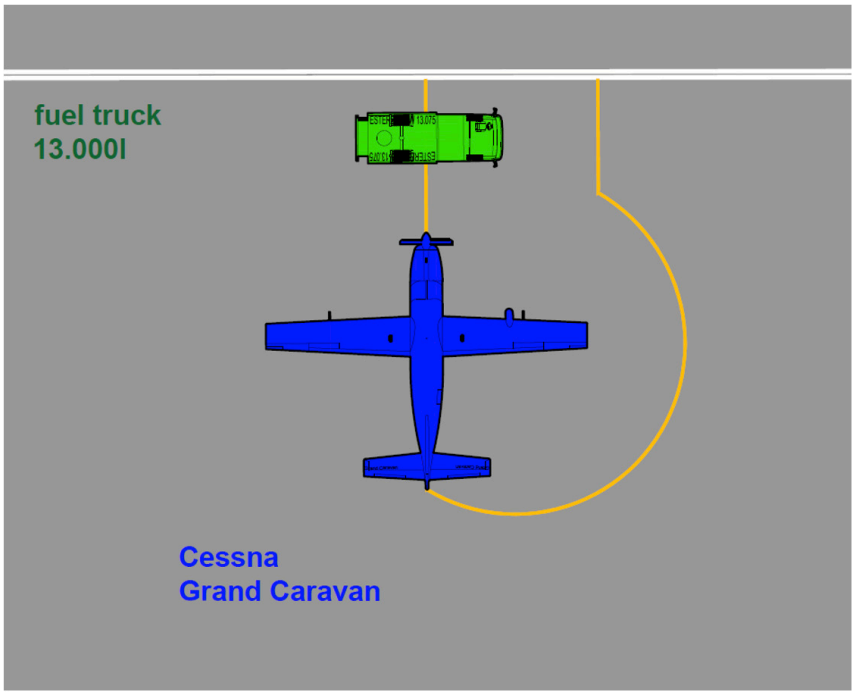


FIGURE 4:
Possible Stand-layout for Cessna Grand Caravan and a Fuelling Truck

3.2.4 FUEL STATION PROCESS

Building on the discussion of hydrogen storage risks and the importance of leak detection and safety zones, the following section offers an overview of current and emerging operational practices for stationary aircraft refuelling. Special attention is given to the unique requirements of hydrogen-powered systems, while also contrasting conventional fuelling methods with the adaptations necessary for alternative fuels. This sets the foundation for a comprehensive understanding of evolving safety and process standards in airport fuel operations.

OVERVIEW OF EXISTING FUELLING PROCESSES

Airports currently use highly standardized processes for the fuelling of conventional aircraft, such as those powered by jet fuel (Jet A-1), and alternative fuels (e.g., biofuels, synthetic fuels). The processes typically involve multiple key stages as listed:

When the aircraft arrives at the gate or stand and has come to a complete stop, the flight crew sets the parking brake and signals that it is safe for the ground crew to approach. The ground crew then secures the aircraft using wheel chocks and safety cones to ensure that it remains stationary during ground operations. Communication is established between the flight crew and ground operations personnel to coordinate the upcoming procedures. At the same time, all required documentation, including the fuel uplift request and fuel release forms, is reviewed and prepared. The aircraft is also assessed for any special fuelling requirements, such as the need for defuelling, fuel balancing, or compliance with specific fuel temperature limits.

At a self-service hydrogen refuelling station, the correct positioning and securing of the aircraft is a critical prerequisite for initiating the fuelling process and ensuring operational safety in accordance with international standards. The aircraft must enter the designated fuelling lane at low speed under the supervision of a marshaller or an automated guidance system. The aircraft must stop at the designated position aligned with the ground markings. This position must ensure a minimum clearance of 5 meters from the fuelling pedestal on the lateral axis and at least 3 meters from any adjacent aircraft or obstacles. Immediately after the aircraft has stopped, wheel chocks must be applied, and the parking brake must be engaged.

Before fuelling operations begin, a restricted safety zone must be established around the fuelling point. Taking the regional airport of the island of Sylt in northern Germany, the best practice for the radius of this safety zone is at least 7,5m. This area is typically marked with cones or illuminated barriers to clearly define the safety boundary. Only trained personnel or authorized crew members equipped with appropriate personal protective equipment are permitted to enter this zone during fuelling operations. To reduce ignition risks, no potential ignition sources such as vehicles, open flames, or electronic devices may be present within a certain distance from the fuelling area. At Sylt airport e.g., this distance amounts to 15m.

Another essential safety measure is the grounding and bonding of the aircraft. Before any fuelling equipment is connected, the aircraft must be bonded to the station grounding point in order to prevent electrostatic discharge. The electrical continuity of the bonding connection must be verified using approved bonding testers.

In addition, engines, the auxiliary power unit (APU), and all non-essential electrical systems must be shut down before fuelling begins. If the aircraft is equipped with hydrogen detection sensors integrated into the cabin or ventilation system, the cabin ventilation should remain active to support continuous monitoring.

Emergency preparedness must also be ensured before the start of the fuelling process. Emergency stop buttons and hydrogen leak detection alarms must be operational and clearly visible to personnel. Appropriate firefighting equipment, including at least Class D and cryogenic-rated fire extinguishers, must be located within immediate reach of the fuelling area. Furthermore, all emergency evacuation routes must always remain clear and unobstructed.

During the fuelling process itself, additional operational considerations apply. For gaseous hydrogen fuelling, pressure equalization must be confirmed before the coupling between the fuelling system and the aircraft is established. In the case of liquid hydrogen fuelling, additional cryogenic personal protective equipment and boil-off gas management procedures would be required. Regardless of the fuelling method, continuous monitoring of the operation through hydrogen sensors and visual inspections is mandatory throughout the entire refuelling process.

FUTURE HYDROGEN REFUELLING PROCESS

Fuel Request and Coordination

- The airline or its ground handling agent initiates the fuel order:
- The required fuel quantity, type (usually Jet A-1), and distribution across tanks are specified.
- The estimated fuelling time and stand number are communicated to the fuelling service provider.
- The fuel provider confirms availability and dispatches the appropriate fuelling equipment (truck or hydrant dispenser).
- Coordination with the flight crew ensures alignment with the flight plan and aircraft performance needs.

Fuel Source and Quality

Fuel is stored in large airport fuel farms and undergoes strict quality control, including:

- Filtration,
- Water detection,
- Temperature checks,
- Additive verification (e.g., anti-icing agents).

Fuelling the Aircraft

- The fuelling operator connects the hose to the aircraft's fuelling port.
- Grounding cables are attached to prevent static discharge.
- The operator starts fuelling, monitoring flow rate and pressure.
- Safety zones are enforced, and fire extinguishers are on standby.

Monitoring and Control

The entire fuelling process is continuously monitored:

- Flowmeters ensure accurate delivery.
- Pressure sensors prevent over-pressurization.
- Visual checks detect leaks or spills.
- Communication with the cockpit is maintained throughout.

Completion and Safety Checks

- Fuelling is stopped once the target quantity is reached.
- The hose is depressurized and disconnected.
- Fuel caps and access panels are secured.
- A final inspection ensures no leaks or hazards remain.
- All documentation is completed and signed by both the fuelling operator and flight crew.

3.2.5 DEFUELLING AND PURGING

Defuelling of the aircraft on the ground may be necessary for a number of reasons, including to allow safe maintenance, following accidental damage, e.g. due to impacts with ground vehicles/ equipment, or prior to long term storage. Defuelling of the aircraft does not include venting of hydrogen from pressure relief devices, e.g. due exposure of the hydrogen system due to fire. The type of defuelling may be dependent on the specific maintenance/damage, and which part(s) of the hydrogen system are affected. For example, minor repairs to parts of the aircraft not related to the hydrogen system may not require defuelling at all, while maintenance to the propulsion system may not require full defuelling of the hydrogen tanks if they can be safely isolated and the affected part of the system purged with an inert gas. In some cases, partial defuelling of the hydrogen system to the recommended minimum pressure may be adequate to restrict the quantity of hydrogen onboard while avoiding certain risks to the integrity of the hydrogen system if unnecessary full defuelling took place. Typically, manufacturers of high-pressure hydrogen storage systems recommend that the systems not be emptied below a certain threshold under normal operating conditions. This is to avoid problems with air or moisture ingress, liner buckling, etc.. BeyondAero e.g. estimates a minimum pressure of around 20 bar in each tank regarding the unusable hydrogen remaining in the storage system. Other maintenance, either directly or indirectly affecting the hydrogen system may require full defuelling of the aircraft, e.g. major work on the hydrogen system, or nearby parts of the aircraft that could cause damage to the hydrogen system, hot work (welding, sparking, grinding, etc), or on control systems that may affect the hydrogen system.

In a hydrogen storage system, there is normally no risk of internal combustion (fire/ explosion) as the hydrogen concentration will be 100%, i.e. there is insufficient air/oxygen for combustion. However, if air enters the system, combustion may occur. If a system is to be fully defueled, then it must be purged of hydrogen with an inert gas such as nitrogen passed through the system to flush out the hydrogen. Appropriate procedures should be developed specifying the number of purge cycles needed to ensure that the hydrogen concentration in the hydrogen system is reduced below flammable levels throughout the system, before the system is either intentionally (e.g. hydrogen system maintenance/ repair) or accidentally (e.g. fuel line damage) opened to atmosphere allowing the ingress of air.

Typically, automotive manufacturers provide detailed maintenance instructions for defuelling and purging of hydrogen vehicles, including the gases and any special venting equipment/tools that may be needed. Aircraft manufacturers, together with their system/components suppliers, should develop appropriate procedures for safely defuelling and purging the aircraft hydrogen systems, including clear guidance on when partial or full defuelling and system purging are required, any special tools or procedures. These should be based on appropriate risk analyses for the aviation environment.

3.2.6 SAFETY ZONES AND MEASURES

It is essential to recognize that national legislation takes precedence when establishing safety zones and implementing safety measures at airports. Harmonizing such protocols across borders is inherently challenging, as the assumptions underpinning safety distances and acceptable risk levels vary significantly from one country to another. At the same time, it is anticipated that EASA will establish standardized safety distances for hydrogen aircraft operations, providing a common regulatory framework across European aviation.

At this early stage however, standards for safety zones for handling and refuelling of hydrogen powered aircraft are not defined yet, as these are highly dependent on the specific aircraft and therefore on the aircraft manufacturer, which are partially already providing initial safety zone assumptions (see Hydrogen Regulatory Framework for France, Beyond Aero).

3.2.7 INCIDENT AND EMERGENCY PROCEDURES FOR HYDROGEN-POWERED AIRCRAFT

The introduction of hydrogen-powered aircraft requires adapted incident and emergency procedures at airports due to the specific physical and operational characteristics of hydrogen as an energy carrier. While the overall response philosophy remains comparable to that applied to conventional fuels, hydrogen-specific risks and mitigation measures must be systematically integrated into existing airport procedures.

International standardisation of incident and emergency response for hydrogen systems should be regarded as a long-term objective. However, as regulatory requirements, safety frameworks, and operational responsibilities currently vary between countries, all procedures described in the following sections are intended as guidance. They shall be adapted to comply with national legislation, regulatory authorities, and local airport emergency plans.

The procedures are therefore structured in two complementary parts:

Incident Procedures, focusing on the organisational framework, scenario classification, and decision-making processes.

Emergency Procedures, addressing the immediate operational response to accidents or abnormal situations involving hydrogen-powered aircraft.

INCIDENT PROCEDURES

Incident procedures provide a structured overview of potential response actions for events involving hydrogen-powered aircraft or hydrogen systems that may affect airport operations. These procedures are primarily intended to support early assessment, coordination, and escalation decisions and shall be integrated into local airport checklists.

Incident response actions shall consider, as a minimum, the following scenarios:

- Incidents occurring within the airport area, including operational surfaces and aprons, as well as within 1,000 metres beyond runway ends.

- Incidents outside the airport perimeter that may nonetheless affect airport safety or require coordination with external authorities.
- Aircraft system faults occurring during flight, including situations requiring priority landing or emergency handling.
- Situations involving leak prevention measures and control of potential ignition sources.
- Fire-related scenarios, including the evaluation of whether fire suppression or controlled burn-off is appropriate.
- Security-related incidents, such as sabotage, bomb threats, or hijacking.
- The integration of other local or national incident checklists, as applicable.

For aircraft using alternative fuels, including hydrogen, and in the case of abnormal or emergency situations, incident procedures shall ensure that the following initial information is identified and communicated:

- The type of fuel(s) and propulsion system used by the aircraft.
- The nature of the situation, such as gaseous or liquid hydrogen leaks, thermal runaway, fire, collision, or structural damage.
- Subsequent actions shall be based on an assessment of:
- The current operation or activity (e.g. landing, taxiing, refuelling).
- The location of the aircraft (runway, taxiway, parking stand, remote position, hangar).
- The presence of persons on board or in the vicinity of the aircraft.
- The quantity and state of flammable substances involved.

EMERGENCY PROCEDURES

Emergency procedures address the immediate operational response to accidents or critical abnormal situations involving hydrogen-powered aircraft. While the general emergency response structure remains consistent with that for conventional aircraft, hydrogen-specific hazards shall be explicitly evaluated and incorporated into firefighting, rescue, and first-aid operations.

In the event of an emergency, the following actions shall be initiated as appropriate:

- Alerting airport rescue and firefighting services.
- Initiating firefighting and medical response.
- Informing flight crew and relevant operational stakeholders.
- Specific abnormal or emergency situations for hydrogen-powered aircraft may arise from:
- The inherent characteristics of hydrogen, including difficulty in detecting leaks, low flame visibility, and high radiative heat from hydrogen fires.
- High-pressure gaseous hydrogen leaks from tanks, hoses, fittings, or associated systems.
- Activation of pressure relief or emergency venting systems.
- Risks of tank rupture or explosion, for example due to collision, fire exposure, or rapid temperature-induced pressure increase.
- Liquid hydrogen (LH_2) leaks, abnormal venting, or loss of thermal insulation.
- In the case of an aircraft accident, the primary objectives of emergency operations are to:
- Detect and assess any significant hydrogen leaks, venting, or accumulation of gaseous or liquid hydrogen in or around the aircraft.
- Evaluate potential damage to hydrogen tanks and assess the risk of explosion, particularly due to exposure to fire, elevated temperatures, or environmental conditions affecting LH_2 systems.
- Emergency procedures shall prioritise personnel safety, hazard zone control, and continuous reassessment of the situation, taking into account the dynamic behaviour of hydrogen-related hazards.

3.2.9 FIRE PREVENTION AND FIRE FIGHTING

The introduction of hydrogen-powered aircraft introduces new dimensions to airport emergency preparedness, fire prevention, and firefighting. As hydrogen operations scale—from gaseous hydrogen (GH2) to cryogenic liquid hydrogen (LH2)—airports must revise existing emergency response frameworks to account for the unique physical properties of hydrogen, its storage and transfer systems, and its behaviour during failures or incidents.

Effective fire prevention and firefighting relies on clear allocation of responsibilities, standardized communication procedures, and robust inter-organizational cooperation. Airport Emergency Response Plans (ERPs) should therefore incorporate hydrogen-specific elements while remaining aligned with ICAO, EASA, SAE, and local regulatory requirements.

Airport Rescue and Fire Fighting Services retain primary responsibility for immediate hazard mitigation across the airside environment. Their scope expands with hydrogen aircraft to include:

- Response to hydrogen leaks, cryogenic spills, and gas cloud formation.
- Handling invisible hydrogen flames using UV/IR flame detection systems.
- Coordination with fuel suppliers, hydrogen system operators, and ground handling providers.
- Operational oversight during hydrogen refuelling, defuelling, and storage operations.

Local fire brigades and hazardous-materials (HAZMAT) units often act as secondary responders, providing specialized support, especially for LH2 storage tank incidents, vapour cloud events, or large-scale terminal evacuations. For hydrogen aircraft operations, firefighting and rescue services (RFFS) need to be equipped and trained to handle hydrogen leaks, cryogenic exposure and hydrogen fires, including the use of specialized detection equipment and appropriate firefighting strategies.

Procedures must describe how airport operations transition from routine activities to emergency mode. This includes the transmission of critical information, such as aircraft fuel type, hydrogen storage configuration, and potential hazards (e.g. hydrogen leak indication, fuel cell malfunction, cryogenic tank overpressure…) from ATC to emergency responders. During the transition phase, the airport operations centre should initiate emergency coordination protocols and alert all relevant organizations.

During the transition period where multiple propulsion types operate in parallel—kerosene, electrified aircraft, and hydrogen—the fuel type must be transmitted to ATC upon arrival. This is essential so that RFFS prepares appropriate resources in advance, as recommended in the ZeroAvia CONOPS and industry working groups.

Types of Emergencies Covered in Hydrogen Operations
Emergency plans must explicitly define hydrogen related and conventional aviation emergencies, including aircraft accidents and ground incidents involving hydrogen:

- H2 leaks (GH2 or LH2), including high pressure line failures.
- Hydrogen fires, both visible and invisible.
- Vapour cloud formation and potential ignition.
- Cryogenic burns or embrittlement-related material failures.
- Boiling Liquid Expanding Vapour Explosion (BLEVE) risk for LH2 tanks.
- Electrical failures in fuel-cell systems.
- Explosions resulting from confined high concentration hydrogen pockets.

These must be integrated into multi-fuel airport emergency frameworks alongside kerosene, SAF, and battery-electric propulsion systems.

Organizations involved in the emergency plan
The emergency plan should list all participating organizations, including airport management, air navigation service providers, aircraft operators, ground handling companies, fuel suppliers, local fire departments, police authorities, emergency medical services, environmental agencies, and municipal authorities. It should also specify the coordination forums in which these stakeholders develop, review, and exercise emergency procedures.

A hydrogen-capable airport requires collaboration among:

- Airport Operator / Emergency Management
- RFFS / ARFF
- Air Traffic Control (ATC)
- Aircraft Operators and MRO Providers
- Hydrogen Fuel Provider(s)
- Hydrogen Storage & Distribution Operators
- Ground Handling Agents
- Local Fire Departments & HAZMAT Units
- Local Municipalities and Environmental Agencies (incl. SEVESO II/III compliance)
- Police, Security, and National Emergency Authorities

Plans should specify:

- How each entity participates in emergency preparedness forums.
- Frequency of hydrogen specific tabletop exercises and on site drills.
- Shared communication protocols and call hierarchies.

The emergency plan must clearly define the operational responsibilities of the airport rescue and firefighting service, including response within the aerodrome boundaries and coordination with municipal or regional fire brigades. For hydrogen aircraft operations, RFFS must be equipped and trained to handle hydrogen leaks, cryogenic exposure, and hydrogen fires, including the use of specialized detection equipment and appropriate firefighting strategies.

Emergency Situations to Be Addressed
Airport emergency plans should include procedures for handling a range of emergency situations, including:

- Aircraft system failures during flight that may lead to an emergency landing involving hydrogen fuel system.
- Hydrogen leaks, fires, or explosions involving aircraft, fuelling equipment, or storage infrastructure.
- Sabotage or bomb threats targeting aircraft or airport facilities.
- Hijacking or unlawful interference with aircraft operations.
- Ground incidents at the airport involving aircraft, vehicles, or hydrogen fuelling systems.
- Incidents involving dangerous goods transported through the airport.
- Fires in airport buildings, including hangars, terminals, or fuel infrastructure.
- Natural disasters such as severe weather events, flooding, or earthquakes that may impact hydrogen infrastructure.
- Public health threats affecting airport operations.
- Environmental or safety impacts on neighbouring communities or businesses.

Hydrogen-Specific Fire Prevention Measures
Hydrogen presents several unique fire safety considerations. Hydrogen flames can be nearly invisible in daylight, hydrogen gas disperses rapidly upward due to its low density, and liquid hydrogen presents cryogenic hazards that may embrittle materials or create cold burns.

Fire prevention strategies should therefore include:

- Continuous monitoring of hydrogen infrastructure using gas detection systems and flame detectors.
- Ventilation systems designed to prevent hydrogen accumulation in enclosed areas.
- Separation distances between hydrogen storage, fuelling equipment, and other airport infrastructure in accordance with relevant safety standards.
- Regular inspection and maintenance of hydrogen pipelines, valves, and storage tanks.
- Personnel training on hydrogen properties, leak detection, and safe handling procedures.
- Clear exclusion zones around fuelling operations and hydrogen storage areas.

Firefighting Considerations for Hydrogen
In the event of a hydrogen fire, the primary firefighting strategy differs from conventional hydrocarbon fuel fires. Hydrogen fires typically involve high temperature but relatively low radiant heat flames that rise vertically. Firefighters must therefore focus on controlling the hydrogen source and protecting surrounding structures rather than extinguishing the flame prematurely if gas release continues.

Typical response measures may include:

- Immediate establishment of safety zones and evacuation of personnel.
- Identification and isolation of the hydrogen source.
- Cooling of surrounding equipment or structures using water to prevent escalation.
- Use of specialized detection equipment to locate invisible flames or leaks.
- Coordination with aircraft operators or hydrogen fuel providers to safely shut down fuel systems.

Coordination with Local Authorities and Communities
The potential impact of hydrogen-related incidents on neighbouring communities must also be addressed. Emergency planning should include coordination with local municipalities, environmental authorities, and regional emergency management organizations. In regions where major accident hazard regulations apply, such as those under SEVESO legislation in the European Union, hydrogen storage and handling facilities may fall under additional regulatory oversight.

Publication of Hydrogen Infrastructure Information
Airports will be required to publish information about hydrogen fuel handling capabilities and aircraft stand design in the Aeronautical Information Publication (AIP), enabling aircraft operators and emergency responders to access relevant operational details. This may include the location of hydrogen fuelling infrastructure, designated stands for hydrogen aircraft, and operational limitations.

A standardized process should be established whereby the aircraft fuel type is communicated to Air Traffic Control upon arrival or during pre-arrival coordination. This information should be relayed to airport rescue and firefighting services so that they are aware of the specific hazards associated with the aircraft in case of an emergency. Such procedures ensure that responders can prepare appropriate equipment and response strategies in advance.

3.3 AIRCRAFT STAND DESIGN

For the long run, the goal should be to handle a hydrogen aircraft on any stand on the airport, unrestricted and independent from adjacent aircraft stands and alongside conventional aircraft. Nevertheless, for the first period, probably stands are to be preferred which offer flexibility and space to test and establish the new technology and specific handling processes. A certain distance to buildings, public areas, evacuation routes, roads, railways and especially fuel storage tanks are needed according to the respective safety distances. Special attention should be paid to any ignition sources in the vicinity of the stand, for example light posts or obstacle lights. As hydrogen from vents and possible leaks will rise in the air and drift away, no ignition sources should be over or near the refuelling area. When it comes to equipment on the stands, an additional earthing could be necessary depending on the aircraft model and manufacturer. Aircraft parking pavement should be constructed according to the requirements posed by hydrogen.

Airports will have to publish their resources regarding fuel handling and aircraft stand design in the Aeronautical Information Publication (AIP). (ZeroAvia Conops)

3.4 PASSENGER HANDLING

Regarding passenger handling, the process is highly dependent on whether parallel boarding is possible. In that case, passenger information and safety measures in the cabin are still to be specified. Aspects to be considered are: Process of parallel Boarding, Passenger Information and safety measures in the cabin.

3.5 OTHER AIRCRAFT HANDLING

This section provides an overview of the key operational procedures and considerations for handling hydrogen-powered aircraft beyond fuelling and passenger processes. It covers essential topics such as de-icing methods, ground power and heating services, and highlights unique safety requirements associated with hydrogen technology. The aim is to outline both the similarities and necessary adaptations in ground operations compared to conventional aircraft, ensuring safety and efficiency as hydrogen aircraft are integrated into airport procedures.

3.5.1 DE-ICING

Procedures for de-icing services for H2 powered aircraft do not change, services for aircraft according to IGOM, AHM and aircraft manual.
Still, it should be mentioned that gaseous hydrogen could have the potential to heat up the wings. This should be observed.

3.5.2 GROUND POWER (INCL. EARTHING) & PRE-CONDITIONED AIR (PCA)

Ground power and heating services for hydrogen-powered aircraft are generally equivalent to those for conventional aircraft and are performed in accordance with IGOM, AHM, and the respective aircraft manuals. However, when hydrogen-powered ground power units (GPU) are used, additional safety measures must be applied.

In particular, 28 V ground power units shall only be operated when positioned at least 3 m away from aircraft fuelling vents and venting points. The GPU shall be started and electrically connected prior to the commencement of fuelling and shall not be disconnected or operated during fuelling activities. In the event of a fuel spill, the GPU must be shut down immediately, provided this can be done safely, and shall remain stationary until the spill has been fully cleared.

GPUs and pre-conditioned air units (PCA) may remain unattended while connected to the aircraft, provided they are serviceable and correctly positioned. Prior to connection, aircraft power receptacles, cables, and plugs shall be inspected for cleanliness, damage, or signs of excessive wear or electrical overheating. The GPU power output shall not be energised until the connection to the aircraft has been completed, and disconnection or shutdown of the GPU shall only be carried out after approval from the flight deck.

DIFFERENCES IN PROCEDURES FOR HANDLING H2 AIRCRAFT

For hydrogen powered aircraft it is particularly important to be properly grounded to avoid electrostatic discharge which increases safety risks.

H2 GPU ADDITIONAL SAFETY ASPECTS

During the electrical supply of H2 powered aircraft through a H2 powered GPU, additional safety measures must be implemented. This includes activating hydrogen leak sensors, overpressure and temperature gauges, and assessing their integration with the acoustic signal system.

Use of hydrogen powered GPU can have an influence on turnaround times of aircraft and needs to be managed. The collaboration of all involved stakeholders through data sharing could enhance the process predictability and is seen as the first step towards robust and reliable processes by the consortium.

3.5.3 LAVATORY & WATER

Procedures for Lavatory & Water services for H2 powered aircraft do not change, services for aircraft according to IGOM, AHM and aircraft manual. Depending on the aircraft design, the refuelling point may be located at the rear of the aircraft. During refuelling, lavatory and water services cannot be provided simultaneously, which may result in longer overall servicing times.

For some aircraft types (like Cessna) the lavatory and water service is not foreseen at all.

3.5.4 BAGGAGE

Based on the current state of knowledge, baggage handling procedures for hydrogen-powered aircraft do not differ from those applied to conventional aircraft. Baggage loading and unloading activities are performed in accordance with established standards such as IGOM, AHM, and the respective aircraft manuals. The processes described cover the planning, supervision, execution, and safety oversight of baggage handling operations and reflect standard industry practice. Within the scope of this project, no hydrogen-specific adaptations to existing baggage handling procedures have been identified.

Supplementary Assessment – Potential Hydrogen-Specific Aspects (Outlook)

Although no deviations from current baggage handling processes are required at present, further development of hydrogen-powered aircraft and associated infrastructure may introduce additional considerations. The following aspects could become relevant in the future and should therefore be taken into account at a conceptual level:

- **Consideration of hydrogen-related hazard zones**
  Awareness or restriction zones around hydrogen tanks, venting points, or pressure relief devices could affect access to cargo holds or personnel positioning near the aircraft fuselage.
- **Coordination with hydrogen-related operational states**
  Baggage handling activities may need to be coordinated with specific aircraft states, such as active venting, refuelling, or system testing of hydrogen components.
- **Ignition source awareness**
  While baggage handling does not typically involve ignition sources, additional procedural guidance or training may be required to maintain appropriate awareness in the vicinity of hydrogen systems, including electrostatic or equipment-related considerations.
- **Interaction with special loads and dangerous goods**
  The compatibility of certain special loads or dangerous goods with hydrogen-powered aircraft configurations may require further assessment as operational experience increases.
- **Training and awareness requirements**
  Even without changes to operational procedures, an increased focus on hydrogen-specific risks may necessitate tailored training or awareness measures for ground handling personnel involved in baggage operations.

3.5.5 OTHER (CLEANING, CATERING)

Procedures for other services (cleaning catering etc.) for H2 powered aircraft do not change, services for aircraft according to IGOM, AHM and aircraft manual.

3.5.6 SUMMARY

Chapter 3.5 addresses the ground handling procedures for hydrogen-powered aircraft, specifically focusing on power and air supply, baggage handling, and other services such as cleaning, catering, lavatory and water. For the most part, these procedures remain unchanged and continue to follow established guidelines from IGOM, AHM, and aircraft manuals. The main exception is that lavatory and water servicing cannot occur simultaneously with refuelling—particularly if the refuelling point is at the aircraft's rear—which may extend overall service times. Otherwise, baggage and other service procedures are unaffected by the introduction of hydrogen propulsion.

3.6 AIRCRAFT MOVEMENT ON AIRPORT

3.6.1 GENERAL - PUSHBACK AND TAXI

Regarding Pushback and Taxi, there possibly won't be any significant changes in comparison with the conventional aircraft. Only "engine start-up procedures will change, as propulsion will be electric". Also, standard operating procedures for single-engine taxi operations and engine start up procedures may need to be reviewed.

3.6.2 WATER AS BY-PRODUCT

As liquid water is a by-product of using hydrogen in a fuel cell, a water trail may be expected by a fuel-cell powered aircraft on the tarmac during operations, consisting of up to 5 litres per minute at ground idle. (ZeroAvia Conops) However, other manufacturers such as BeyondAero state a lower value. The quantity and location of water discharge are expected to depend on the aircraft design, fuel cell architecture, operational power demand, and the manufacturer's water management strategy. As a result, both discharge rates and discharge locations may vary between aircraft concepts and should be considered during airport infrastructure and operational planning, as they determine where water may accumulate on the apron and whether specific mitigation measures are required. Based on these discharge characteristics, several operational and infrastructure-related considerations emerge for airports accommodating fuel-cell powered aircraft.

Accumulation on the stand

Depending on the duration of ground operations and local weather conditions, discharged water may accumulate on the apron surface near the aircraft stand. The extent of accumulation will depend on factors such as discharge rates, pavement characteristics, stand gradient, and existing drainage capacity.

Drainage considerations

Adequate drainage systems may be required to prevent the formation of standing water in aircraft parking areas. Existing apron drainage infrastructure should therefore be assessed to determine whether it can accommodate continuous water discharge from fuel-cell powered aircraft during normal ground operations.

Interaction with GSE and staff

The presence of water on the apron may affect ground support equipment (GSE) movements and personnel working around the aircraft. Operational procedures may need to consider potential slip hazards, as well as the positioning of equipment in areas where water discharge is expected.

Icing risk in cold weather

In cold weather conditions, particularly when ambient temperatures fall below 0°C, discharged water may freeze on apron surfaces and create localized icing hazards. Appropriate mitigation measures, such as enhanced monitoring, de-icing procedures, or stand-specific operational restrictions, may therefore be required to maintain safe operations.

3.7 TAKE-OFF AND LANDING

In this regard, the overall procedure for hydrogen-powered aircraft will likely be similar to that for conventionally fuelled aircraft. The main differences will concern how the firefighting service handles the fuel. However, the aircraft itself will most likely be managed in the same way. It is the airline's responsibility to incorporate hydrogen-specific procedures into ground handling manuals, depending on the aircraft type.

One less noticeable change in hydrogen-powered aircraft concepts is the altered relationship between Operating Empty Weight (OEW) and Maximum Take-off Weight (MTOW). Unlike kerosene-fuelled aircraft, whose mass diminishes significantly during flight due to the kerosene consumed, the mass of hydrogen consumed will be relatively small, as the hydrogen itself is lighter than kerosene. However, the tanks and fuel systems will be heavier, particularly with liquid hydrogen (ZeroAvia Conops).

3.8 CONCLUSION OF HANDLING PROCESS

In summary, the handling process for hydrogen-powered aircraft largely mirrors that of conventional aircraft, with key procedures guided by IGOM, AHM, and manufacturer manuals. Most services, including baggage, cleaning, and catering, remain unchanged. Pushback and taxi procedures will require minor adjustments due to electric propulsion and water by-product considerations, especially in cold conditions. Take-off and landing protocols are similar, though emergency response must account for hydrogen-specific risks. Ground handling manuals must be updated to reflect these changes. The altered weight dynamics of hydrogen aircraft, particularly with heavier fuel tanks, are a noteworthy operational factor. Overall, integrating hydrogen aircraft into standard airport processes is achievable with careful planning and targeted procedural updates.

The overall duration of the turnaround may change due to a possible need to perform handling process steps separately which can take place in parallel for conventional aircraft. However, the objective is to keep turnaround times unchanged so that overall airport operations are not affected significantly.

3.9 NIGHT-STOP (OUTDOORS/INDOORS)

This chapter describes the procedures and considerations for the night-stop of hydrogen-powered aircraft, both outdoors and indoors. In general, the night-stop process remains largely comparable to that of conventionally fuelled aircraft. The primary differences arise from hydrogen-specific safety requirements, particularly regarding safety zones, aircraft markings, and the clear identification of the fuel type for emergency response purposes. Aircraft handling activities themselves are expected to follow established practices, provided that hydrogen-related precautions are integrated into local procedures and airline ground handling manuals. The following section outlines the key steps to be performed upon arrival, parking, and securing of the aircraft during a night-stop.
The overall process will be very much as it is with “conventional fuels” the mayor changes will most likely be connected to safety zones and markings of the plane. The aircraft itself will most likely be handled the same way as today.

Arriving Aircraft	
Check LDM and see that enough resources are available	Make sure the correct personnel are in place. Check that the correct equipment is in place. Perform daily inspection on equipment and make sure stairs are clean and safe to use. It is the Airlines responsibility to incorporate H2 into ground handling manuals according to aircraft type
Inspect the standing place	-Inspect that the standing is free of FOD and that the equipment is placed within marked areas. - Inspect that the standing area is free from contamination that could result in unsafe operation. -Make sure no personnel are within the risk area (exclusion zone for activities in parallel to refuelling).
Ranging	See E3.1H Ground signals and ranging signals. Ranging rods are to be used.
When parked	-Add blocks on nose wheel. -Connect ground power and make sure the correct power is supplied, see E3.1D regarding Startup and E3.1F Connect and disconnect ground power. -Place cones and restrain boundaries according to airline requirements.
	-Place blocks according to airline requirements. - Indicate the different fuel type (in this case hydrogen) for respond teams to quickly recognise the fuel type use.
Perform arrival check	-Inspect the aircraft for any damage -Report any damage to the commander, before any work is done, also into the airport reporting system.
Tailsupport	Place tail support according to airline requirements.

TABLE 5: Process for night stops

3.10 CONDITIONS FOR HANGAR USE MAINTENANCE (LINE&BASE)

Parking a gaseous-hydrogen-fuelled aircraft in an enclosed hangar introduces unique safety challenges and regulatory considerations. Hydrogen's properties – particularly its extreme flammability, rapid dispersion, and invisible flame – require careful planning of hangar design, operational processes, and compliance with evolving codes. This report provides a comprehensive overview of the hazards and safety objectives associated with hydrogen in hangars (Section 1), outlines the regulatory frameworks and guidelines relevant to hydrogen-fuelled aircraft storage (Section 2), and details key technical measures for ventilation, leak detection, ignition source control, grounding, and emergency response (Sections 3–5). Finally, a comparative analysis is given between requirements for hydrogen aircraft hangars and analogous practices in hydrogen bus/truck depots (Section 6).

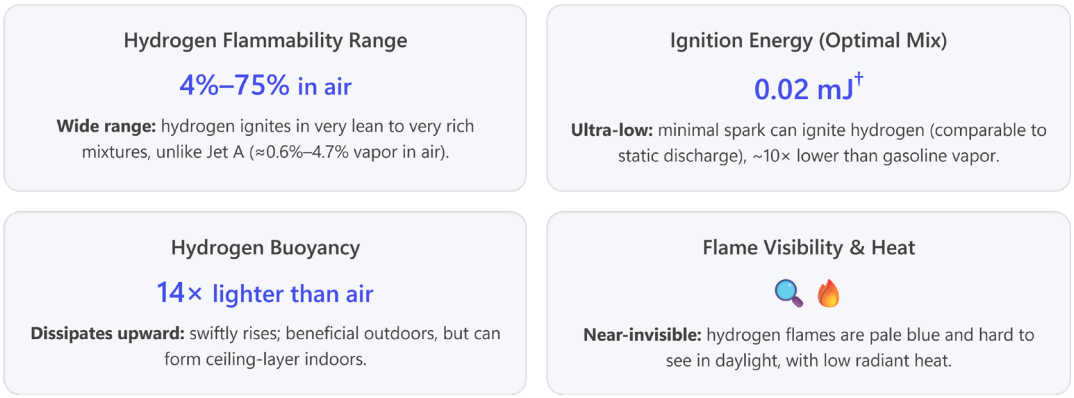
3.10.1 HYDROGEN HAZARDS AND SAFETY OBJECTIVES IN HANGARS

Hydrogen's Unique Hazards: Gaseous hydrogen (H_2) has distinct physical and chemical properties that necessitate special precautions in any enclosed space. It is odourless, colourless, and lighter than air, meaning leaked hydrogen rises rapidly and can accumulate near the ceiling of an enclosure. Hydrogen also has a wide flammability range (from about 4% to 75% by volume in air) and ignites with very low energy, meaning even a tiny static spark can set it off under optimal conditions. Unlike jet fuel or gasoline, which produce heavy vapours that tend to stay low to the ground, hydrogen disperses upward. Thus, in a confined unventilated space, a hydrogen leak can form an invisible flammable layer at the top of the hangar. (compare chapter 3.1.2.1 for more information)

The overarching safety goal when housing hydrogen aircraft in a hangar is to prevent formation of combustible hydrogen–air mixtures, and to ensure that any leak or fire is rapidly detected, contained, and mitigated. Key objectives include:

- **Leak Prevention & Early Detection:** Ensure hydrogen leaks are minimized through robust aircraft maintenance and design and promptly detected via redundant H_2 gas sensors.
- **Ventilation & Dilution:** Continuously ventilate the hangar to prevent hydrogen accumulation near the roof. Ventilation systems must dilute any leak well below flammable limits or extract hydrogen to the outside before dangerous concentrations (≥4% H_2 in air) are reached.
- **Ignition Source Control:** Eliminate potential ignition sources within areas where hydrogen could be present by proper electrical equipment classification (explosion-proof fixtures) and procedures to prevent sparks or open flames.
- **Structural Safety:** If a hydrogen leak does ignite or detonate, ensure the hangar structure and safety systems (e.g., explosion venting panels, fire suppression) can withstand and mitigate pressure or flame effects.
- **Emergency Preparedness:** Establish clear emergency response procedures (for leaks, fire, or explosion), with trained firefighting/rescue personnel and coordination with local authorities, reflecting hydrogen's unique firefighting challenges (e.g. near-invisible flames, low radiant heat, high flame temperature).

Hydrogen vs. Conventional Fuel Risks: It is helpful to contrast hydrogen with conventional jet fuel to appreciate the different hangar risks:



Overall, these characteristics mean that while hydrogen itself is non-toxic and dissipates quickly in open air, any hydrogen leak in a closed hangar space can create a serious fire and explosion hazard if not properly managed. The safety approach thus centres on proactive leak prevention, robust detection, continuous ventilation, and rigorous control of potential ignition sources.

3.10.2 EVOLVING REGULATIONS, CODES, AND STANDARDS FOR HYDROGEN IN HANGARS

Hydrogen-powered aviation is an emerging field, and specific dedicated regulations for hydrogen-fuelled aircraft in hangars are still under development. Currently, international aviation safety regulators like ICAO, EASA, and FAA are working with industry to identify regulatory gaps and needed standards for ground operations, fuelling, and maintenance of hydrogen aircraft. Until these are finalized, existing safety codes for hydrogen in industrial and vehicle applications provide interim guidance:

- **International Fire & Building Codes:** Many national building codes and fire safety standards address hydrogen installations. For example, NFPA 2 – Hydrogen Technologies Code (USA) specifies ventilation rates and hazard controls for hydrogen use in buildings, and International Fire Code (IFC) mandates hydrogen gas detection and ventilation in enclosed garages. The European ATEX directives require classification of explosive atmospheres and suitable equipment in any facility with flammable gas hazards, which would apply to hydrogen hangars
  (e.g., fans, lighting, and electrical systems must be explosion-proof in potential H_2 zones).
- **Airport & Hangar Fire Codes:** Traditional aviation standards like NFPA 409 (Standard on Aircraft Hangars) and ICAO or EASA aerodrome rules focus on liquid fuel fire protection (e.g. foam sprinkler systems for large hangars storing fuelled aircraft). These provide a baseline but may not fully address hydrogen's different behaviour (e.g. hydrogen doesn't pool on the floor, and foam has limited effect on a gas fire). Adaptation of such standards, potentially incorporating explosion venting or enhanced ventilation/detection, is anticipated as hydrogen aircraft become more common.

- **Hydrogen Vehicle Facility Guidelines:** In absence of explicit aviation-specific codes, best practices from hydrogen bus/truck maintenance facilities are instructive. For example, the U.S. Department of Energy's Fuel Cell Bus Maintenance Facility Guidelines outline requirements for leak detection, ventilation, and electrical classification that can be applied to hangars (see Section 8). Similarly, European industry guidance indicates that garages need upgrades for hydrogen vehicles (extra ventilation, sensors, and venting for fuel system purging) beyond conventional vehicle standards.

Aviation-specific standards are being drafted. SAE International and EUROCAE are working on hydrogen fuelling and safety guidelines (e.g., SAE AIR8466 / EUROCAE ER 034 for hydrogen fuelling safety) to harmonize with codes like NFPA. Meanwhile, ICAO's Alternative Fuels Task Force has published a 2025 Concept of Operations to guide global regulatory changes, highlighting gaps in current provisions and listing necessary updates to aerodrome design manuals and emergency planning documents for hydrogen-fuelled aircraft. Multinational efforts (IATA, ACI, EASA, FAA and AZEA) are focused on integrating hydrogen into existing frameworks (e.g., updating ICAO Annex 14, Airport Services Manual, and other guidance) and promoting risk-based design of airport facilities.
Some countries have begun addressing hydrogen in aviation on a project basis. For instance, Germany has considered hydrogen hangar storage under both aviation regulations and general industrial safety laws such as TRGS (Technical Rules for Hazardous Substances) and European Seveso Directive for large-scale hydrogen storage near communities. In the UK, the Civil Aviation Authority (CAA) acknowledges hydrogen integration requires cross-domain regulatory alignment (aviation fuel regulations & ground safety codes).

Today's hydrogen aircraft hangar safety must align with a mix of aviation safety principles and established hydrogen facility codes. The regulatory philosophy is risk-based and conservative: until dedicated standards (ICAO/EASA/FAA) are formalized, airports should implement known hydrogen safety measures from industrial and automotive domains to meet the highest standard of care.

3.10.3 VENTILATION AND GAS DETECTION IN HYDROGEN HANGARS

Continuous Ventilation is the cornerstone of hydrogen safety in enclosed spaces. Adequate ventilation prevents accumulation of hydrogen above its Lower Flammable Limit (LFL ~4% by volume) by diluting and expelling any leaks. Codes like NFPA 2 prescribe mechanical exhaust or natural ventilation at a minimum of 1 ft^3/min per ft^2 of floor area (~0.0051 m^3/s per m^2), equivalent to roughly 4–10 air changes per hour in many buildings. In practice, hydrogen-capable facilities often design "positive ventilation" systems that operate at a base rate (e.g. 6 air changes per hour) and can ramp up to higher rates (e.g. 12 ACH) upon detection of hydrogen. The increased airflow ensures leaked H_2 is rapidly diluted and exhausted to safe outdoor areas (via roof vents or high exhaust fans) rather than forming a cloud under the hangar ceiling.

Because hydrogen cannot be detected by the human eye, fixed hydrogen gas detection must be installed in hangars. Typically, multiple sensors are mounted near the ceiling or other high points (since H_2 rises) and interlocked with the ventilation and alarm systems. Best practices from transit bus depots call for at least two detector heads over each hydrogen maintenance area. Alarm thresholds are set at conservative fraction of LFL.

For example, many facilities use a two-stage alarm:

- **Low-level alarm (20% LFL ≈ 0.8% H_2 by vol):** triggers audible/visual alarms inside and outside, activates a warning at a monitoring station, shuts off all hydrogen supply valves (if present, automatically opens hangar doors (if feasible), and doubles ventilation rate (e.g. from 6 to 12 ACH).
- **High-level alarm (40% LFL ≈ 1.6% H_2 by vol):** escalates response—emergency alarms for evacuation, automatic shutdown of non-essential power (to minimize ignition risk), and automatic fire service notification.

These detection setpoints align with common practice for hydrogen facilities and ensure that even minor leaks are quickly mitigated well before reaching the 100% LFL (4% H_2) threshold for ignition. Portable hand-held H_2 detectors are also recommended so personnel can check for small leaks or verify that the environment is safe before maintenance work.

Hangar design should avoid any architectural features where hydrogen could trap or stagnate (e.g., high ceilings with pockets or poorly ventilated corners). Ventilation intakes and exhaust should be arranged to sweep the entire overhead volume, so that any leaking hydrogen is swiftly carried out rather than gathering in isolated pockets. In large hangars, this might require multiple exhaust fan units at ceiling level, with intake openings at lower levels to promote circulation. Some designs use continuous air sampling tubes along the ceiling as an alternative to multiple point detectors, ensuring detection coverage over wide areas.

Given that ventilation is safety-critical, systems should have redundant fans and power supplies, plus alarms for fan failure, to ensure continuous operation. Fail-safe design is advisable. Additionally, because hydrogen can accumulate if ventilation fails, facilities may consider backup power (e.g., emergency generators or battery backup for fans) and monitoring of hydrogen concentration by independent systems integrated into building management or fire alarm systems.

Unlike normal HVAC, hydrogen safety ventilation should avoid recirculating interior air; instead, it should exhaust it directly outside. This prevents recycling hydrogen. Ductwork must be carefully planned to avoid igniting or confining any flammable mixture – for example, using non-sparking fans and avoiding ignition sources in ducts.

Note that GH_2 (compressed gaseous hydrogen) aircraft typically do not experience routine boil-off like liquid hydrogen tanks do. LH_2-fuelled aircraft, if parked for long periods, might require connecting boil-off vent lines to carry evaporating hydrogen outside the hangar. However, for gaseous H_2 storage (e.g., 350–700 bar tanks), no venting should occur in normal conditions; the focus remains on handling accidental leaks or emergency pressure relief. It is still advised to close all storage valves when storing the aircraft inside a hangar.

Overall said, robust ventilation and detection systems are non-negotiables for hydrogen hangar safety. Combined, they serve to maintain hydrogen concentrations far below flammable levels, alert personnel, and automatically trigger mitigations if an unexpected release occurs.

3.10.4 HAZARDOUS AREA CLASSIFICATION AND IGNITION SOURCE CONTROL

Inside a hydrogen-aircraft hangar, any area that could contain a flammable H_2 mixture must be treated as a hazardous (explosive) atmosphere zone. Both U.S. (NFPA/NEC) and European (ATEX) standards set criteria for classifying such zones and controlling ignition sources:

- In the U.S., per NFPA 70 (National Electrical Code) and NFPA 2, equipment within ~5 ft (1.5 m) of a potential hydrogen source (e.g. a vent or fill connection) is typically Class I Division 1 (where ignitable concentrations are likely during normal operation). Within 15 ft (~4.6 m), a broader Class I Division 2 area is designated (ignitable concentrations only in abnormal conditions). All electrical devices in these zones must be explosion-proof or intrinsically safe.
- In the EU (ATEX/IECEX) framework, similar principles apply using Zone 1/Zone 2 classifications for gas atmospheres (Zone 1 ~ likely presence, Zone 2 ~ not likely but possible in abnormal cases). The upper reaches of a hangar or any enclosed space where hydrogen could accumulate might be classified as Zone 2 if ventilation is normally effective in preventing sustained H_2 pockets, but where a leak could create a short-term hazard before alarms/ventilation mitigate it. Vent pipe outlets or controlled hydrogen release points (like pressure relief device outlets) could require a Zone 1 classification around the immediate vicinity.

Based on these classifications, all potential sources of ignition must be eliminated or controlled within the hazard zones. This includes:

- **Electrical Equipment:** Use explosion-proof lighting, switches, and motors in ceiling areas or other classified zones in the hangar. Standard electrical fixtures or tools that could spark are prohibited in these areas. Unclassified electrical gear (e.g. non-EX-rated equipment) should be located outside of areas where hydrogen could be present, or de-energized if an H_2 alarm triggers.
- **Heating Systems:** Hangar heating must not involve open flames or exposed high-temp surfaces. For example, no direct-fired space heaters or radiant elements in H_2 zones. Heat should be supplied from outside the zone via indirect methods (e.g., ducted hot air or hot water) to avoid ignition risks.
- **Vehicles and Tools:** Any vehicles or ground support equipment operating in the hangar with a hydrogen-filled aircraft should keep its distance to the parked Aircraft according to ATEX Zones and regulations. Pushback processes need to be considered carefully and done if no danger emanates from the aircraft.
- **Static Electricity & Bonding:** All hydrogen systems and tools should be properly grounded/bonded to dissipate static electricity safely. While parking a hydrogen aircraft (not fuelling), it is prudent to connect the aircraft to a grounding point as a standard practice. This protects against static buildup or lightning-induced potentials, reducing ignition risk. During any hydrogen fuel transfer operations (which are usually performed outdoors, not in a hangar), bonding cables ensure the aircraft and equipment share a common ground.
- **Hot Work & Special Processes:** Standard hangar rules about “hot work” (welding, soldering, grinding, etc.) apply with even greater strictness. No such activities should occur in a hangar containing a fuelled hydrogen aircraft unless the aircraft’s fuel system is completely defueled and inerted and the area has been verified free of hydrogen.

By implementing these controls, the risk of any spark or heat source igniting leaked hydrogen is dramatically reduced. This approach mirrors the practices in hydrogen bus facilities, which prohibit any uncontrolled ignition sources near hydrogen-fuelled vehicles and use equipment conforming to Class I Div. 2 / ATEX Zone 2 requirements in maintenance bays.

3.10.5 HANGAR OPERATIONAL PROCEDURES FOR HYDROGEN-FUELLED AIRCRAFT

Parking a hydrogen aircraft in a hangar begins with ensuring safe conditions before entry. Ground crews should verify there are no active hydrogen leak indications on the aircraft (e.g., via onboard instruments or manual checks with portable detectors) and that fuel system valves are secured. This is analogous to the practice in bus depots where any vehicle known or suspected of leaking hydrogen is forbidden from entering an indoor facility. If a leak is detected, the aircraft must remain outside until addressed.

Activation of Hangar Safety Systems before bringing the aircraft in:

- **Ventilation and detection systems** should be confirmed operational, ideally in high ventilation mode during aircraft entry (hangar doors open and fans running) to immediately dilute any unforeseen minor leak. Many facilities keep ventilation running continuously while hydrogen-powered vehicles are inside.
- **Grounding/Bonding:** As soon as practicable after the aircraft stops at its parking position, connect a grounding cable from the aircraft to the hangar's grounding point (common on hangar floors). This measure, though primarily used during fuelling, ensures any static charge is safely dissipated.

If possible, hydrogen aircraft should be assigned specific parking positions in the hangar with optimized safety features. For instance, such positions might be directly beneath hydrogen gas detectors and high-capacity exhaust vents, and near large doors for emergency egress. U.S. guidelines for hydrogen bus maintenance facilities recommend dedicated parking bays with all required safety systems (detectors, alarms, ventilation) just like maintenance areas and also advise locating hydrogen-fuelled vehicles such that they can be quickly moved outside if a leak occurs. A similar philosophy can apply in aircraft hangars: positions closest to exits may allow rapid evacuation of the aircraft by towing in case of an emergency.

As a rule, hydrogen fuelling or defuelling inside a hangar should be avoided. All planned refuelling is expected to occur outdoors or at specialized fuelling areas on the apron where ventilation is unlimited and safety zones can be maintained. If exceptional circumstances required fuelling or venting operations inside (e.g., emergency defuelling of a stranded aircraft), the hangar should be treated as a temporary fuelling site with measures equivalent to an outdoor station: maximum ventilation, no ignition sources, all personnel evacuated except essential operators, and continuous monitoring by fire crews.

It is important to distinguish between simply storing (parking) a hydrogen aircraft versus performing active maintenance on its hydrogen systems:

- **Storage/Parking (Normal Hangar Stay):** The aircraft is left mostly dormant with its hydrogen fuel on board. The hangar's role is to monitor and protect. The plane's own hydrogen leak detection may be powered down when the aircraft is off (as is the case with hydrogen buses), so the hangar's detection system takes over this role. Periodic inspections by trained staff with handheld detectors are advisable, especially immediately after parking and before entering the hangar to perform any tasks.
- **Hydrogen System Maintenance:** If maintenance or inspections will involve opening the fuel system or any task that could release significant H_2, defuelling and inerting of the aircraft's hydrogen storage is necessary. Standard practice (drawn from hydrogen vehicle maintenance) is to safely discharge the hydrogen fuel outdoors or via a vent stack and purge the system with an inert gas such as nitrogen before bringing the plane inside for such work. This ensures no large hydrogen release will occur during maintenance. If inerting and venting must be done indoors, a dedicated vent line system that pipes hydrogen to the outside (above the roof) should be used, and the area around the vent outlet must be classified as a temporary ATEX Zone (explosion risk zone) for the duration of the operation.

Operating procedures should also cover towing or taxiing hydrogen aircraft into/out of the hangar. During these transitions:

- The hangar doors should be fully opened, maximizing natural ventilation as the aircraft moves in or out.
- If the aircraft's engines or fuel cells must be operated (e.g., for repositioning under its own power), this should ideally happen only outside, not inside or near the doorway, to avoid any release in the enclosed space.
- Hangar floor markings and guides should help position the aircraft precisely in the designated safe parking spot to align with safety systems (e.g., under detectors).

Personnel handling hydrogen-fuelled aircraft must receive hydrogen safety training. This includes recognizing hydrogen hazards, understanding the hangar's detection alarms and emergency ventilation, and knowing not to perform unauthorized tasks on the hydrogen system. Only qualified maintenance staff should interact with the H_2 fuel system, and only after proper defuelling/purging if necessary.

3.10.6 PARALLELS WITH HYDROGEN BUS/TRUCK MAINTENANCE FACILITIES – A COMPARATIVE VIEW

Experience from hydrogen bus and truck depots offers valuable lessons for hydrogen aircraft hangars. The table below compares key safety measures:

Safety Aspect	Hydrogen Bus/Truck Depot Practice	Hydrogen Aircraft Hangar Considerations
Ventilation Rate	Typically, 6 ACH normal, auto-boost to ~12 ACH on H_2 detection NFPA 2 requires min. ~0.0051 m^3/s per m^2 (1 cfm/ft^2) floor area.	Similar baseline ventilation requirements (≥6 ACH), scaled for larger volume. High-capacity fans and roof vents sized for hangar dimensions. Possibly even higher ACH given larger H_2 inventories.
H_2 Gas Detection	Ceiling-mounted sensors trigger alarms at 0.8% H_2 (20% LFL) and emergency shutdown at 1.6% H_2 (40% LFL). Portable detectors used for routine checks. Onboard vehicle sensors may be inactive when powered down.	Adopt similar multi-level detection strategy. More sensors distributed over vast ceiling area of hangar, integrated into alarm/ventilation control. Confirm aircraft's own detectors (if any) are active; otherwise rely on hangar system during parking.
Hazardous Area (EX) Zoning	Classified electrical equipment in H_2 zones: e.g., NFPA/NEC Class I Div 1 within ~1.5 m of H_2 equipment, Div 2 within ~4.6 m. Explosion-proof lights, motors, and heating; no open flames.	Likewise, electrical installations in any zone where H_2 may accumulate (e.g. near ceiling or vent outlets) to meet ATEX Zone 1/2 or Class I, Div 1/2 requirements. All potential ignition sources eliminated in these areas. Higher roof might reduce the horizontal extent of hazardous zone, but vertical
	(https://wha-international.com/hydrogen-ventilation-standards/)	accumulation zone at ceiling is key focus.
Designated Parking Bays	Hydrogen vehicles are parked in specific bays equipped with H_2 safety features; ensure easy egress (ability to quickly move vehicle out). Leaking vehicles never parked indoors. If LH_2-fuelled, connect boil-off vent to outside. (https://wha-international.com/hydrogen-ventilation-standards/)	Assign specific positions in hangar for hydrogen aircraft with dedicated ventilation and detection coverage. Keep near hangar door for quick towing out if needed. Routine policy: if any H_2 leak is suspected, do not park in hangar. LH_2 aircraft may require quick connect to roof vent systems for boil-off control (GH_2 aircraft typically do not vent when idle).
Maintenance Procedures	Minor maintenance with potential small H_2 release allowed in ventilated area with sensors. Major maintenance (involving fuel system) requires prior defueling and inerting; hydrogen purged via vent stack to outdoors.	Similar: Standard line maintenance (non-intrusive) can occur with fuel onboard if detectors/ventilation are active. Major maintenance on H_2 storage or fuel lines should only occur after defueling and purging tanks with inert gas outside or via safe vent system. Hangar infrastructure may include fixed inert gas purge connections and vent systems for this purpose.
Alarms & Emergency Actions	At 40% LFL alarm, cut power (except safe fans), evacuate, auto-notify fire dept. Doors open automatically to flush out H_2. Staff training to handle H_2 leaks (open doors, increase ventilation).	The same principles, with integration into airport's ARFF response. Hangar doors can open automatically on high alarm to prevent overpressure buildup. Fire crews respond with H_2-specific tactics (UV flame detectors, focus on leak source). Regular H_2 emergency drills included in airport's plan.

Similarities: The core safety strategies for hydrogen are largely universal across industries. Both hydrogen bus garages and future aircraft hangars emphasize leak detection, ventilation, removal of ignition sources, and robust emergency protocols. In both cases, storing vehicles with pressurized hydrogen onboard in enclosed facilities demands special ventilation and detection equipment beyond what is needed for conventional fuels.

Key differences will arise from scale and context:

- **Fuel Quantities:** A large hydrogen-fuelled aircraft may carry significantly more hydrogen (potentially hundreds of kilograms in future airliners) than a single bus (often 20–40 kg), although small regional hydrogen aircraft could be comparable to buses or trucks. Larger quantities mean potentially larger leak scenarios and thus even more robust ventilation and detection may be required.
- **Facility Size:** Aircraft hangars are much larger by volume than bus garages. This can be a safety advantage. A given quantity of leaked H_2 will be more diluted in a large volume but also means a need for higher-capacity fans and possibly more numerous sensors to cover the space. The hangar's large doors, when open, can provide very rapid ventilation in emergencies, but reliance on natural ventilation is weather-dependent; hence mechanical systems sized for the full volume are essential.
- **Certification and Oversight:** Aviation is a highly regulated environment. Introducing hydrogen into the airport setting involves not only local building codes but also oversight by aviation safety authorities. This can lead to additional layers of safety analysis, risk assessments, and possibly certification of hangar modifications before hydrogen aircraft are allowed. For example, any major changes to a certified aerodrome may require regulatory approval and demonstration of an equivalent level of safety as conventional operations.
- **Aircraft Systems Integration:** Unlike road vehicles, aircrafts might incorporate their own safety interlocks with ground infrastructure. Future hydrogen aircraft could have features like fuel tank health monitoring that communicates with hangar systems, or automated purge connections when parked. These are not yet standardized, but concepts are being explored by industry to ensure overnight parking does not lead to overpressure (especially for LH_2 tanks warming over time).

Early deployments of hydrogen-fuelled ground vehicles (buses, forklifts, etc.) have proven that indoor use of hydrogen is feasible and safe with proper precautions. These experiences underline the importance of risk-based design: simply meeting minimum code ventilation may not suffice for worst-case leaks. Instead, facility designers are encouraged to perform detailed hazard analyses (e.g., leak and dispersion modelling) to tailor ventilation rates, sensor placements, and emergency responses to their specific hangar configuration and hydrogen quantities. This approach – going beyond the "checklist" mentality – ensures that hydrogen safety measures are robust and effective for the actual conditions of the hangar, just as recommended for industrial hydrogen systems.

Concluding Remarks

The parking of a gaseous hydrogen-powered aircraft in a hangar demands a comprehensive safety strategy combining engineering controls, procedures, and training. By understanding hydrogen's unique behaviour and leveraging both existing codes (like NFPA 2, ATEX, etc.) and emerging aviation guidance, airports can establish hangar environments that meet the twin goals of decarbonizing aviation and maintaining uncompromised safety. Key considerations include ensuring continuous ventilation and leak detection, eliminating ignition sources through proper design, and having robust emergency plans that factor in hydrogen's special characteristics (buoyant, invisible flame, rapid flame speed). The main focus should lay on preventions of fire or explosions by precautions and safety rules concerning building design and handling procedures.

As international standards bodies and regulators refine the rules in the coming years, the practices described above - many drawn from proven hydrogen vehicle facility experiences – form a solid foundation for safe hydrogen aircraft hangar operations. By proactively implementing these measures and learning from hydrogen bus/truck depot safety, the aviation industry can confidently manage hydrogen fuel on the ground, thus enabling the next generation of sustainable aircraft without compromising on safety.

4 PILOTING ACTIVITIES

The targeted output of the working group, which addressed the handling of hydrogen powered aircraft, were "Tested airport operations with hydrogen-powered aircraft". This goal was achieved in two different ways which are presented in the following.

4.1 PROOF OF CONCEPT WITH BEYON DAERO

To achieve tested airport operations with hydrogen-powered aircraft in theory, this implementation concept was sent to the aircraft manufacturing company BeyondAero (France, founded in 2020) for review as a proof of concept. The received comments were incorporated in the document at hand.

4.2 TAXI TEST AT ROTTERDAM DE HAGUE AIRPORT

Partners of the BSR HyAirport project participated on-site in the hydrogen-powered aircraft taxi test at Rotterdam The Hague airport (RTHA). This chapter documents the testing activities, operational framework conditions and initial findings.

The primary goal of this participation was to gain insights into the processes involved in carrying

out hydrogen-related activities at an airport. From the airport's perspective, particular emphasis was placed on understanding the preparatory steps, such as the permitting process, and operational implementation, especially regarding safety aspects and infrastructure requirements. The knowledge gained served as input for this document.

4.2.1 OVERVIEW OF THE TEST

The test took place on the 21.05.2026 around 4 - 5 pm at RTM. It included the following aspects:

- Hydrogen refuelling
- Powertrain test
- Taxi operations using gaseous hydrogen

The objective of the test was to verify the functionality of the hydrogen-based propulsion system under realistic conditions. It also aimed to gain insights into infrastructure, safety requirements and operational procedures in an airport environment. The aircraft used was a two-seat Sling 4 aircraft powered by a hydrogen fuel cell.

The test was conducted by AeroDelft. They are a student team working on propulsion systems that run on hydrogen using fuel cells. They use a converted propeller plane that is intended to be powered first by gaseous hydrogen and later by liquid hydrogen.

RTHA played a key role as the host, operational test environment and overall safety body for the hydrogen aircraft taxi test. The airport supported the test by facilitating safety coordination and operational planning.

The demonstration was part of the Rotterdam the Hague Innovation Airport DutcH2 Aviation Hub (RIHA) programme. This collaborative programme develops hydrogen aviation infrastructure, operating and testing at RTM. Further involved parties were TU Delft and Air Products Benelux.

4.2.2 SAFETY ASPECTS AND PERMITTING PROCESS

Preparation for the demonstration took approximately seven months, with the permitting process accounting for around three months of the overall preparation period. This highlights the importance of early stakeholder involvement and coordination when planning hydrogen-related activities in an airport environment.

The environmental permitting process was the first step in preparing the demonstration. It focused primarily on safeguarding the surrounding area rather than the airport site itself. The important aspect here is the fact, that people in the surrounding areas, in contrast to airport personnel, are unaware that hydrogen is used and the risks of it. During the assessment, different categories of receptors were considered, including vulnerable populations such as hospitals and schools, less vulnerable populations such as residential areas and offices, and non-vulnerable areas. Based on these categories, risk contour maps were developed using a prescribed modelling methodology. The size of the risk contours depended largely on the hydrogen volume and its intended use.
As part of the permitting process, a Quantitative Risk Assessment (QRA), documentation demon-

strating compliance with PGS 35 and an incident response plan had to be provided. PGS 35 was used largely as a checklist to verify that all relevant safety measures had been implemented. Most requirements could be directly applied, while a limited number required alternative means of compliance for gaseous hydrogen.

The environmental authority granted approval for the demonstration. Prior to the test, the hydrogen equipment provided by Air Products was inspected to verify its safe installation and intended operation.

In addition to the regulatory approval process, RTHA carried out its own airport-specific safety assessment. This assessment considered operational scenarios relevant to the airport environment, such as potential collisions between aircraft and GSE. The aircraft itself was treated as a conventional aircraft from an operational and ATC perspective, resulting in the aircraft being integrated in normal air traffic, while particular attention was paid to avoiding unintended interfaces with existing airport systems.

The safety assessment also included the calculation of how a hydrogen cloud would disperse in the event of a potential leak. This analysis was used to determine safety distances and emergency procedures in airport operations. In particular, it examined whether a hydrogen cloud could interfere with air traffic control activities or other airport functions.

ATEX zones around the hydrogen infrastructure were predefined by Air Products, those around the aircraft were predefined by AeroDelft. Access to these zones was restricted to authorised and trained personnel only.

Another aspect of the approval process concerned the involvement of the Civil Aviation Authority (CAA). According to the organisers, only a notification of the planned activities was required, and no further regulatory questions were raised.

Furthermore, an emergency response card for the hydrogen-powered aircraft was prepared.

4.2.3 TEST ACTIVITIES

Hydrogen Refuelling

The refuelling process included the connection of the aircraft to the hydrogen refuelling infrastructure. A simplified refuelling concept was used. Refuelling was carried out with a non-communicating system at a flow rate of 10 g/s. The fuel tank includes 6 kg hydrogen at 700 bar. The station operated without a compressor and utilised pressure equalisation from the existing hydrogen storage tank. The refuelling pressure was at approximately 180 bar. Although the pressure level is lower than in conventional hydrogen refuelling applications, it was entirely sufficient for the taxi test. Due to the reduced complexity of the system, this enabled rapid commissioning. Hydrogen refuelling was performed in accordance with the SAE J2601 standard. There had to be a protection zone around the vent stack and a protection zone



FIGURE 5:
Aircraft Refuelling & Powertrain Test



FIGURE 6:
Aircraft and Refuelling Station

Taxi test
The hydrogen-powered aircraft demonstrated stable taxiing. There were no deviations from normal operation during the test.



FIGURE 7:
Taxiing

4.2.4 FINDINGS AND CONCLUSION

The taxi test at RTHA demonstrates that the ground operations of hydrogen-powered aircraft are feasible and that they can be integrated into the airport environment. It also showed that, while hydrogen aircraft operations require additional safety assessments, permitting activities and specialised procedures, these can be managed within existing airport and regulatory frameworks.

5 CONCLUSION AND OUT LOOK

5.1 CONCLUSION

This concept document has systematically explored the operational, regulatory, and safety requirements for the handling and refuelling of hydrogen-powered aircraft at airports in the Baltic Sea Region. The findings highlight that, while many established ground handling procedures can be adapted for hydrogen, the transition introduces distinct technical and organisational challenges that must be addressed to ensure safe and efficient operations including emergency / firefighting procedures.

A central outcome of the project is the development of standardised processes for the use of compressed gaseous hydrogen (GH_2) in smaller aircraft, typically up to 80 seats. The document details how GH_2 can be integrated into airport operations by adapting existing refuelling concepts, implementing robust leak detection systems, and establishing new safety zones and emergency protocols to take into account the different hazards of H2 compared to JET-A1. The practical experience gained from pilot projects and collaboration with industry partners demonstrates that, with appropriate training and procedural updates, airports can safely accommodate GH_2-powered aircraft without significant disruption to overall operations. Notably, the document emphasises the importance of clear communication between ground staff, operators, and emergency services, as well as the need for harmonised documentation and ongoing staff training.

In contrast, the findings indicate that liquid hydrogen (LH_2) will become relevant for larger aircraft in the coming decade. LH_2 offers higher energy density, making it suitable for long-haul flights and larger aircraft types. However, the document identifies several additional challenges associated with LH_2: the requirement for cryogenic storage and handling, increased risks of cold burns and material embrittlement, and the need for specialised infrastructure and safety protocols increases even more in comparison to GH2. The behaviour of LH_2 during leaks and its physical properties differ significantly from GH_2, necessitating further research and the development of tailored emergency procedures and safety zones.

The project also underscores the variability of national regulations and the difficulty of harmonising safety standards across borders. As such, the recommendations provided serve as guidance and must be adapted to local legal frameworks, international standardisation always being the long-term goal.

In summary, the findings of this document demonstrate that the integration of hydrogen into airport operations is both feasible and essential for the decarbonisation of aviation. The proof of concept with aircraft manufacturer BeyondAero shows this even better. GH_2 represents a practical solution for smaller aircraft in the near term, with established processes and manageable risks. LH_2, while promising for future large-scale applications, requires further technological development and regulatory alignment. The concepts and procedures outlined here provide a robust foundation for airports preparing to handle hydrogen-powered aircraft, supporting the industry's transition towards sustainable aviation.

5.2 LIQUID HYDROGEN

LIQUID HYDROGEN: DIFFERENCES, FOCUS, AND CHALLENGES

While this concept document primarily focuses on the use of compressed gaseous hydrogen (GH_2) for airport operations and aircraft handling, it also addresses the future relevance of liquid hydrogen (LH_2) for larger aircraft. The decision to concentrate on GH_2 in this project is based on several key findings:

1. Technological Readiness and Aircraft Size

GH_2 is expected to be used in smaller aircraft (up to 80 seats), which will enter commercial service earlier. These aircraft can be retrofitted or newly designed to use compressed hydrogen at high pressures, and the required infrastructure is more readily available.
LH_2, with its higher energy density, is more suitable for larger aircraft and long-haul flights. However, such aircraft are not expected to be operational before 2035, and the necessary airport infrastructure is still under development.

2. Handling and Safety Differences

GH_2 Handling: Storage and refuelling of GH_2 involve high-pressure tanks and robust leak detection systems. The main risks are related to hydrogen's high diffusivity, invisible flame, extreme flammability in air and the need for strict explosion protection. These challenges are significant but manageable with current technology and procedures.

LH_2 Handling: LH_2 must be stored at extremely low temperatures (around -253°C), requiring specialised cryogenic tanks and insulation. The risks associated with LH_2 include cold burns, material embrittlement, rapid expansion in case of leaks, and changes in flammability limits. LH_2 vapours are initially heavier than air, which affects dispersion and safety zone planning. The infrastructure for LH_2 handling is more complex and costly, and emergency procedures must be adapted to address cryogenic hazards.

3. Project Focus and Rationale

The project focuses on GH_2 because it is the most immediate and practical solution for airports preparing for hydrogen-powered aircraft in the near term as well as product availability was closer to reality than liquid powered aircrafts to the time of project start. The processes for GH_2 are already being piloted and tested, and the operational experience gained can be transferred to future LH_2 applications.

LH_2 presents additional challenges that go beyond those of GH_2, including the need for new materials, advanced insulation, and specialised training for ground staff. The document highlights that the transition to LH_2 will require further research, regulatory development, and investment in infrastructure.

4. Summary of Additional LH_2 Challenges (compared to GH_2)

Cryogenic Storage: LH_2 requires tanks and pipelines that can withstand extremely low temperatures, increasing complexity and cost, while GH2 Systems have very high storage pressures (350/700 bar).

Material Compatibility: Many materials become brittle at cryogenic temperatures, necessitating careful selection and testing.

Boil-off Management: LH_2 naturally evaporates over time, so systems must be in place to manage pressure and prevent tank rupture when the hydrogen is not drawn off for use.

Safety Zones: LH_2 leaks behave differently than GH_2, requiring revised safety distances and emergency protocols.

Personnel Safety: Risk of cold burns and frostbite is unique to LH_2, demanding additional protective equipment and training.

Conclusion The findings of this document justify the current focus on GH_2 for airport operations, while recognising that LH_2 will become increasingly important as larger hydrogen-powered aircraft are developed. By addressing the specific challenges of GH_2 now, airports and stakeholders can lay the groundwork for a safe and efficient transition to LH_2 in the future, ensuring that the aviation sector remains at the forefront of sustainable innovation.

5.3 FURTHER TOPICS TO CONSIDER IN THE FUTURE

Looking ahead, the future of sustainable aviation will be guided by a blend of emerging technologies and evolving practices. Electric and hybrid propulsion systems are moving from concept to reality, offering quieter and more efficient options for shorter routes. Hybrid engines, combining conventional and electric power, bridge the gap as full electrification advances. Investments in battery development and lightweight materials are crucial for these innovations to thrive.

Automation is set to reshape operations, enhancing both safety and efficiency, but also necessitating robust cybersecurity to protect increasingly digital systems. As artificial intelligence and data analytics become embedded in aviation, predictive maintenance and real-time monitoring will help streamline processes and improve decision-making.

Developing sustainable aviation fuels (SAFs) is also vital, as they can significantly cut carbon emissions. Yet, expanding production and supply chains requires close cooperation between stakeholders and supportive policies. The circular economy, focusing on recycling and resource efficiency, encourages manufacturers and operators to design for durability and sustainability.

Climate resilience is another priority. With weather patterns changing and new regulations emerging, it is essential to invest in adaptable infrastructure and advanced forecasting tools. Airline partnerships are growing more dynamic, allowing companies to share expertise and resources to meet future challenges collectively.

Ultimately, a skilled and adaptable workforce is key to embracing these changes. By keeping pace with technological advancements and maintaining flexibility, aviation organisations can remain competitive and relevant in an industry that is constantly evolving.

Aircraft Handling



IMPLEMENTATION CONCEPT FOR AIRPORT HANDLING AND FUELLING OF HYDROGEN POWERED AIRCRAFT

Appendix A

Prepared by AEROTHRIVE GmbH
04 December 2025

ASSESSMENT OF REGULATIONS

Content

WP 1.3 Aircraft Handling 1
0. List of Abbreviations 2
00. List of Figures 3
1. Introduction 4
2. Methodology 5
2.1 Phase 1 – Regulatory Mapping and Compilation of the Cross-Reference Register 5
2.2 Phase 2 – Hydrogen-Specific Gap Analysis 11
3. Key Outcomes of the Two-Phase Methodology 18
3.1 Deliverables of phase 1 18
3.2 Deliverables of Phase 2 18
4. Interim Conclusion 19
5. Analysis the Hydrogen-Specific Gap Assessment 20
Step 1 – Hydrogen Operational Requirements Baseline 20
Step 2 – Clause-by-Clause Regulatory Assessment 20
Step 3 – Impact Assessment on Ground Handling Processes 21
Step 4 – Hazard and Change Triggers Assessment 21
6. Summary of Gaps Identified 23
6.1 Overarching category: Hydrogen-Specific Fuelling and de-fuelling procedures 23
6.2 Overarching category: Emergency Response and Firefighting 23
6.3 Overarching category: Training and Competence Requirements not Hydrogen-Ready 24
6.4 Overarching category: Apron Safety, Turnaround and Coordination Provisions 25
6.5 Overarching category: Aerodrome Operator Oversight and Interfaces 26
6.6 Overarching category: GSE and Infrastructure 27
7. Recommendations 29
7.1 Initiate a formal Management of Change Process 29
7.2 Develop Hydrogen-Specific Operational Procedures as part of the MoC 30
7.3 Update Training and Competency Frameworks 31
7.4 Establish Hydrogen Infrastructure Certification and Oversight Processes 32
7.5 Integrate Hydrogen Hazards into SMS and ERP Structures 33

7.6 Prepare for regulatory engagement and future rulemaking 34
8. Conclusion 35
9. The Annex 35

0. List of Abbreviations

ADR	Aerodrome
AMC	Acceptable Means of Compliance
BADV	Bodenabfertigungsdienst-Verordnung (Germany)
BetrSichV	Betriebssicherheitsverordnung (Germany)
BSR	Baltic Sea Region
CAMO	Continuing Airworthiness Management Organization
EASA	European Aviation Safety Agency
EU	European Union
GefStoffV	Gefahrstoffverordnung
GH	Ground Handling
GHSP	Ground Handling Service Provider
GSE	Ground Service Equipment
H2	Hydrogen
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ISAGO	IATA Safety Audit for Ground Operations
ISO	International Organization for Standardization
Jet A-1	Aviation fuel, based on kerosene
JIG	Joint Inspection Group (Aviation Fuel Supply Standards)
LBA	Luftfahrt Bundesamt (German Civil Aviation Authority)
LuftVG	Luftverkehrsgesetz (Germany)
MoC	Management of Change
OEM	Original Equipment Manufacturer
OPS	Operations
ORGH	Organization of Ground Handling
PPE	Personal Protective Equipment
RFFS	Rescue and Fire Fighting Services
SAE AIR	SAE Aerospace Information Report (by SAE International)

SAF	Sustainable Aviation Fuel(s)
SARP	Standards and Recommended Practices
SMS	Safety Management System(s)
SPI	Safety Performance Indicator
TRG	Training

00. List of Figures

Figure 1 – Overview of Applicable Regulatory Sources 6
Figure 2 – Categorization by Ground Handling Activity 8
Figure 3 – Gap Analysis Results 12
Figure 4 – Hydrogen Requirements against Existing Regulations 14
Figure 5 – Ground Handling Category Primary to Regulation with Gap 16

1. Introduction

AEROTHRIVE GmbH was invited to establish a legal register for aircraft ground handling regulations and industry standards (phase 1 of our project), and once that register is established to conduct a gap analysis by analyzing each specific regulatory requirement identified, if that requirement would cover hydrogen powered aircraft without jeopardizing aviation safety. A high uniform level of aviation safety should always be maintained aligned with the Basic Regulation for aviation safety (EU) 2018/1139 in the "Whereas" section para (1) and Article 1 para (1).

In the light of the above, our group examined each identified requirement regarding potential safety gaps for the ground handling of hydrogen powered aircraft (phase 2 of our project). As a result, potential safety gaps for the handling of hydrogen powered aircraft require further examination prior to be closed and may be subjected to management of change including a risk evaluation to determine appropriate risk treatment and mitigation measures. Therefore, the output (or deliverable) of this report may be the input for further steps in which AEROTHRIVE may assist.

AEROTHRIVE provided a group of aviation experts to work on this matter. All members work or have worked for more than 10 years in aviation organizations in safety critical management functions:

- Cpt. Tobias Westen: Captain on A320 family aircraft and LBA approved Safety and Compliance Monitoring Manager for an Air Operator Certificate and CAMO organization.
- Mrs. Barbara Achleitner: former Nominated Person Ground Operations (LBA) for a major Air Carrier and former Accountable Manager (Austro Control) for a major Air Operator and CAMO organization.
- Mr. Henrik Baark: Aviation Lawyer and Compliance Monitoring as well as Safety Manager (LBA) for Air Operator Certificates, CAMO organizations and Approved Training Organizations.

The transition towards hydrogen-powered aircraft represents a fundamental change in airport operations and ground handling environments across Europe and particularly the BSR region. To support aerodromes, ground handling service providers and competent authorities in preparing for this technological step, a structured, evidence-based methodology was applied in two consecutive project phases.

2. Methodology

Phase 1 focused on building a Regulatory Register and Cross-Reference List identifying relevant legal requirements and industry standards applicable to the ground handling of aircraft: from arrival through turnaround operations to departure.

Phase 2 assessed these requirements against the operational characteristics, hazards, and demands in the light of aviation safety as the overall objective of the regulation, but associated with gaseous and liquid hydrogen systems, thereby identifying gaps, inconsistencies and areas where existing regulations or standards may not yet accommodate hydrogen-powered aircraft.

Together, these phases provide the analytical regulatory aviation safety foundation for subsequent Management of Change (MoC) processes, risk assessments and the design of operational concepts for hydrogen aircraft handling.

2.1 Phase 1 – Regulatory Mapping and Compilation of the Cross-Reference Register

2.1.1 Objective and Scope

Phase 1 aimed to establish a structured regulatory baseline in a legal register for all aircraft ground handling processes relevant to hydrogen operations as specified above in the introduction.

The resulting Regulatory Register serves as a reference framework for aircraft ground handling against which the hydrogen-specific gap analysis in phase 2 is conducted.

2.1.2 Methodological Approach

The methodology for phase 1 consisted of five steps:

Step 1: Identification of Regulatory Sources

As part of the foundational work for the regulatory assessment, all potentially relevant regulatory and industry sources with implications for aircraft ground handling and aviation safety were systematically identified. This step was essential for establishing the scope of the subsequent mapping and gap analysis, ensuring that the review captured international, European, national, and industry-level provisions that may intersect with hydrogen-related operations. Figure 1 (see enclosed) illustrates the proportional distribution of identified sources, highlighting the current dominance of established EU legislation, complemented by international standards, national laws, and industry best-practice documents.

At the international level, several key ICAO Annexes and guidance materials were included in the assessment. These comprised Annex 14 (Aerodromes), Annex 19 (Safety Management), and pivotal manuals such as Doc 9137 (Airport Services Manual), Doc 9977 (Fueling Procedures), and Doc 10121 (Guidelines for Alternative Fuels). These documents provide the foundational global framework for aerodrome design, safety management, and refuelling operations, yet they remain predominantly oriented toward kerosene-based practices.

At the European level, the review encompassed the EASA Basic Regulation along with a range of Implementing Rules (IRs). Of particular relevance were:

- Regulation (EU) 139/2014 governing EASA Part-ADR for aerodrome operators;
- Regulation (EU) 965/2012 covering operational requirements under Part-ORO; and
- the emerging Regulation (EU) 2025/20, which will introduce the GH.OPS framework for ground handling organisations and define binding requirements for ground operations at EU aerodromes.

These European instruments constitute the majority of currently applicable regulatory material (as illustrated in Figure 1), while also representing the area where future hydrogen-relevant provisions are expected to be integrated.

National legislation, here exemplified by German regulatory instruments, was also incorporated to reflect domestic oversight structures. Relevant sources included the Luftverkehrsgesetz (LuftVG), BADV, Betriebssicherheitsverordnung (BetrSichV) and Gefahrstoffverordnung (GefStoffV), each of which may impose obligations on operators regarding hazardous substances, technical installations, or workplace safety in the context of hydrogen handling.

Finally, a selection of industry standards was integrated into the regulatory inventory. These included SAE AIR8466 (hydrogen ground handling guidance), JIG 4 (fuelling standards), ISO fuel quality and hydrogen storage standards (e.g., ISO 19881), as well as ISAGO provisions applicable to ground handling service providers. These documents offer valuable technical and procedural guidance, particularly where formal regulation has not yet evolved to address hydrogen-specific conditions.

Together, these regulatory categories form the comprehensive corpus from which the Phase 1 mapping and Phase 2 gap analysis were conducted. Their distribution, as depicted in Figure 1, underscores the current reliance on conventional regulatory sources and highlights the emerging need for hydrogen-specific rulemaking at both EU and international levels.

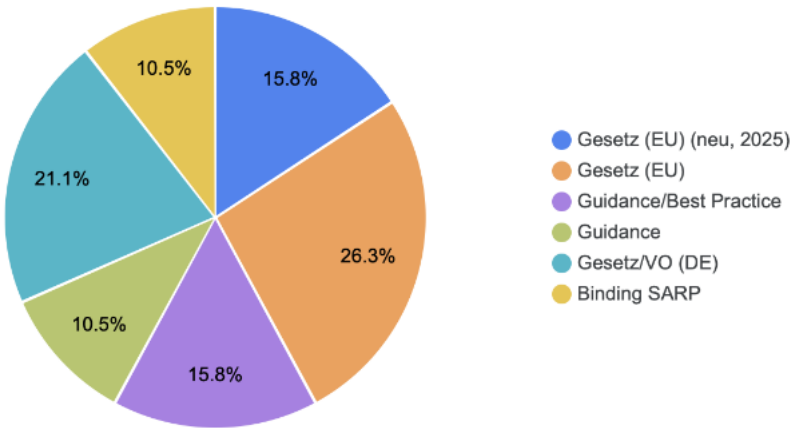


Figure 1 – Overview of Applicable Regulatory Sources

These were recorded and categorised in the Regulatory Register (Annex A), which is attached to this report.

Step 2: Extraction of Relevant Articles and Clauses

As part of the Phase 1 regulatory mapping, a systematic extraction of all articles, clauses, and provisions relevant to aircraft ground handling operations was undertaken. For each regulatory reference included in the review, whether an ICAO source, EASA implementing rule, national requirement, or industry standard the team identified every section that holds potential relevance across the full operational continuum, from aircraft arrival through turnaround activities to departure. This comprehensive extraction ensured that no procedural, safety-related, or organisational requirement affecting hydrogen ground operations was overlooked.

The analysis encompassed provisions related to apron safety, including spatial zoning, personnel access control, marshalling procedures, and hazard area management. Equally, all clauses pertaining to refuelling and defuelling were captured, with particular attention to those specifying bonding requirements, safety distances, fuelling coordination, and general fuel-handling procedures areas where hydrogen is expected to introduce deviations from conventional practice.

Regulations addressing ground support equipment (GSE) requirements and vehicle operations were also included, given the potential need for new equipment categories, modified maintenance regimes, and enhanced operational controls in a hydrogen context. Clauses relating to emergency response were extracted to assess the readiness of existing frameworks to accommodate hydrogen-related hazards, such as invisible flames, high-pressure releases, and cryogenic spill events.

In addition, provisions concerning training and competency were identified to determine the extent to which current regulatory sources define personnel qualification pathways, technical skill requirements, and safety training obligations elements that will require expansion for hydrogen operations. The review also included all clauses addressing Safety Management Systems (SMS) and risk management, as these provide the organisational structures through which hydrogen hazards should ultimately be integrated, monitored, and controlled.

Finally, all requirements specifying aerodrome operator responsibilities were documented, focusing on oversight duties, infrastructure management obligations, emergency preparedness, and coordination with ground handling service providers and air operators.

For each extracted clause, the regulatory team documented the applicable scope, legal status (binding requirement, acceptable means of compliance, guidance material, or industry standard), and a concise descriptive summary. This structured documentation approach provided a transparent and traceable foundation for the clause-by-clause comparison conducted in Phase 2 and ensured that all regulatory elements relevant to hydrogen ground handling were consistently captured and categorised.

Step 3: Categorization by Ground Handling Activity

Following the extraction of all relevant regulatory articles and clauses in Phase 1, the requirements were systematically categorised according to the ground handling activity domains defined in the project outline. This step translated the raw regulatory material into an operationally meaningful structure, thereby enabling a targeted comparison between the existing, hydrogen-agnostic regulatory landscape and the procedural requirements anticipated for hydrogen-powered aircraft.

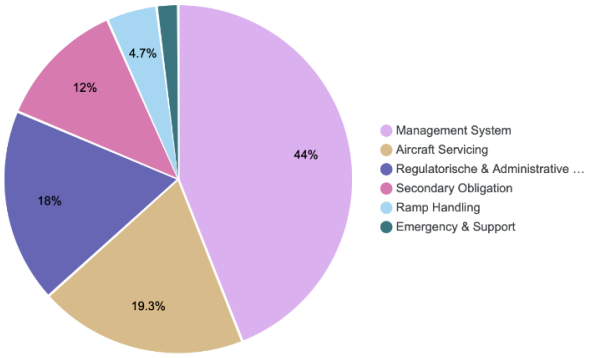


Figure 2 – Categorization by Ground Handling Activity

The categorisation aligned each regulatory provision with one of the core ground handling activity groups: *Aircraft Servicing*, *Ramp Handling*, *Emergency and Support Services*, *Management System Requirements*, and *Regulatory and Administrative Requirements*. Figure 2 visualises the proportional distribution of extracted regulatory content across these categories and demonstrates a clear dominance of management-system-related provisions (44%). This distribution is consistent with the strong emphasis of current ICAO and EASA frameworks on organisational processes, safety management, oversight, and administrative compliance.

Aircraft Servicing (19.3%) accounted for a substantial portion of the mapped clauses, reflecting the centrality of fuelling and servicing procedures in ground operations. Given that hydrogen introduces distinct requirements for fuel quality assurance, contamination control, bonding, leak detection, and cryogenic handling, this category is expected to undergo some of the most significant procedural transformations.

The *Ramp Handling* category (18%) captured provisions related to apron safety, GSE operation, vehicle movements, and marshalling areas where hydrogen's dispersion characteristics, modified hazard zones, and equipment requirements may introduce new operational constraints. The figure illustrates that ramp-related regulations form the second largest operational domain in the dataset.

Regulatory and Administrative Requirements (12%) formed another notable category, comprising provisions on operator responsibilities, documentation, qualification obligations, approval processes, and regulatory interfaces. These administrative structures will be essential in supporting future hydrogen-specific oversight mechanisms and approval pathways.

In contrast, the categories of *Secondary Obligations* (4.7%) and *Emergency and Support Services* (approximately 2%) contained comparatively fewer regulatory provisions. This imbalance highlights a structural gap: hydrogen introduces new emergency response complexities (e.g., invisible flames, cryogenic spills, high-pressure releases), yet existing regulations provide limited operational guidance in these domains. The low representation of emergency-related material in Figure 2 therefore visually reinforces several key gaps later confirmed in the Phase 2 analysis.

By categorising the regulatory material in this way, the project team established a structured analytical framework that enabled a systematic comparison between conventional regulatory expectations and the operational demands that hydrogen-powered aircraft will impose. The distribution shown in Figure 2 illustrates both the strengths of the current regulatory environment, particularly in management system governance and the areas where substantive development will be required to support safe hydrogen integration.

This methodology allowed a structured comparison between the hydrogen-agnostic regulatory framework and the operational steps required for hydrogen powered aircraft.

Step 4: Assessment of Hydrogen Relevance

Following the categorisation of regulatory provisions by ground handling activity, Phase 1 proceeded with a structured assessment of hydrogen relevance for each regulatory reference. This evaluation served as a bridge between the existing regulatory landscape, largely developed for kerosene-based operations, and the emerging operational requirements associated with hydrogen-powered aircraft. The purpose of this step was to determine the extent to which current rules provide meaningful guidance for hydrogen operations, and where gaps, ambiguities, or incompatibilities exist.

Each regulatory provision was reviewed individually by a trained subject-matter expert, who assessed its applicability according to four relevance categories. First, provisions were identified as directly applicable when they addressed operational principles or safety requirements that remain valid for hydrogen technologies without modification (e.g., generic apron safety rules or SMS obligations). Second, some provisions were judged to be indirectly applicable or applicable by analogy that is, conceptually relevant but framed around assumptions tied to Jet A-1 fuelling, conventional hazard patterns, or established equipment types. These provisions may offer structural guidance but still require adaptation before being applied to hydrogen operations.

Third, several regulatory clauses were found to be not applicable due to hydrogen's fundamentally different physical and chemical properties. These included requirements whose validity presupposes the behaviour of liquid hydrocarbon fuels, conventional ignition mechanisms, or standard temperature and pressure conditions assumptions that do not align with hydrogen's cryogenic temperatures, rapid dispersion behaviour, or high-pressure systems. Fourth, some provisions were assessed as likely to require amendment or supplementation, particularly where the regulatory text hints at relevance for fuel handling but does not sufficiently address hydrogen-specific hazard characteristics, such as invisible flame phenomena, contamination sensitivity, or cryogenic spill dynamics.

To ensure transparency and traceability of the assessment, the regulatory register included a dedicated column titled “Hydrogen-Relevanz / GAP”. This column captured the evaluator’s classification of each requirement, along with a short contextual annotation explaining the rationale behind the relevance rating. This structured documentation approach enabled a clear identification of where existing regulations provide adequate coverage, where interpretative flexibility may allow adaptation, and where explicit regulatory gaps exist that should be addressed through new rulemaking, guidance materials, or operational procedures.

Together, the hydrogen relevance assessment created the analytical foundation for the Phase 2 gap analysis, supporting a rigorous comparison between current regulatory provisions and the operational needs of hydrogen-powered aircraft.

Step 5: Creation of the Regulatory Register with a Cross-Reference Matrix (Annex A)

The culmination of Phase 1 was the development of a comprehensive Regulatory Register supported by an integrated Cross-Reference Matrix. This combined tool served as the foundational output for the regulatory mapping exercise and provided the analytical infrastructure required for the hydrogen-focused assessments conducted in Phase 2 and beyond.

The cross-reference matrix enabled the project team to systematically match each regulatory citation to specific hydrogen-related operational steps. By linking individual provisions to distinct phases of the ground handling process, such as aircraft arrival, ramp operations, fuelling and defuelling, GSE operation, emergency response, and departure, the matrix clarified exactly where regulatory guidance is available and where procedural or infrastructural gaps exist.

In parallel, the matrix also facilitated the identification of linkages between legal obligations and relevant industry standards. This comparative structure made it possible to understand how mandatory requirements (e.g., ICAO SARPs, EASA Implementing Rules, national legislation) align with or diverge from industry-developed practices such as SAE AIR8466, JIG 4, ISO hydrogen specifications, and ISAGO ground handling standards. The ability to see these relationships side-by-side was essential for determining whether industry guidance could serve as an interim bridge where formal regulation has not yet evolved to address hydrogen operations.

Furthermore, the completed matrix provided the basis for hydrogen safety and risk assessments. By mapping regulatory provisions to operational steps and hazard domains, the tool created a structured pathway for identifying where hydrogen introduces new or modified risks, where existing risk controls may be insufficient, and where future change management efforts will be required. This mapping process ensured that the subsequent Phase 2 gap analysis would be grounded in a traceable and comprehensive regulatory foundation.

Together, the Regulatory Register and its associated Cross-Reference Matrix constitute the formal and final deliverable of Phase 1. They provide a clear, transparent, and methodologically robust dataset that supports regulatory interpretation, operational planning, risk assessment, and future rulemaking discussions relevant to the safe integration of hydrogen-powered aircraft.

2.2 Phase 2 – Hydrogen-Specific Gap Analysis

2.2.1 Objective and Purpose

Phase 2 of the project was designed to undertake a detailed and systematic evaluation of all regulatory and industry standards identified in Phase 1, with the overarching aim of determining their applicability to the emerging operational context of hydrogen-powered aircraft. Building upon the regulatory mapping and categorisation completed in the earlier phase, this stage of the project sought to establish how far the existing legal framework, predominantly developed around Jet A-1 operations, can effectively accommodate hydrogen-related requirements across the entire aircraft turnaround process. The scope of this assessment extended from the moment an aircraft enters aerodrome airspace through landing, taxiing, ramp handling, servicing, fuelling, and eventual departure. Particular emphasis was placed on the safety-critical phases of turnaround management and emergency response planning, as these operational areas contain the highest potential divergence between conventional fuels and hydrogen.

The purpose of Phase 2 was fourfold:

1. To identify regulatory gaps where hydrogen-specific provisions are entirely absent from ICAO, EASA, national, or industry documents.
2. To recognise potential hazards arising from the fundamental physical and chemical differences between Jet A-1 and hydrogen, such as invisible flame behaviour, rapid dispersion, cryogenic temperatures, and high-pressure system risks.
3. To determine regulatory insufficiencies that are likely to trigger a Management of Change (MoC) process within aerodromes and ground handling organisations, including required updates to procedures, qualification standards, infrastructure, and hazard control strategies.
4. To identify areas requiring new industry standards or supplementary regulatory development, recognising that hydrogen introduces risks and operational dynamics not addressed in existing rule sets.

Figure 3 shows the results of the gap analysis and the regulatory applicability to Hydrogen Operations. It provides a quantitative representation of the hydrogen relevance assessment conducted in Phase 2. For each regulatory source, the figure depicts the number of clauses deemed hydrogen-relevant (“YES” in green) versus those considered not relevant, insufficient, or incompatible (“NO” in orange). This visualisation offers important insights into the structural readiness of the current regulatory landscape. Several key conclusions emerge from Figure 3:

1. A high proportion of non-applicable provisions in major regulatory instruments.
   EU delegated and implementing regulations, JIG 4, and ICAO Doc 9137 show orange bars, reflecting that many provisions assume kerosene fuel properties or conventional apron configurations. These documents therefore lack procedural guidance for hydrogen operations.
2. Industry standards provide partial, but incomplete, hydrogen coverage.
   SAE AIR8466 and specific ISO standards include some hydrogen-focused content (green bars), yet they remain far from sufficient to form a comprehensive operational rule set.
3. National-level rules exhibit minimal hydrogen relevance in their current form.
   Regulations such as GefStoffV, BetrSichV, or legacy ICAO Annexes display only very small

numbers of hydrogen-relevant clauses, illustrating that domestic frameworks have not yet adapted to hydrogen safety or infrastructure challenges.

4. Systemic gaps across all regulatory families.
   The visual predominance of orange bars relative to green confirms that the introduction of hydrogen cannot be accommodated through minor regulatory amendments; instead, significant redesign and supplementation of the regulatory environment will be necessary.

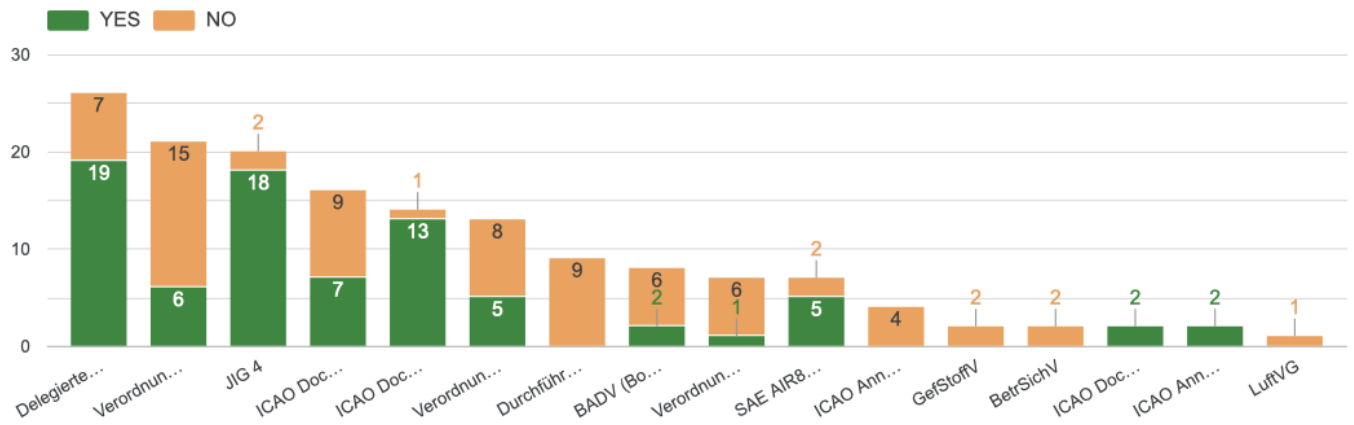


Figure 3 – Gap Analysis Results

Implications for the Purpose of Phase 2

The analysis reflected in Figure 3 provided clear evidence that:

- existing fuelling, servicing, and apron safety regulations cannot be directly transferred to hydrogen operations;
- emergency response provisions are inadequate for hazards such as cryogenic spills or invisible flames;
- SMS obligations require expansion to incorporate hydrogen-specific hazard identification, reporting, and performance monitoring;
- new procedures, training programme, and infrastructure approval pathways will be necessary.

Thus, Phase 2 successfully fulfilled its purpose: it established an evidence-based understanding of where hydrogen introduces operational, procedural, and regulatory discontinuities, and where future rulemaking, industry guidance, and MoC processes should focus.

2.2.2 Analytical Method

Phase 2 employed a structured analytical methodology that built directly upon the regulatory database and cross-reference matrix produced in Phase 1. The purpose of this methodological step was to evaluate the extent to which the existing regulatory environment can accommodate the operational and safety requirements associated with hydrogen-powered aircraft.

Step 1 – Comparison of Hydrogen Requirements Against Existing Regulations

The first analytical step involved a systematic comparison between hydrogen-specific operational requirements and the provisions contained in the existing regulatory framework. Using the entries in the Phase 1 regulatory register, each clause was examined to assess whether it meets, partially meets, or fails to meet the requirements associated with hydrogen handling.

The hydrogen requirements used for comparison were derived from four key reference sources:

- SAE AIR8466 (covering gaseous and liquid hydrogen aircraft fuelling operations),
- ISO hydrogen standards, particularly those governing hydrogen storage, transfer, and material compatibility,
- emerging EU regulations for ground handling (notably the GH.OPS proposals planned for implementation in 2028–2030), and
- safety characteristics identified in contemporary aviation hydrogen research, including cryogenic behaviour, dispersion dynamics, invisible flame behaviour, high-pressure system risks, and contamination sensitivity.

These sources collectively provided an evidence-based foundation for defining what hydrogen-powered aircraft will require in terms of ground handling, fuelling, monitoring, emergency response, and operational controls.

The comparison revealed whether individual regulatory provisions already incorporate hydrogen considerations (“YES”), or whether they remain grounded in assumptions associated with Jet A-1 and conventional aviation operations (“NO”). Provisions coded as “NO” were typically those that presuppose hydrocarbon fuel behaviour, conventional ignition risks, standard equipment categories, or traditional apron configurations, none of which align with the unique properties of hydrogen.

Figure 4 (Hydrogen Requirements Against Existing Regulations) provides a high-level representation of the outcome of this comparison. The bar chart displays the relative proportion of regulatory provisions assessed as not meeting hydrogen requirements (“NO”) versus those that do meet or may meet them (“YES”).

Several insights emerge from this figure:

1. A clear majority of existing regulatory provisions are not compatible with hydrogen. The “NO” category dominates the chart, indicating that most current regulations lack any reference to

hydrogen or are based on assumptions that are incompatible with hydrogen's physical and operational characteristics.

2. Only a limited subset of regulations show potential hydrogen applicability. The smaller "YES" segment indicates that only a minority of provisions either explicitly mention alternative fuels, are framed in technology-neutral terms, or contain adaptable risk-based language that could be extended to hydrogen operations.
3. This imbalance confirms a structural regulatory gap. The marked difference between the two bars visually reinforces one of the central findings of Phase 2: the transition to hydrogen aviation cannot be supported by the existing rule set without amendment, supplementation, or the development of new regulatory and industry standards.
4. Figure 4 provides the quantitative rationale for deeper analysis. The strong prevalence of "NO" entries formed the basis for subsequent steps in Phase 2, including hazard assessment, operational impact analysis, and identification of Management of Change (MoC) triggers.

Step 1 demonstrated that the current regulatory framework is aligned with Jet A-1 assumptions and is therefore insufficient for hydrogen-powered aircraft operations. The systematic comparison, complemented by the visual summary in Figure 4, establishes the analytical foundation for identifying hydrogen-specific gaps, risks, and necessary regulatory developments in subsequent methodological steps.

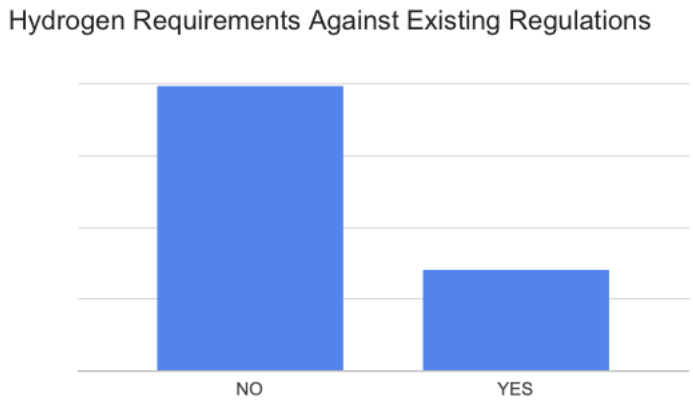


Figure 4 – Hydrogen Requirements against Existing Regulations

Step 2 – Identification of Explicit and Implicit Regulatory Gaps

A central component of the Phase 2 methodology involved identifying both explicit and implicit regulatory gaps within the existing legal and industry frameworks. Using the clause-by-clause hydrogen relevance assessments from the Phase 1 Regulatory Register, the project team evaluated where regulatory provisions fail to address hydrogen-specific operational, technical, or safety requirements.

This evaluation revealed several distinct categories of gaps, each reflecting a structural misalignment between current regulatory assumptions and the operational realities of hydrogen-powered aircraft.

Procedural gaps emerged prominently, particularly in areas where established regulations, such as GH.OPS.310 provide detailed procedural expectations for Jet A-1 fuelling but contain no equivalent provisions for gaseous or liquid hydrogen. Key omissions include hydrogen-specific bonding and earthing requirements, cryogenic hose handling procedures, venting protocols, and operational controls for high-pressure transfer systems. These gaps indicate that existing fuelling regulations cannot simply be adapted but should be supplemented or restructured to align with hydrogen's fundamentally different characteristics.

Safety and emergency response gaps were also identified. Numerous safety provisions in ICAO and EASA documentation are predicated on behaviour associated with hydrocarbon fuels, such as visible flame cues, predictable pool fire behaviour, and kerosene spill dynamics. Hydrogen's invisible flame properties, rapid vertical dispersion, cryogenic risks, and high-pressure system failure modes are not reflected in these emergency response frameworks. The absence of hydrogen-appropriate firefighting guidance or detection technology requirements represents a critical gap for both aerodrome emergency services and operational safety.

Training gaps were identified across key training regulations and AMCs, including ORGH.TRG.100 and GH.OPS.100. These provisions do not include hydrogen competencies such as cryogenic hazard recognition, hydrogen sensor operation, invisible flame identification, contamination control, or specialised emergency response. The absence of hydrogen modules in existing competency frameworks underscores the need for an entirely new hydrogen-specific training architecture.

Oversight and responsibility gaps appear where roles and interfaces between aerodrome operators, ground handling service providers (GHSPs), and air operators remain defined entirely around kerosene-based operations. Current regulations do not assign responsibilities for hydrogen infrastructure oversight, sensor calibration, leak detection systems, venting area management, or hydrogen emergency preparedness. These omissions create ambiguity regarding regulatory accountability and operational ownership in a hydrogen-enabled environment.

Technical and GSE gaps arise due to the lack of hydrogen-relevant design criteria in existing standards such as JIG 4, ISO aviation fuel specifications, and EASA ground support equipment provisions. Requirements for materials compatibility, anti-embrittlement features, cryogenic protection, and high-pressure system integrity are not currently addressed. As a result, there is no regulatory pathway for certifying hydrogen-capable ground support equipment or mobile fuelling units.

Figure 5 (Mapping of Ground Handling Categories to Regulations with Identified Gaps) visually illustrates the mapping between ground handling activity categories and the regulatory sources in which hydrogen-related gaps were found. This Sankey diagram provides several insights into the structure and distribution of regulatory deficiencies:

1. Regulatory and Administrative Requirements exhibit the most extensive set of gaps.
   The broad flows from this category toward multiple regulatory documents, including the upcoming GH.OPS regulation, ICAO Docs 10121 and 9977, and national oversight regulations indicate that administrative and oversight frameworks lack hydrogen-relevant provisions across the board.

2. Management System gaps are widely distributed.
   Significant flows link SMS-related requirements to ICAO Annex 19, EASA Part-ADR, and various national regulations, confirming that hydrogen hazards, SPIs, reporting obligations, and change management triggers have not yet been integrated into existing SMS architectures.
3. Aircraft Servicing and fuelling-related gaps link prominently to JIG 4, ICAO Doc 9137, and EU servicing regulations.
   These regulatory sources assume kerosene properties and therefore do not accommodate hydrogen's cryogenic, high-pressure, or venting behaviours.
4. Secondary obligations and technical standards (e.g., SAE AIR8466, Basic Regulation) also show multiple disconnects.
   This demonstrates that even where hydrogen-specific industry guidance exists, it has not yet been systematically incorporated into the regulatory foundation.

Overall, Figure 5 reveals that hydrogen-related gaps are not isolated within one regulatory domain but are distributed across every major category of ground handling activity. This confirms that the transition to hydrogen operations represents a systemic challenge requiring coordinated regulatory reform and not merely the modification of individual clauses or procedures.

The identification of explicit and implicit gaps demonstrates that the current regulatory environment is insufficient for supporting hydrogen-powered aircraft operations. The combined insights from the textual analysis and the visual mapping in Figure 5 confirm that procedural, safety, training, oversight, and technical reforms will be necessary to ensure safe hydrogen integration at aerodromes.

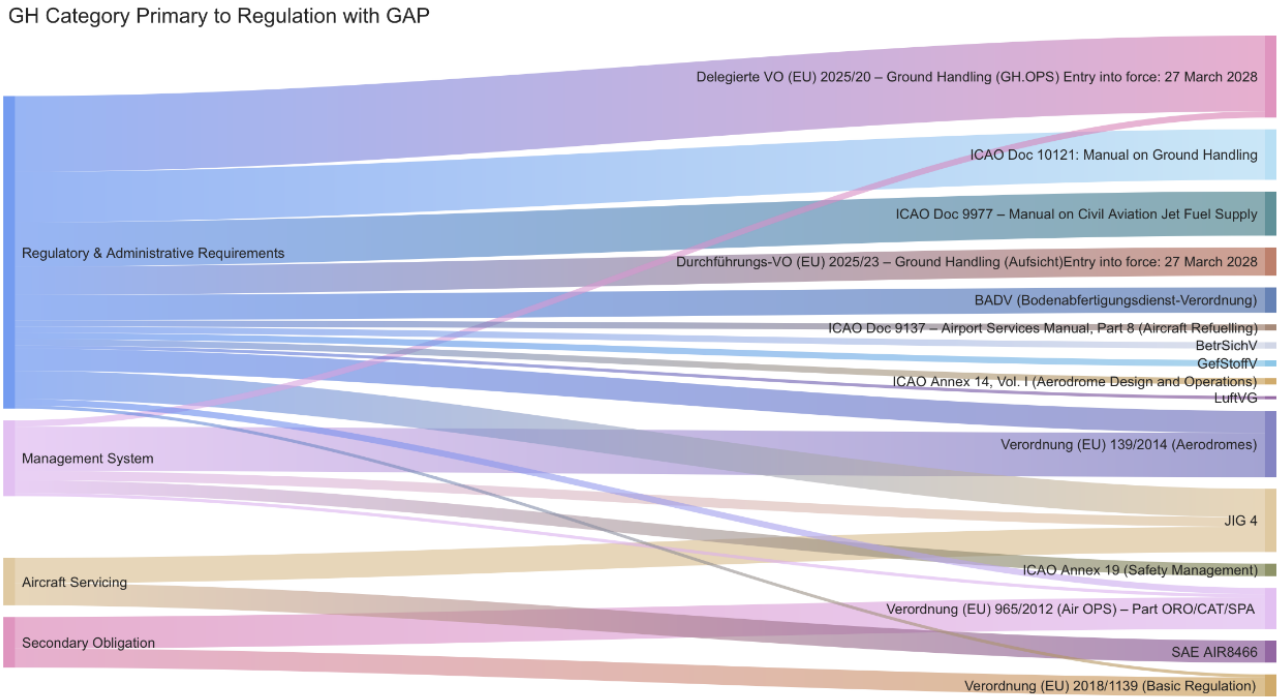


Figure 5 – Ground Handling Category Primary to Regulation with Gap

Step 3 – Hazard Identification

In accordance with established safety principles derived from ICAO Annex 19 and contemporary Safety Management System (SMS) expectations, the project conducted a systematic identification of hydrogen-specific hazards. This process focused particularly on those areas in which existing regulatory provisions offer insufficient operational guidance. As a result, several key hazard domains were recognised. These included the risk of cryogenic burns arising from the handling of liquefied hydrogen; the potential for failure within high-pressure storage and distribution systems; and the unique behaviour of hydrogen flames, which may be invisible to the naked eye. Further hazard characteristics were identified in relation to the extremely low ignition energy of hydrogen, the routine need for controlled hydrogen venting as part of normal aircraft operation, the specific dispersion patterns of hydrogen that may require expanded safety clearances, and the susceptibility of certain metal components to material embrittlement. Collectively, these hazard categories informed the subsequent development of Management of Change (MoC) considerations, as outlined later in the project framework.

Step 4 – Evaluation of Impact on Ground Handling Processes

Following the identification of gaps within the regulatory landscape, the project team undertook an evaluation of their potential operational consequences. This assessment considered the full spectrum of ground handling processes that may be affected by the introduction of hydrogen-powered aircraft. Implications were analysed for aircraft servicing activities, ramp handling procedures, fuelling operations, apron safety management, turnaround processes, and emergency response arrangements. By examining the intersection between regulatory gaps and operational practice, the project team was able to determine where revised procedures, new equipment specifications, or updated operational protocols may be required to ensure safe and compliant handling of hydrogen aircraft.

Step 5 – Identification of Change Triggers

The final analytical step involved mapping the identified gaps to formal MoC criteria. The introduction of hydrogen technologies into the ground handling environment activates several recognised triggers for organisational change. These include the requirement for new or adapted infrastructure, the need to introduce revised qualification and competence frameworks for personnel, modifications to existing operational sequences, and a substantive alteration of the organisation's hazard landscape. Each of these triggers directly corresponds to the MoC elements defined in AEROTHRIVE Phase 3, thereby providing a structured basis for determining the scope and priority of subsequent change actions.

3. Key Outcomes of the Two-Phase Methodology

3.1 Deliverables of phase 1

Phase 1 produced a set of foundational deliverables designed to establish the regulatory baseline for assessing the suitability of existing standards in the context of hydrogen-powered aircraft operations. The first of these deliverables was a comprehensive Regulatory Register encompassing the full spectrum of applicable international, European, national, and industry standards, including ICAO provisions, EASA regulations, EU legislation, domestic regulatory requirements, and sector-specific guidance materials. This register served as the authoritative reference corpus for all subsequent analytical activities.

A second deliverable consisted of a Cross-Reference Matrix that systematically mapped each identified regulatory provision to the full range of ground handling processes. This matrix enabled a structured examination of how existing requirements interface with operational activities such as fuelling, aircraft servicing, GSE operation, apron management, and emergency response planning. It also facilitated the identification of areas where current regulations offer insufficient, partial, or no coverage for hydrogen-related scenarios.

The regulatory texts were further categorised based on their relevance to hydrogen operations. This classification distinguished between provisions that are directly applicable, partially applicable, only indirectly relevant, or entirely inapplicable due to assumptions grounded in conventional Jet A-1 operations. The categorisation also identified explicit gaps instances where no hydrogen-specific requirements exist. Thereby providing clarity on where new or revised provisions will be needed.

Finally, Phase 1 resulted in the development of a structured database designed to support analytical comparison, scenario-based assessment, and strategic regulatory planning. The database allows users to filter provisions by regulatory source, operational domain, hydrogen relevance category, and identified gaps, thereby providing a flexible and robust tool for guiding subsequent phases of the project.

Together, these deliverables form a comprehensive and methodologically sound foundation for Phase 2's gap analysis and for future regulatory development in support of hydrogen aviation integration.

3.2 Deliverables of Phase 2

Phase 2 produced a suite of deliverables that build directly upon the regulatory baseline established in Phase 1 and provide a detailed understanding of the extent to which existing frameworks are insufficient for hydrogen-powered aircraft operations. The central output of this phase was a comprehensive hydrogen-specific gap analysis, which systematically evaluated each regulatory provision against the operational and safety requirements associated with hydrogen handling. This analysis enabled a nuanced determination of where current standards fail to address hydrogen's unique properties, behaviours, and associated risks.

A further key deliverable was the identification of regulatory deficiencies, operational incompatibilities, and missing provisions. These findings highlight areas where existing rules, whether international, European, national, or industry-based do not provide adequate coverage for critical operational elements

such as hydrogen fuelling, cryogenic handling, leak detection, or emergency response. The identification of such deficiencies enables stakeholders to determine where new regulatory mechanisms, guidance materials, or procedural adaptations will be necessary.

Phase 2 also delivered a recognition of hydrogen-specific hazards that require procedural or regulatory intervention. These include hazards arising from hydrogen's physical and chemical properties, such as invisible flame behaviour, rapid dispersion, high-pressure system risks, and cryogenic exposure. Documenting these hazards ensures that they can be systematically incorporated into Safety Management System (SMS) structures, emergency planning processes, and future regulatory amendments.

Another deliverable was a prioritised overview of regulatory gaps likely to trigger a Management of Change (MoC) process. This prioritisation distinguishes between gaps that have immediate operational implications and those with longer-term strategic significance. It provides aerodrome operators and ground handling organisations with a structured basis for planning procedural updates, training needs, infrastructure adjustments, and oversight mechanisms in a controlled and risk-informed manner.

Finally, Phase 2 established a foundational framework for the development of hydrogen-specific procedures, training programme, and operational concepts. This foundation will support subsequent project phases, ensuring that future operational documentation and training curricula are aligned with both identified hazards and anticipated regulatory developments.

Collectively, these deliverables provide a robust analytical platform for guiding hydrogen integration efforts and informing future regulatory, procedural, and organisational change.

4. Interim Conclusion

The two-phase methodology established a rigorous and defensible framework for assessing regulatory readiness for hydrogen-powered aircraft at airports.

Phase 1 produced a structured regulatory register for ground handling of an aircraft from its arrival until its departure, which captured the full scope of applicable regulations and standards.

Phase 2 built upon this foundation to reveal where existing rules require adaptation or augmentation to reflect the fundamentally different risk profile of hydrogen systems.

Together, these phases provide the essential groundwork for designing safe hydrogen ground handling operations, updating aerodrome procedures, and implementing MoC processes across the European aviation system.

5. Analysis the Hydrogen-Specific Gap Assessment

Following the regulatory mapping undertaken in Phase 1, Phase 2 employed a structured analytical methodology to assess the adequacy of existing international, European, national, and industry standards for the safe ground handling of hydrogen-powered aircraft. This analytical phase drew upon the *Regulatory GAP Catalogue* and the consolidated regulatory register (Annex A), each of which documents hydrogen-specific omissions across the relevant regulatory domains, including Part-ADR, GH.OPS, ORGH.DOC/TRG, ICAO Annexes and associated guidance material, JIG 4, SAE AIR8466, ISO standards, and additional industry specifications.

Phase 2 applied a four-step methodological framework that operationalised the gap analysis and extended it beyond the high-level applicability assessment presented in Section 2.2.

Step 1 – Hydrogen Operational Requirements Baseline

A dedicated baseline of hydrogen operational requirements was established to serve as the technical reference for all subsequent regulatory evaluations. This baseline encompassed the principal operational and hazard characteristics unique to hydrogen, including:

- invisible flame behaviour,
- cryogenic temperature exposure,
- high-pressure gaseous storage and distribution conditions,
- venting dynamics and vertical dispersion patterns, and
- contamination sensitivity and associated material compatibility considerations.

This reference model provided a structured foundation enabling a consistent, transparent, and technically defensible assessment of each regulatory clause with respect to hydrogen-specific operational needs.

Step 2 – Clause-by-Clause Regulatory Assessment

Using the catalogue of extracted regulatory provisions from Phase 1, each requirement was examined to determine its relevance and applicability to hydrogen ground handling operations. The assessment differentiated between:

- directly applicable provisions,
- partially applicable provisions requiring adaptation,
- indirect or insufficient provisions, and
- non-applicable provisions, typically because they presuppose Jet A-1 or other conventional aviation fuels.

Where no hydrogen-relevant requirement existed, explicit regulatory gaps were recorded. All assessments were documented within the GAP Register (“Hydrogen-Relevanz / GAP”), including

contextual annotations for provisions that referenced hydrogen only indirectly or insufficiently (e.g., GH.OPS.310, ADR.OPS.B series, ORGH.TRG.100, and selected ICAO Doc 9137 and JIG 4 content).

Step 3 – Impact Assessment on Ground Handling Processes

For each regulatory gap identified, the project team undertook a detailed examination of its operational consequences across the full scope of ground handling activities. The assessment began with aircraft servicing and fuelling procedures, recognising that hydrogen's unique properties, including cryogenic temperatures, high-pressure storage, and venting dynamics, may necessitate procedural redesigns, additional safety barriers, or specialised equipment. Apron safety and passenger handling processes were similarly reviewed, with a focus on how hydrogen-related hazards might alter zoning requirements, access control, marshalling practices, or protective measures for both staff and passengers.

The implications for ground support equipment (GSE) operation and maintenance were also analysed, particularly in relation to compatibility with hydrogen systems, potential ignition sources, material embrittlement risks, and changes in inspection regimes. Turnaround coordination processes were evaluated to determine whether existing sequencing, communication, and role allocations remain adequate when hydrogen technologies are introduced.

Emergency response planning was another critical area of assessment. The gap analysis considered whether aerodromes possess the necessary detection systems, extinguishing capabilities, response protocols, and training frameworks to manage hydrogen-related incidents, including invisible flames, rapid dispersion characteristics, and potential high-energy release scenarios.

In addition, the review examined how identified gaps affect Safety Management System (SMS) functions, including hazard identification, occurrence reporting, risk assessment methodologies, and internal oversight structures. The analysis also encompassed aerodrome operator responsibilities under Part-ADR, assessing where new obligations may arise due to hydrogen infrastructure, operational interfaces, or altered risk profiles.

By expanding the analysis beyond textual regulatory interpretation to include these operational dimensions, the project ensured that the gap assessment was not merely a legal comparison. Instead, it constituted a comprehensive evaluation of system integration challenges, procedural vulnerabilities, and the broader organisational changes required to safely incorporate hydrogen-powered aircraft into aerodrome environments.

Step 4 – Hazard and Change Triggers Assessment

Where existing regulations were found to provide insufficient coverage of hydrogen-related hazards, the project team proceeded to identify corresponding change triggers specific conditions that necessitate amendments to operational procedures, upgrades to infrastructure, or adjustments in organisational roles and responsibilities. These triggers emerged particularly in areas where hydrogen introduces novel risks or operational characteristics that are not contemplated within current regulatory frameworks, such

as the handling of cryogenic fuels, management of high-pressure systems, or the need to account for invisible flame behaviour and hydrogen dispersion dynamics.

The identification of such triggers aligns closely with the Management of Change (MoC) principles described in the project documentation. In this context, the introduction of hydrogen technologies represents a substantive alteration to the aerodrome's operational environment, thereby activating several core MoC elements. These include the requirement for new or adapted infrastructure, such as modified fuelling systems, enhanced detection technologies, or revised safety zoning and the need to establish new competencies through specialised training and qualification programme for ground handling personnel, emergency responders, and technical staff.

Furthermore, the presence of hydrogen necessitates revisions to established operational sequences, including turnaround procedures, fuelling protocols, emergency response workflows, and communication interfaces between aerodrome stakeholders. These modifications also contribute to a transformed hazard landscape, in which existing risk assessments, mitigations, and SMS processes should be updated to reflect the distinct characteristics and behaviours of hydrogen.

By systematically identifying these change triggers, the project ensures that hydrogen integration is approached not merely as a technical adaptation but as a comprehensive organisational transition. This reinforces the importance of embedding hydrogen-related developments within the aerodrome's MoC framework, thereby ensuring controlled, traceable, and risk-informed implementation of all necessary changes

6. Summary of Gaps Identified

The gap analysis confirmed that current regulatory frameworks predominantly assume kerosene-based fuelling and therefore do not reflect key requirements for hydrogen-powered aircraft. The detailed regulatory entries in the GAP Register document numerous instances where hydrogen is absent, indirectly referenced, or where operational concepts differ significantly from Jet A-1.

These gaps fall into five overarching categories.

6.1 Overarching category: Hydrogen-Specific Fuelling and de-fuelling procedures

Provisions such as GH.OPS.310 and the associated AMC1/AMC2 GH.OPS.310 for example were found to lack the hydrogen-specific procedural guidance necessary to ensure safe and effective ground handling of hydrogen-powered aircraft. In their current form, these regulations and acceptable means of compliance are largely framed around conventional fuel operations and therefore do not address several critical technical and operational requirements associated with hydrogen.

Most notably, the existing provisions do not incorporate procedures for hydrogen leak detection and continuous monitoring, an essential omission given hydrogen's low molecular weight, rapid dispersion characteristics, and the tendency of leaks to accumulate in confined or semi-enclosed spaces. Similarly, the regulations do not provide guidance on bonding and equipment earthing practices that differ from those used with Jet A-1, despite the distinct electrostatic and ignition risks associated with gaseous and cryogenic hydrogen.

The absence of requirements for cryogenic handling is also significant. Liquid hydrogen introduces hazards related to extreme low temperatures, including material embrittlement and cryogenic burns, which are not reflected in the current procedural expectations. Likewise, the provisions do not address safety measures for high-pressure storage and transfer systems, although these form a fundamental component of hydrogen ground operations.

Venting protocols represent another area where the regulatory material is incomplete. Hydrogen operations require defined procedures for planned venting events, including designated venting areas, atmospheric dispersion considerations, exclusion zones, and real-time monitoring. None of these elements are captured within GH.OPS.310 or its interpretive guidance.

Finally, the regulations omit requirements for contamination control and verification of hydrogen fuel specification, both of which are crucial for ensuring fuel purity and preventing operational anomalies that may arise from the presence of particulates, moisture, or incompatible materials.

Taken together, these omissions underscore the need for revised or supplementary regulatory material that explicitly addresses the unique procedural demands of hydrogen ground handling operations.

6.2 Overarching category: Emergency Response and Firefighting

Provisions contained in ADR.OPS.B.010 and related emergency planning requirements were also found to be insufficient for addressing the specific challenges posed by hydrogen-related incidents. These

regulatory materials are largely designed around the characteristics of kerosene-based fuel fires and therefore do not incorporate several critical elements necessary for effective emergency preparedness in a hydrogen operational environment.

First, the regulations do not account for the behaviour of hydrogen flames, which may be invisible to the naked eye due to their low radiative emission. This characteristic has profound implications for responder situational awareness, hazard zone delineation, and tactical approach strategies. None of which are addressed within the current ADR framework.

Second, hydrogen introduces unique considerations regarding extinguishing agent compatibility. Conventional firefighting methods designed for hydrocarbon fuels may be ineffective or inappropriate for hydrogen-related incidents, particularly those involving gaseous releases or high-pressure storage system failures. The absence of hydrogen-specific extinguishing guidance represents a notable regulatory gap.

Third, emergency planning rules do not reflect the need to revise water access routes, responder egress pathways, or isolation distances. Hydrogen disperses rapidly, forms flammable mixtures across a wide range of concentrations, and behaves differently in open versus confined environments. These properties necessitate re-evaluated spatial planning and modified emergency response zoning, which current provisions do not contemplate.

Fourth, the existing regulations do not establish requirements for detection technologies suitable for hydrogen operations. Effective emergency planning should incorporate sensors capable of detecting hydrogen leaks, monitoring vapour concentrations, and supporting automatic shutdown or isolation measures. The absence of such requirements further reduces the adequacy of the current regulatory guidance.

Additionally, several provisions within JIG guidance materials and relevant ICAO documentation remain explicitly centred on kerosene operations. As a result, they do not provide operationally relevant direction for the emerging context of hydrogen-powered aircraft, nor do they acknowledge the fundamentally different hazard landscape associated with hydrogen.

Together, these omissions demonstrate that current emergency planning regulations and industry standards should be updated or supplemented to reflect the distinctive risks and response requirements associated with hydrogen technologies.

6.3 Overarching category: Training and Competence Requirements not Hydrogen-Ready

The training provisions contained in ORGH.TRG.100, together with the associated Acceptable Means of Compliance, such as AMC1/AMC2 GH.OPS.100 and AMC4 ORGH.TRG.100 were also found to be inadequate for supporting the competencies required in a hydrogen-enabled operational environment. These training frameworks are built predominantly around conventional fuel handling scenarios and therefore do not incorporate several critical knowledge areas and skill sets necessary for personnel working with hydrogen-powered aircraft.

Importantly, the existing material does not address the recognition of hydrogen fire behaviour. Unlike kerosene-based fires, hydrogen flames may be nearly invisible under daylight conditions, requiring personnel to rely on indirect indicators such as thermal cues, sound, or heat shimmer. The absence of formal training guidance on this phenomenon represents a fundamental gap in hazard awareness and situational assessment.

Similarly, the regulatory provisions do not include instruction on cryogenic risk handling, even though liquid hydrogen is stored at extremely low temperatures that can cause severe cold burns, material embrittlement, and equipment failure. Proper handling techniques, protective equipment use, and awareness of cryogenic-specific hazards should therefore be embedded in training, yet these aspects are not reflected in the current AMCs.

Training requirements also omit the definition and management of safe approach distances and hydrogen-specific hazard zones. Given hydrogen's rapid dispersion characteristics, low ignition energy, and high buoyancy, personnel should receive training in spatial risk assessment, exclusion zone management, and safe routing around hydrogen systems elements that are absent from the present regulatory texts.

Furthermore, existing guidance does not mandate training in the operation of hydrogen detection sensors or basic first-response intervention procedures tailored to hydrogen incidents. Such training is essential for early leak identification, escalation management, and coordinated emergency response.

Finally, the regulatory provisions do not address hydrogen's sensitivity to contamination. Both gaseous and cryogenic hydrogen systems require strict cleanliness standards to avoid particulate introduction or chemical incompatibility, which can present safety and operational risks. Training in contamination control, fuel specification awareness, and equipment handling for purity preservation is therefore critical but currently unaddressed.

Taken together, these omissions demonstrate that ORGH.TRG.100 and its associated AMCs require significant revision to incorporate hydrogen-specific competencies. Without these enhancements, ground handling personnel, technical staff, and first responders will not be adequately prepared for the operational and safety challenges associated with hydrogen technologies.

6.4 Overarching category: Apron Safety, Turnaround and Coordination Provisions

The operational provisions set out in GH.OPS.300, GH.OPS.400 and their associated Acceptable Means of Compliance may also require expansion to accommodate the specific requirements of hydrogen ground handling operations. These sections of the regulatory framework are currently structured around conventional fuel practices and therefore do not reflect the altered spatial, procedural, and safety considerations introduced by hydrogen.

A primary area of insufficiency lies in the definition and management of hazard zones. Hydrogen's dispersion characteristics, buoyancy, and wide flammability range mean that the spatial configuration of hazardous areas differs considerably from those associated with Jet A-1 operations. As a result, the

existing provisions do not adequately address the need for modified hazard zones that reflect hydrogen's unique behaviour in both open and confined environments.

Similarly, hydrogen operations necessitate increased clearance areas around fuelling equipment, venting points, storage systems, and transfer interfaces. These expanded zones are intended to mitigate ignition risks, accommodate monitoring equipment, and provide sufficient buffer space for emergency interventions. Current regulatory material does not capture these altered clearance requirements, thereby limiting its applicability to hydrogen scenarios.

Another critical gap concerns procedures for fuelling with passengers on board or during boarding and disembarkation. Hydrogen's distinct risk profile, particularly regarding invisible flame behaviour, venting dynamics, and high-pressure systems demands revised protocols, enhanced coordination with cabin crew and flight crew, and expanded safety briefings. The existing GH.OPS provisions do not reflect these necessary adaptations.

The introduction of hydrogen also generates new monitoring responsibilities for ground personnel. Continuous leak detection, assessment of venting plumes, verification of bonding and earthing, and hydrogen-specific pre-fuelling checks all require explicit regulatory guidance. Current AMCs do not provide such direction, leaving operators without a structured compliance pathway for these critical tasks.

Finally, hydrogen fuelling infrastructure necessitates redefined escape path requirements. Whether involving mobile hydrogen tankers, fixed cryogenic storage units, or high-pressure gaseous delivery systems, hydrogen operations should ensure that personnel have safe and unobstructed egress routes in the event of a leak, ignition, or equipment malfunction. These requirements differ materially from those associated with conventional fuel operations and are not reflected in the existing GH.OPS framework.

Collectively, these gaps highlight the need for a comprehensive revision of GH.OPS.300, GH.OPS.400, and their related AMCs to incorporate hydrogen-specific operational, spatial, and safety considerations. Without such updates, the current regulatory provisions cannot provide a robust foundation for safe hydrogen ground handling activities.

6.5 Overarching category: Aerodrome Operator Oversight and Interfaces

The Part-ADR regulatory framework, particularly the requirements set out in ADR.OR.C.005 and Annex VII 2.1(g) also exhibits gaps when considered in the context of hydrogen-powered aircraft operations. These provisions were developed with conventional fuels in mind and therefore do not capture essential elements required for the safe integration of hydrogen into aerodrome environments.

First, the existing Part-ADR text does not address hydrogen purity verification or contamination testing requirements. Given hydrogen's sensitivity to impurities, including particulates, moisture, and incompatible materials, rigorous purity assurance is fundamental to preventing operational anomalies or system failures. The absence of defined standards, testing procedures, or acceptance criteria represents a regulatory omission that directly affects fuel safety and equipment reliability.

Second, the provisions do not establish approval or certification pathways for hydrogen-related infrastructure. Hydrogen storage systems, distribution pipelines, mobile or fixed fuelling units, and associated transfer interfaces differ markedly from their kerosene counterparts in terms of engineering design, operating pressures, cryogenic properties, and safety systems. Without explicit approval and certification processes, aerodrome operators lack a clear regulatory basis for designing, installing, or validating such infrastructure.

Third, oversight expectations for hydrogen storage, distribution, and hydrant systems are not defined within the current regulatory text. Effective oversight would require aerodromes to implement structured inspection regimes, performance monitoring activities, and verification of safety-critical components, including sensors, pressure relief devices, vent stacks, insulation systems, and emergency shutdown mechanisms. The lack of such oversight guidance limits the ability of competent authorities and aerodrome operators to ensure consistent safety performance across hydrogen installations.

Finally, Part-ADR does not integrate hydrogen-specific hazards into emergency planning obligations or Safety Management System (SMS) structures. Hydrogen introduces unique risk factors, such as invisible flames, rapid dispersion, cryogenic exposure, and high-pressure releases that should be embedded into hazard identification processes, risk assessments, emergency response plans, and training programme. The failure to incorporate these considerations means that current SMS and emergency planning frameworks are insufficiently equipped to manage hydrogen incidents effectively.

Taken together, these gaps illustrate that Part-ADR requires extension and adaptation before it can provide a robust and comprehensive regulatory basis for hydrogen operations within the aerodrome environment.

6.6 Overarching category: GSE and Infrastructure

A further shortcoming in the current regulatory framework lies in the absence of any requirements relating to hydrogen-compatible ground support equipment (GSE) or mobile fuelling units, as reflected in GH.OPS.305. Existing provisions are premised on conventional fuelling technologies and therefore do not address the specialised design features, safety systems, inspection regimes, or operational controls necessary for equipment used in the storage, transfer, or delivery of hydrogen. Without explicit regulatory guidance, there is no structured basis for ensuring that hydrogen GSE meets appropriate safety, performance, or compatibility standards.

Similarly, the oversight and certification pathways for hydrogen-related infrastructure remain undefined within both ADR.OR.C provisions and the broader Part-ADR framework. Hydrogen installations, whether involving gaseous high-pressure systems, cryogenic storage tanks, distribution networks, or hydrant-based delivery systems require tailored engineering approvals, commissioning procedures, and periodic safety verification. The absence of such requirements creates ambiguity for both aerodrome operators and competent authorities, limiting their ability to ensure that hydrogen infrastructure is designed, installed, and maintained to an acceptable level of safety.

Taken together, these omissions underscore that the introduction of hydrogen does not constitute a minor or incremental adjustment to existing operational practices. Rather, hydrogen technologies represent a significant systemic change across aerodrome and ground handling environments. This transformation affects infrastructure, equipment, procedures, workforce competencies, emergency planning, and regulatory oversight mechanisms. As such, hydrogen integration necessitates a comprehensive re-evaluation of current regulatory structures to ensure that they are capable of supporting the safe and effective handling of hydrogen-powered aircraft.

7. Recommendations

Considering the gaps identified, several strategic recommendations emerge. These align with the project outline and the scope of AEROTHRIVE's proposed MoC deliverables.

7.1 Initiate a formal Management of Change Process

The introduction of hydrogen into aerodrome and ground handling operations has far-reaching implications that extend well beyond the simple substitution of one fuel type for another. Hydrogen integration affects multiple dimensions of the operational system simultaneously. At the infrastructure level, new storage facilities, distribution networks, venting systems, and fuelling interfaces should be established or adapted to accommodate hydrogen's cryogenic or high-pressure characteristics. Personnel qualification requirements likewise expand, as staff should acquire new competencies in hydrogen hazard recognition, cryogenic handling, leak detection, contamination control, and hydrogen-specific emergency response.

Operational procedures will require comprehensive revision to reflect hydrogen's distinct properties, including altered hazard zones, revised bonding and earthing practices, redesigned fuelling sequences, and enhanced monitoring protocols. These procedural changes, in turn, increase overall operational complexity and demand enhanced coordination among ground handlers, aerodrome operators, and air operators. Hydrogen's handling characteristics may also affect turnaround performance, as fuelling duration, safety verifications, and venting procedures differ materially from those associated with Jet A-1 operations.

Emergency preparedness frameworks should also evolve towards emerging technologies. Hydrogen introduces unique emergency response considerations, such as invisible flames, high-pressure release scenarios, and cryogenic exposure that require updated equipment, new detection technologies, revised zoning, and specialised responder training. Moreover, the interfaces between aerodromes, ground handling service providers (GHSPs), and air operators become more intricate, necessitating clearer communication pathways, jointly defined responsibilities, and harmonised hydrogen-specific operating protocols.

Given the breadth of these impacts, the initiation of a structured Management of Change (MoC) process is essential. Such a process should begin with a hydrogen-specific hazard identification and risk assessment, ensuring that emerging threats are systematically characterised and understood. Appropriate mitigation measures should then be defined, addressing procedural, technical, and organisational dimensions. Stakeholder engagement is critical throughout, as the safe integration of hydrogen depends on coordinated action across multiple entities and jurisdictions.

The MoC process should also incorporate updates to documentation, such as procedures, manuals, training programme, and emergency plans along with articulated approval pathways to ensure regulatory traceability and compliance. Finally, validation should be conducted through scenario-based audits or simulations, enabling organisations to test the effectiveness of newly implemented measures and verify operational readiness under realistic hydrogen-related scenarios.

7.2 Develop Hydrogen-Specific Operational Procedures as part of the MoC

Drawing upon the technical frameworks provided in SAE AIR8466, relevant ISO standards, and manufacturer-specific guidance, it becomes necessary to develop a suite of new procedures tailored to the operational realities of hydrogen-powered aircraft. These sources collectively offer the foundational engineering principles, safety parameters, and operational expectations upon which hydrogen-specific ground handling procedures should be constructed.

Foremost, dedicated procedures for hydrogen fuelling and defuelling should be established. These procedures should incorporate requirements for managing high-pressure or cryogenic transfer systems, ensuring controlled flow rates, preventing contamination, monitoring system integrity, and integrating real-time leak detection measures. Venting operations likewise require formalised protocols, including defined venting sequences, designated venting locations, dispersion modelling considerations, and exclusion zones reflecting the behaviour of gaseous or cryogenic hydrogen under varying environmental conditions.

Procedures for bonding and equipment earthing should be revised to reflect hydrogen's distinct electrostatic and ignition characteristics. Conventional methods derived from Jet A-1 fuelling may be insufficient, necessitating enhanced grounding verification, non-sparking equipment requirements, and continuous monitoring of electrostatic potential.

Cryogenic handling protocols, including associated personal protective equipment (PPE) should also be incorporated into procedural documentation. This includes the safe manipulation of extremely low-temperature hoses, couplings, valves, and connectors, measures to prevent material embrittlement, and guidelines for the use of cryogenic-rated gloves, face shields, and protective garments.

Furthermore, ground support equipment (GSE) used in hydrogen operations will require dedicated procedures for operation, inspection, and maintenance. These should include compatibility assessments, integrity checks for high-pressure or cryogenic components, contamination control standards, and hydrogen-specific maintenance intervals.

Finally, passenger-while-fuelling protocols should be redefined to account for hydrogen's unique risk profile. Procedures should address communication with flight and cabin crew, adapted apron safety zoning, emergency standby requirements, and evacuation readiness during fuelling operations, ensuring that both regulatory expectations and hydrogen-specific hazards are adequately managed.

Collectively, these procedural developments form a critical component of the operational readiness framework for hydrogen integration and ensure that aerodrome environments, ground handling service providers, and air operators can meet the technical and safety requirements associated with hydrogen-powered aviation.

7.3 Update Training and Competency Frameworks

To ensure that aerodrome operators and ground handling organisations are adequately prepared for the introduction of hydrogen technologies, a modular and competency-based hydrogen training concept should be developed. Such a framework should reflect the diverse responsibilities of personnel across the aerodrome environment and recognise that hydrogen introduces hazards, behaviours, and operational complexities not encountered in conventional Jet A-1 operations. A structured, tiered approach to training enables the development of differentiated skill sets while ensuring a consistent baseline of safety knowledge across all stakeholders.

The first module should consist of basic hydrogen awareness training targeted at all apron and terminal personnel. This foundational module should familiarise staff with hydrogen's physical and chemical properties, key hazard characteristics such as invisible flames or cryogenic temperatures, general safety precautions, and appropriate behavioural responses in the event of abnormal conditions. As these personnel often operate within or near safety-critical zones, a common level of awareness is essential for maintaining situational vigilance and ensuring proper adherence to exclusion areas, signage, and supervisory instructions.

A second module should provide operational hydrogen handling training specifically for fuelling personnel and technical staff directly engaged in hydrogen transfer activities. This module should address procedural competence in fuelling and defuelling, management of high-pressure or cryogenic systems, leak detection methods, contamination control practices, bonding and earthing requirements, operational monitoring responsibilities, and hydrogen-specific PPE usage. Such training should be highly practical, supported by simulations or scenario-based exercises to ensure personnel can safely execute hydrogen operations under varying operational conditions.

A third module should equip Rescue and Firefighting Services (RFFS) and first responders with hydrogen-specific emergency response training. This module should cover detection of hydrogen fires, tactical considerations for invisible flame incidents, appropriate extinguishing agents, cryogenic risk mitigation, isolation zone management, and coordination with aerodrome control units. Hydrogen incidents may require unique intervention strategies, and therefore specialised responder training is essential to maintain adequate emergency preparedness across the aerodrome.

Finally, managerial personnel should receive training focused on Safety Management System (SMS) adaptations and risk management processes associated with hydrogen operations. This includes the integration of hydrogen hazards into risk registers, change management requirements, oversight responsibilities, performance monitoring, and the establishment of appropriate reporting and investigation procedures. Managers should be able to assess the organisational implications of hydrogen technology, allocate resources appropriately, and ensure regulatory and procedural compliance across all operational areas.

Taken together, the modular training concept establishes a structured, scalable, and role-specific approach to workforce readiness, enabling aerodromes and ground handling service providers to build the competencies required for the safe and effective integration of hydrogen-powered aircraft.

7.4 Establish Hydrogen Infrastructure Certification and Oversight Processes

In parallel with procedural and operational adaptations, it is essential to establish clear regulatory pathways for the approval of hydrogen-related aerodrome infrastructure. The transition to hydrogen-powered aircraft introduces a range of technical systems and spatial configurations that fall outside the scope of existing approval mechanisms, necessitating the development of structured, transparent, and safety-focused regulatory processes. These pathways should provide both aerodrome operators and competent authorities with a coherent framework for demonstrating compliance, ensuring operational readiness, and maintaining oversight across the lifecycle of hydrogen installations. Currently, an aerodrome operator has general obligations, but no hydrogen-specific approval framework.

A first regulatory pathway should address the approval of designated areas for the handling of hydrogen aircraft. Such areas will require revised zoning considerations, expanded safety and clearance distances, and integration of hydrogen-specific hazard assessments into apron management plans. Approval processes should therefore ensure that designated handling locations are supported by appropriate risk analyses, infrastructure safeguards, and operational procedures, reflecting hydrogen's unique dispersion and ignition characteristics.

Approval pathways are also required for hydrogen storage tanks, whether mobile or stationary. These installations present distinct engineering, cryogenic, and high-pressure system requirements that differ fundamentally from conventional fuel tanks. Regulatory approval should encompass design verification, materials suitability, safety valve and venting system integrity, insulation performance, and compliance with relevant ISO and SAE standards. Additionally, commissioning, inspection, and periodic re-certification processes should be formalised to ensure continued safe operation.

Similarly, hydrant-based or mobile hydrogen fuelling systems necessitate dedicated approval mechanisms. These systems should be evaluated for compatibility with aircraft interfaces, operational control measures, pressure management, bonding and earthing systems, and emergency isolation capabilities. Approval pathways should incorporate performance testing, failure mode analysis, and verification of safety interlocks to mitigate high-energy release risks.

Hydrogen detection and safety interlock systems represent another critical infrastructure category requiring regulatory oversight. These systems, such as integrating leak detection, plume monitoring, automatic shutdown functions, and alarm interfaces form essential protective layers within hydrogen operations. Approval processes should verify sensor sensitivity, response time, reliability, redundancy, and integration with aerodrome emergency management systems.

Finally, hydrogen quality and contamination testing facilities should be subject to regulatory approval. Ensuring fuel purity is fundamental to the safe and reliable operation of hydrogen-powered aircraft, and testing facilities should therefore comply with established analytical methodologies, contamination thresholds, calibration standards, and sample handling procedures. Regulatory pathways should require demonstration of traceability, accuracy, and conformity with applicable ISO fuel quality standards.

Collectively, the establishment of these approval pathways is essential for enabling aerodromes to integrate hydrogen technologies in a controlled and compliant manner. They also ensure that competent

authorities can conduct effective oversight, thereby supporting a safe transition to hydrogen-powered aviation.

7.5 Integrate Hydrogen Hazards into SMS and ERP Structures

The integration of hydrogen-specific hazards into existing Safety Management System (SMS) and Emergency Response Plan (ERP) structures represents a critical component of preparing aerodromes and ground handling organisations for hydrogen-powered aircraft operations. Because hydrogen introduces a fundamentally different risk profile compared with conventional fuels, SMS and ERP frameworks should be systematically adapted to ensure comprehensive coverage of the associated hazards, mitigation measures, and response strategies.

Central to this integration is the revision and expansion of emergency response plans. Updated ERPs should explicitly address hydrogen-related scenarios, including invisible flame events, high-pressure system failures, cryogenic spills, and unplanned or abnormal venting occurrences. These updates require the definition of new response protocols, revised spatial zoning and isolation procedures, hydrogen-specific tactical guidance for emergency responders, and enhanced communication pathways across aerodrome stakeholders.

Scenario-based exercises form an essential element of preparedness and validation. Exercises should simulate hydrogen-specific emergencies such as cryogenic liquid releases, gaseous hydrogen dispersions, ignition of invisible flames, and large-scale venting events, enabling personnel to practise detection methods, tactical approaches, isolation techniques, and inter-organisational coordination. Such simulations are indispensable for testing the adequacy of procedures, identifying latent vulnerabilities, and confirming operational readiness.

The SMS framework should also incorporate new safety performance indicators (SPIs) tailored to hydrogen systems. These may include metrics related to leak detection frequency, venting control performance, sensor reliability, equipment integrity trends, or response times during hydrogen-related events. SPIs provide the quantitative basis for monitoring system behaviour, assessing the effectiveness of mitigations, and detecting emerging risk patterns.

In addition, aerodrome operators should revise their risk registers and hazard logs to integrate hydrogen-specific hazards. This includes documenting new failure modes, updating risk assessments to reflect hydrogen's unique dispersion and ignition characteristics, and establishing appropriate risk controls. Hazard logs should track hydrogen-related occurrences, anomalies, procedural deviations, and near-misses, thereby strengthening the continuous improvement function of the SMS.

By embedding hydrogen hazards across ERP, SMS, and performance monitoring structures, aerodromes and ground handling service providers can ensure that hydrogen operations are managed within a robust, proactive, and transparent safety framework. This approach also aligns with international expectations under ICAO Annex 19 and supports a controlled, evidence-based transition to hydrogen aviation.

7.6 Prepare for regulatory engagement and future rulemaking

In light of the regulatory gaps identified across operational, infrastructural, and safety management domains, proactive preparation for regulatory engagement and future rulemaking processes is essential. Hydrogen-powered aviation represents an emerging technological domain in which regulatory frameworks are still under development, and early engagement with competent authorities and international bodies is critical to ensuring that aerodrome operators, ground handling organisations, and air operators remain aligned with evolving requirements.

To this end, structured dialogue with the European Union Aviation Safety Agency (EASA) is strongly recommended, particularly in anticipation of the forthcoming GH.OPS rulemaking activities planned for 2028. Engagement with EASA will allow stakeholders to contribute empirical insights from operational assessments, infrastructure planning processes, and hydrogen-specific hazard evaluations, thereby informing the development of coherent and practicable regulatory provisions for ground handling and aerodrome operations.

Interaction with the International Civil Aviation Organization (ICAO) is equally important, especially through participation in working groups focused on Sustainable Aviation Fuels (SAF), alternative energy carriers, and future aviation technologies. Given ICAO's role in establishing global standards and recommended practices, early engagement ensures that hydrogen considerations are integrated into Annexes, guidance materials, and operational manuals at the international level. It also provides an opportunity for stakeholders to advocate for harmonisation between global, regional, and national regulatory frameworks.

Finally, early coordination with national aviation authorities is essential to preparing for domestic oversight processes, infrastructure approvals, certification pathways, and emergency planning obligations. National regulators will play a key role in interpreting and enforcing emerging hydrogen regulations, and early dialogue can accelerate the alignment of local procedures, approval documentation, and compliance expectations with forthcoming rulemaking outcomes.

Collectively, these engagement efforts will position aerodrome operators and ground handling service providers to anticipate regulatory developments, contribute to evidence-based rulemaking, and facilitate a smooth transition toward hydrogen-enabled aviation operations.

8. Conclusion

The results of the gap analysis demonstrate that the existing regulatory framework governing aircraft ground handling is not yet aligned with the operational, safety, and infrastructural requirements associated with hydrogen-powered aircraft. The assessment highlights that current standards developed primarily for conventional Jet A-1 operations do not provide sufficient guidance for managing the distinct physical properties, hazards, and procedural complexities introduced by hydrogen. The identified gaps represent critical deficiencies that should be addressed through the development of dedicated procedures, enhanced training programme, updated infrastructure standards, and strengthened oversight mechanisms.

In view of the scale and systemic nature of the changes required, the initiation of a formal Management of Change (MoC) process is both necessary and urgent. Such a process should be supported by the drafting of hydrogen-specific operational procedures, the establishment of modular and competency-based training concepts, and the development of new operational frameworks tailored to hydrogen's unique characteristics. These measures will ensure that organisations are able to adapt their safety management systems, emergency response capabilities, and operational practices in a structured and evidence-informed manner.

Adopting a phased implementation strategy further enables aerodromes and ground handling service providers to progressively build the organisational capability required for the safe and efficient handling of hydrogen aircraft. This approach ensures that operational readiness evolves in parallel with technological advancements and future regulatory developments at European, international, and national levels.

Ultimately, the findings underscore that hydrogen integration is not a routine or incremental adjustment to existing ground handling operations. Instead, it constitutes a significant transformation that requires coordinated regulatory evolution, enhanced operational preparedness, and robust organisational adaptation. By following the recommended pathway, stakeholders can position themselves to support the emerging hydrogen aviation ecosystem in a safe, compliant, and future-oriented manner.

9. The Annex

The excel document for the

- Regulatory Register as well as the
- Gap Analysis Register

is attached to this report as an Annex and may be utilized by the project stakeholders to their discretion.

END

Appendix B

Prepared by AEROTHRIVE GmbH
16 September 2026

Management of Change and Risk Assessment

BSR HyAirport
Work Package 1.3

Phase 3 narrative report with the
Phase 1 and Phase 2 methodology

0. Document control and purpose

This report sets out the change programme needed to introduce hydrogen aircraft handling into an airport operating system. It explains how the regulatory mapping in Phase 1 and the hydrogen-specific gap analysis in Phase 2 lead to the hazards, risk assessments, barriers and Management of Change actions developed in Phase 3. The report is addressed to the BSR HyAirport project partners and the organisations that will develop and accept local operating arrangements.

Our principal conclusion is that the project has established a useful assessment baseline, but the recorded evidence does not yet support operational release. Fourteen initial risk rows are intolerable under the project matrix, and 82 of the 83 residual-risk records remain unassessed. These findings define the next work programme. They do not establish that every proposed hydrogen configuration has the same risk, or that the technology cannot be introduced safely.

Control item	Report identification
Document reference	AEROTHRIVE BSR WP13 P3 Narrative 20260915
Issue	Expanded technical report for partner review
Report owner	AEROTHRIVE WP 1.3 Project Manager
Primary numerical baseline	Integrated Gap Risk Bowtie MOC Audit workbook v3 supplied for this assessment
Supporting status reference	Preliminary Results presentation dated 1 September 2026
Technical scope	Aircraft handling and associated airport interfaces with GH_2 as the primary project case
Intended decision	Agree validation priorities and evidence required for controlled implementation

This report retains useful scenario material, identifies changes in interpretation, and separates recorded results from proposed controls. An action described as recommended in this report has not thereby been completed, assigned or accepted by a participating organisation.

Throughout the report, references S1 to S5 identify the eight project documents. References R1 to R6 identify regulatory and institutional material used to clarify the framework. The reference list provides the titles and locations. Workbook citations identify the sheet and, where necessary, the relevant GAP ID or cell. Row references relate to the supplied v3 Excel file.

Local operational release remains a decision for the accountable organisations within their respective powers. Aircraft limitations, required authority decisions, facility permits and the local safety management system must be satisfied before a trial or routine operation proceeds. The proposed gate model provides a way to assemble that evidence and make the decision explicit.

Content

0. Document control and purpose 2

1. Executive summary 5

2. Project context and scope 7

2.1. Purpose within BSR HyAirport 7

2.2. Operational boundary and exclusions 8

3. Aviation Safety as the Overarching Objective 9

4. Phase 1 regulatory mapping 10

4.1. Source identification and clause extraction 10

4.2. Applicability and the regulatory hierarchy 11

5. Phase 2 hydrogen specific gap analysis 12

5.1. Comparison method and change triggers 12

5.2. Principal gap themes 13

5.3. Interpretation of Phase 1 and Phase 2 results 14

6. Demand scenarios and handling exposure 15

6.1. Scheduled aviation assumptions 15

6.2. General and business aviation assumptions 16

6.3. Translating demand into risk exposure 17

7. Phase 3 assessment framework 18

7.1. Method derived from the AEROTHRIVE proposal 18

7.2. Workbook structure and traceability 19

7.3. Reconciled populations and maturity 20

8. Hazard identification and operational baseline 21

8.1. Hydrogen states and combined energy systems 21

8.2. HAZID workshop method 22

8.3. Hazard families in the integrated register 23

8.4. Normal GH_2 handling sequence 24

8.5. LH_2 and simultaneous operation interfaces 25

9. Risk assessment and acceptance 26

9.1. The project risk matrix 26

9.2. Initial risk and residual risk reasoning 27

9.3. Application of the ALARP principle 28

9.4. Initial risk portfolio and prioritisation 30
9.5. Residual risk and conditional acceptance 31
10. Priority operational risk assessments 32
10.1. Fuelling and passenger exposure 32
10.2. Emergency response and facility segregation 33
10.3. Fuel quality and control system interfaces 34
11. Bow tie analysis and control assurance 35
11.1. Causal structure and barrier placement 35
11.2. Worked physical bow tie 36
11.3. Governance bow tie and a worked trace 37
11.4. Control performance and continuing assurance 38
12. Management of Change programme 39
12.1. Trigger and action reconciliation 39
12.2. Workstreams and implementation dependencies 40
13. MoC gates and evidence decisions 41
13.1. Gates 0 to 2 41
13.2. Gates 3 to 6 42
14. Governance and responsibility 43
15. Procedures competence and human factors 44
16. Emergency validation and operational trials 45
17. Safety assurance and monitoring 46
18. Implementation sequence and release criteria 47
19. Conclusions and recommended decisions 48
20. Appendix A Initial risks requiring priority review 49
20.1. Intolerable rows in the first part of the register 49
20.2. Remaining intolerable rows and unassessed cases 50
21. Appendix B MoC triggers without direct actions 51
22. Appendix C Earlier scenario targets reconciled 52
23. Appendix E Project references 53
23.1. Regulatory references and terminology 54

1. Executive summary

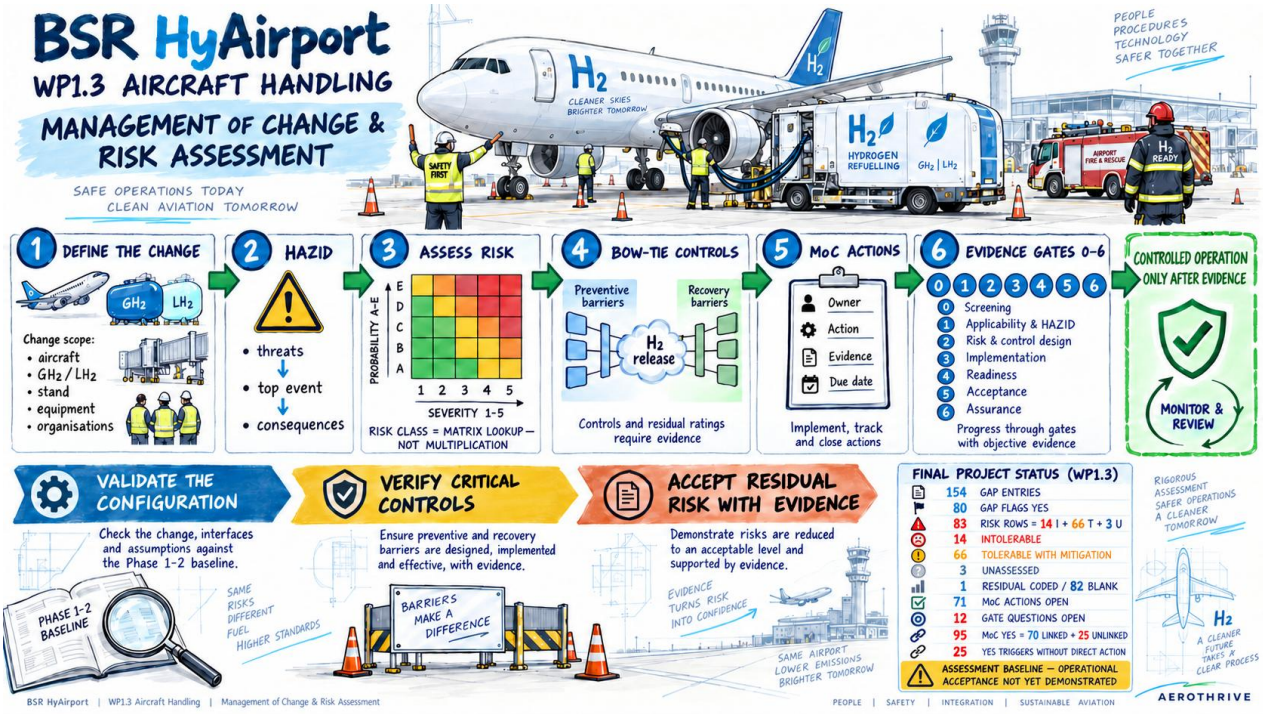
AEROTHRIVE recommends progressing Phase 3 as a validation and implementation programme with explicit evidence gates. The regulatory and operational analysis has identified the changes that need attention. The next task is to demonstrate, for a defined aircraft and airport configuration, that the selected controls work together and that the responsible organisations accept the remaining risk.

Reconciled v3 measure	Recorded result	Management significance
Integrated gap entries	154	Requirement and gap records, not 154 independent hazards
Gap flags	80 YES and 74 NO	Separate from local compliance and completion status
Initial risk rows	83	14 intolerable, 66 tolerable with mitigation, 3 unassessed
Residual risk rows	1 coded and 82 blank	The coded row is GAP-001 at 3E, with no assurance evidence entered
MoC trigger flags	95 YES, 58 CHECK, 1 NO	Requires reconciliation against the action register
MoC actions	71, all Open	Owners, due dates, control packages and closure evidence are blank
Control catalogue	44 controls	22 preventive, 22 recovery; 30 marked Critical

These values are derived from the underlying records in S2. The initial-risk and readiness totals agree with S3. The more detailed MoC reconciliation shows 70 direct links to the 95 YES entries, leaving 25 without a direct action. The remaining action, MOC-010, refers to GAP-012, which is now marked MoC NO. The net difference of 24 therefore conceals two separate reconciliation tasks.

The priority scenarios concern fuelling, emergency response, facility segregation and passenger interfaces. Technical review must separate high-pressure GH_2 from cryogenic LH_2. Fuel-cell electrical systems, mixed-energy stands, abnormal aircraft arrivals and maintenance handovers also need explicit interface controls.

We recommend first resolving the assessment boundaries and data links, then validating the hazards and controls with the relevant specialists. Procedures, equipment, competence and emergency arrangements should be demonstrated before residual risk is accepted. All applicable unassessed or intolerable risks must be resolved before operational release. Completion of this report is a project milestone; completion of the local safety case is a separate evidence-based decision.


BSR HyAirport
WP1.3 AIRCRAFT HANDLING
MANAGEMENT OF CHANGE & RISK ASSESSMENT
SAFE OPERATIONS TODAY
CLEAN AVIATION TOMORROW
PEOPLE
PROCEDURES
TECHNOLOGY
SAFER TOGETHER
CLEANER SKIES
BRIGHTER TOMORROW
HYDROGEN REFUELLING
SAFETY FIRST
AIRPORT FIRE & RESCUE
READY
1 DEFINE THE CHANGE
Change scope:
• aircraft
• GH2 / LH2
• stand
• equipment
• organisations
2 HAZID
• threats
• top event
• consequences
3 ASSESS RISK
PROBABILITY A-E
SEVERITY 1-5
RISK CLASS = MATRIX LOOKUP — NOT MULTIPLICATION
4 BOW-TIE CONTROLS
Preventive barriers
Recovery barriers
H2 release
Controls and residual ratings require evidence
5 MoC ACTIONS
Owner
Action
Evidence
Due date
Implement, track and close actions
6 EVIDENCE GATES 0–6
0 Screening
1 Applicability & HAZID
2 Risk & control design
3 Implementation
4 Readiness
5 Acceptance
6 Assurance
Progress through gates with objective evidence
CONTROLLED OPERATION ONLY AFTER EVIDENCE
MONITOR & REVIEW
VALIDATE THE CONFIGURATION
Check the change, interfaces and assumptions against the Phase 1-2 baseline.
PHASE 1-2 BASELINE
SAME RISKS DIFFERENT FUEL HIGHER STANDARDS
VERIFY CRITICAL CONTROLS
Ensure preventive and recovery barriers are designed, implemented and effective, with evidence.
BARRIERS MAKE A DIFFERENCE
ACCEPT RESIDUAL RISK WITH EVIDENCE
Demonstrate risks are reduced to an acceptable level and supported by evidence.
EVIDENCE TURNS RISK INTO CONFIDENCE
SAME AIRPORT LOWER EMISSIONS BRIGHTER TOMORROW
FINAL PROJECT STATUS (WP1.3)
154 GAP ENTRIES
80 GAP FLAGS YES
83 RISK ROWS = 14 I + 66 T + 3 U
14 INTOLERABLE
66 TOLERABLE WITH MITIGATION
3 UNASSESSED
1 RESIDUAL CODED / 82 BLANK
71 MoC ACTIONS OPEN
12 GATE QUESTIONS OPEN
95 MoC YES = 70 LINKED + 25 UNLINKED
25 YES TRIGGERS WITHOUT DIRECT ACTION
ASSESSMENT BASELINE — OPERATIONAL ACCEPTANCE NOT YET DEMONSTRATED
RIGOROUS ASSESSMENT SAFER OPERATIONS A CLEANER TOMORROW
A CLEANER FUTURE TAKES A CLEAR PROCESS
AEROTHRIVE
BSR HyAirport | WP1.3 Aircraft Handling | Management of Change & Risk Assessment
PEOPLE | SAFETY | INTEGRATION | SUSTAINABLE AVIATION

2. Project context and scope

2.1. Purpose within BSR HyAirport

BSR HyAirport addresses the preparation of airports for hydrogen as an aviation energy source. The project poster records a programme period from November 2023 to October 2026 and cooperation across Estonia, Finland, Germany, Latvia, Lithuania, Poland and Sweden. Its stated purpose includes airport preparation for storing, handling and delivering green hydrogen. WP 1.3 addresses the aircraft-handling part of that wider system.

The AEROTHRIVE proposal defines the aircraft-handling boundary from entry into airport airspace until departure from it, including turnaround and emergency response. Phase 1 compiles relevant requirements. Phase 2 examines their applicability to hydrogen powered aircraft and identifies gaps and potential hazards. Phase 3 takes the significant changes forward into a Management of Change process supported by a hazard log and risk register. This sequence is the organising principle of this report.

The original proposal prioritises GH_2. The Phase 1–2 report and v3 workbook also contain LH_2 and cryogenic scenarios. These are retained as clearly identified branches because they are already part of the technical evidence and because airport interfaces may eventually serve both technologies. Their inclusion does not turn an assessment for one fuel state into authorisation for the other. An airport introducing only GH_2 should justify the exclusion of LH_2-specific tasks at screening while retaining relevant common interfaces.

WP 1.3 sits between aircraft, airport and fuel-supply responsibilities. The operator needs an aircraft that can be handled within its approved limitations. The aerodrome needs compatible stands, traffic arrangements and emergency capability. The ground handler and fuel provider need workable instructions, suitable equipment and competent personnel. Safe operation depends on the consistency of these arrangements at their handover points.

The report therefore covers the operational consequences of the change, the method for assessing them and the evidence needed for acceptance. It supports a transferable regional approach while allowing each airport to record national requirements and local conditions. Transferability means reusing the method and validated control principles; it does not mean copying another airport’s accepted risk score without examining differences.

Phase 3 also identifies candidate mitigations because a residual-risk assessment cannot be meaningful without them. The proposal separately envisages further development of mitigation material in a potential Phase 4, which is currently out of scope. Accordingly, this report provides control objectives and implementation requirements without representing that final OEM procedures, engineered designs or detailed training packages have already been produced.

2.2. Operational boundary and exclusions

The reference operating sequence is planning and pre-arrival coordination; arrival, landing and taxi-in; stand positioning and preparation; connection and fuelling; completion and disconnection; aircraft release and taxi-out; and departure. Abnormal and emergency response overlays every stage. This sequence preserves the airspace-to-airspace scope of the proposal while keeping the detailed assessment focused on the airport handling interface.

The planning stage establishes the aircraft variant, fuel state, expected uplift, stand, compatible equipment and available responders. Arrival and taxi require usable aircraft status information and a clear response if a leak, fire warning or technical defect is reported. At the stand, the organisations establish the agreed safe state, access restrictions, communications and hold points before transfer. Departure follows positive confirmation that the aircraft interface and stand have been released.

Boundary	Treatment in WP 1.3
Hydrogen transfer and GSE	Included where equipment, procedures and people affect aircraft handling
Aircraft systems	OEM limitations and ground interfaces included; aircraft design certification remains outside the report
Infrastructure	Layout, emergency access and operational compatibility included; detailed production, storage and civil design require separate engineering
Passenger and baggage activity	Exposure, evacuation routes and simultaneous operations included; the general commercial handling process is outside the detailed analysis
Maintenance and preservation	Safe-state handovers and effects on handling included; full maintenance programmes and long-term preservation procedures remain with responsible organisations
National approvals	Applicability and interfaces identified; country-specific permissions require local confirmation

A hydrogen aircraft manufacturer suggested both adding fuel-cell/HV interfaces and excluding aircraft systems that do not directly concern hydrogen. We resolve this by distinguishing design work from operational interfaces. High-voltage design is outside WP 1.3, but an electrical isolation state that constrains fuelling or rescue is within the handling assessment. Similarly, passenger services are not redesigned here, but passenger exposure cannot be excluded from a fuelling risk assessment.

No generic safe distance, fill pressure, flow rate, purge quantity or intervention tactic is established by this report. Such values depend on the specific aircraft, equipment, release case, local environment and applicable requirements. The assessment must record the source of each adopted limit. A statement that a topic is outside detailed design scope creates an interface requirement; it does not remove the hazard from consideration.

3. Aviation Safety as the Overarching Objective

The overarching aim of BSR HyAirport Work Package 1.3 is to ensure that the introduction of hydrogen-related aircraft-handling activities does not adversely affect aviation safety and that a high level of safety is maintained throughout the operational change. This reflects Article 1(1) of Regulation (EU) 2018/1139, which establishes the maintenance of a "high uniform level of civil aviation safety" as the principal objective of the European aviation regulatory framework. The Regulation is directly relevant to this work package because its scope includes aircraft operation, safety-related aerodrome equipment and groundhandling services, together with the organisations and personnel involved in those activities. Regulation (EU) 2018/1139, Articles 1 and 2.

In this context, aviation safety may be understood as the condition in which risks arising from aviation activities, or from activities directly supporting aircraft operations, are reduced and controlled to an acceptable level. It is therefore not the complete absence of hazards or risk. Rather, it requires hazards to be identified systematically, their possible consequences for aircraft operations to be assessed, and effective technical, operational and organisational controls to be implemented and monitored. This risk-based understanding is consistent with the safety-management principles applied by the International Civil Aviation Organization.

Aviation safety and occupational health and safety (OHS) are closely connected but have different primary perspectives. OHS is principally concerned with protecting workers from work-related injury, illness and harmful exposure and with the employer's duty to ensure workers' safety and health in every aspect related to their work. Aviation safety focuses primarily on preventing aviation accidents and incidents and on protecting the safe operation of aircraft, passengers, crew, ground personnel and third parties who may be affected by aviation activities

For hydrogen aircraft handling, these perspectives frequently overlap. A hydrogen release, cryogenic exposure, fire, explosion, vehicle collision or incorrect handling procedure may simultaneously endanger workers and compromise an aircraft, apron operation or wider aerodrome system. The assessments undertaken in WP1.3 therefore apply an aviation-safety-led Management of Change process while recognising and addressing the associated OHS interfaces. The purpose is not to replace the legally required workplace risk assessments, but to ensure that every proposed change is assessed for its possible effect on the aviation system and is introduced only when the necessary controls, responsibilities, procedures, competence, emergency arrangements and assurance evidence are in place.

4. Phase 1 regulatory mapping

4.1. Source identification and clause extraction

Phase 1 established the regulatory baseline against which hydrogen-related changes could be assessed. The method described in S1 consists of five steps: identify the relevant sources, extract applicable clauses, categorise them by handling activity, assess hydrogen relevance, and create the register with a cross-reference matrix. This sequence makes the eventual risk discussion traceable to an operational obligation or source assumption.

Source identification considered international aviation material, European legislation, national requirements and industry standards. These are different kinds of evidence. ICAO Annexes contain Standards and Recommended Practices for implementation through the relevant legal framework. EU regulations may impose directly applicable obligations within their scope. AMC and guidance assist interpretation and compliance demonstration. Industry material can describe accepted practice or technical performance, but its authority depends on how it is adopted and used.

The clause extraction step translated broad documents into reviewable records. Each record needed a source title and a paragraph or article reference, an operational category, and an explanation of its relevance. The operational review covered fuelling, ground equipment, apron coordination, training, emergency response, safety management and aerodrome responsibilities. It was intended to expose interfaces that can be missed when each organisation reads only the material addressed directly to it.

The v3 Integrated Gap Register contains 154 entries grouped under 16 source labels. These are record counts, not counts of unique statutes or independent legal duties. For example, the 2025/20 group includes rule and AMC references, while JIG 4 and ICAO Doc 9977 contribute multiple clauses. The register should therefore be read as an operational cross-reference set rather than as a statistical measure of regulatory completeness.

A useful extraction record also distinguishes what the source requires from the reviewer's interpretation. The text stating a general duty to maintain safety should remain separate from the judgement that hydrogen needs a new procedure. In v3, the "Details from Rechtskataster" field often contains that judgement. Local review should retain the original citation and record the implementation conclusion in a separate controlled field.

4.2. Applicability and the regulatory hierarchy

The second half of Phase 1 connects the extracted clauses to the handling system. Categorisation tells the reviewer where a requirement operates; applicability tells the reviewer whether and how it governs the defined configuration. These questions must be answered before declaring a hydrogen-specific gap. A general safety requirement can apply fully even where the source does not mention hydrogen.

Assessment term	Operational criterion	Required record
Directly applicable	The duty and its scope cover the activity without changing their meaning	Applicable entity, task and evidence of compliance
Applicable with adaptation	The safety objective applies, but the existing implementation assumes different fuel or equipment characteristics	Retained requirement and the procedure or control to adapt
Supporting by analogy	The source offers useful practice outside its exact application envelope	Transferability assessment and unresolved differences
Not applicable	The legal or technical scope does not cover the defined case	Specific exclusion rationale and reviewer
Coverage unresolved	The source or technical assumptions do not allow a reliable determination	Owner, question and evidence needed to resolve it

These explicit criteria develop the relevance categories described in S1 and address a hydrogen aircraft manufacturer's request for clearer assessment rules. They are proposed review criteria for consistent local use. They are not asserted to be a classification already completed for every v3 row.

The existing aerodrome and air-operator frameworks remain central. Local change screening should consider ADR.OR.B.040 and ADR.OR.D.005 under Regulation 139/2014, and the operator's applicable management of change system provisions under Regulation 965/2012. Continuing-airworthiness and maintenance changes require their own review under Regulation 1321/2014, including CAMO.A.130 and CAMO.A.200 where applicable. The organisation responsible for each approval, notification or internal decision must be identified.

The 2025 EU ground-handling package is adopted legislation with a generally deferred application date of 27 March 2028. The workbook's source label "Entry into force: 27 March 2028" conflates entry into force with application. ORGH.GEN.125 and ORGH.GEN.130 provide the relevant industry-standard and change-management references in Regulation 2025/20; Regulation 2025/23 addresses oversight. The standards evaluation or acknowledgement route should be considered with the authority, but this report does not establish that any hydrogen standard has received acknowledgement.

National workplace, pressure-system, fire and environmental requirements must be assessed alongside aviation obligations. German examples in the register are not substitutes for the requirements of another participating country. A local annex should identify the competent bodies and the legal basis for each required decision.

5. Phase 2 hydrogen specific gap analysis

5.1. Comparison method and change triggers

Phase 2 asks whether the Phase 1 baseline can be implemented safely for hydrogen aircraft. S1 describes a five-step analytical method: compare hydrogen requirements with the existing material, identify explicit and implicit gaps, identify hazards, evaluate operational impact, and identify change triggers. Its later four-step explanation develops the same logic through a hydrogen baseline, clause review, process impact and hazard/change assessment. These descriptions are complementary views of one method.

The first task is to define the hydrogen operating case. GH_2 requires assessment of pressure, temperature during filling, containment integrity and gas release. LH_2 adds cryogenic transfer, phase change, insulation and boil-off behaviour. Both require attention to ignition, ventilation, materials, fuel quality and emergency response, but the equipment and procedure evidence differ. An undefined generic “hydrogen aircraft” is too broad a comparison baseline for a dependable gap judgement.

The clause review then considers whether the requirement’s safety objective remains valid and whether existing means of meeting it remain adequate. For example, maintaining an unobstructed emergency route is still a valid objective. The route’s position may need to change because a hydrogen vent, transfer hose or exclusion area occupies space previously used by passengers or responders. The gap is the unresolved local implementation of the objective, rather than the disappearance of the duty itself.

An explicit gap may concern the absence of an agreed aviation interface specification. An implicit gap may concern a conventional-fuel procedure that assumes different release behaviour. A third category is an implementation gap, where suitable requirements or technical guidance exist but have not been incorporated into the airport’s procedures, equipment or training. Keeping these types separate helps determine whether the remedy is standards development, technical validation, organisational action or a combination.

The impact assessment follows the affected task through the turnaround. Changes in connection, monitoring or disconnection can affect stand occupancy, vehicle access, passenger routes and crew duties. Changes in emergency response can affect aircraft acceptance even before the aircraft reaches the stand. Each impact should identify the responsible organisations and the conditions under which an operational consequence could occur.

Finally, the assessor records whether formal MoC is required and why. Triggers include a new fuel state, aircraft variant, supplier, transfer system, stand, software configuration, procedure, competence requirement or response capability. Temporary arrangements also require screening. The output of Phase 2 is therefore a set of traceable questions and change needs that can be risk-assessed in Phase 3, rather than an operational permission.

5.2. Principal gap themes

S1 presents six numbered themes in sections 6.1 to 6.6, although the introductory text calls them five categories. The six themes are retained below because each represents a distinct implementation question. They connect the earlier clause review to the workstreams now needed in Phase 3.

Phase 2 theme	Change requiring assessment	Phase 3 evidence sought
Fuelling and defuelling	Transfer procedures, interface compatibility and abnormal termination	OEM-aligned sequence, equipment limits, verified hold points and isolation tests
Emergency response	Detection, tactical information, access and coordination	Configuration-specific ERP, responder capability and joint exercise results
Training and competence	Tasks, qualifications and practical response skills	Role matrix, assessed competence and task authorisation
Apron and turnaround	Safety areas, passengers, vehicles and simultaneous activities	Stand compatibility assessment and coordinated operating restrictions
Aerodrome oversight and interfaces	Responsibility for fuel quality, approvals and monitoring	Named duty holders, interface agreements and assurance records
GSE and infrastructure	Suitability, maintenance, inspection and configuration	Engineering evidence, acceptance tests and continuing maintenance controls

The fuelling theme is prominent because it brings the aircraft, ground equipment and fuel provider into a single physical system. A suitable hose is insufficient if the connector, control protocol or permissible temperature differs from the aircraft requirement. A sound procedure is insufficient if a person cannot reach the emergency stop or if isolation leaves a hazardous trapped inventory. Phase 3 therefore evaluates the whole transfer arrangement.

Emergency and competence gaps are similarly connected. Training must teach personnel the actual alarm meanings, safe positions and stop actions used at their airport. RFFS preparation must address both information received from the aircraft and the ground installation’s isolation arrangements. Generic awareness can support this process but cannot demonstrate task competence or local response capability.

The apron and oversight themes prevent the analysis from ending at the fuelling connector. An adjacent stand can introduce ignition sources, obstruct escape or change responder access. A contractor can maintain a detector without owning the fuelling decision that depends on it. These interfaces need assigned responsibilities and observable checks.

The six themes do not constitute six independent risk events. One scenario can involve several themes, and one control can address several gaps. The integrated workbook provides the identifiers needed to retain those relationships. Consolidation is useful when it removes duplicate work while preserving every obligation and affected scenario. It is unsuitable when it hides an unresolved responsibility or a configuration-specific requirement.

5.3. Interpretation of Phase 1 and Phase 2 results

The principal outcome of Phases 1 and 2 is a structured baseline for action. The v3 register contains 80 entries with “Gap in Rechtskataster” set to YES and 74 set to NO. These values must be interpreted according to that column’s meaning. They do not mean that 80 requirements apply to hydrogen and 74 do not. Nor do they measure the proportion of the legal framework that is adequate.

This distinction matters because parts of S1 discuss YES as hydrogen coverage and NO as insufficient coverage. The Phase 3 report uses the explicit v3 gap flag and does not carry forward the earlier chart semantics. The proposed hazard family is populated for all 154 rows, including rows without a positive gap flag. Consequently, a count of mapped hazard families describes assessment workload and linkage, not a count of confirmed hazards or failures.

The earlier category percentages also cannot be reused as v3 statistics. In the current primary-category column, 99 entries are Regulatory and Administrative Requirements, 24 are Management System, 15 are Aircraft Servicing and 16 are Secondary Obligation. These four labels differ from the earlier six-category chart and its percentages. The common lesson is that obligations cross several operational domains; the numerical distributions are specific to their dataset and coding scheme.

A lack of hydrogen-specific detail should not be reported as a complete absence of legal protection. The register itself contains general duties concerning management systems, fire prevention, emergency planning and fuel quality. Those duties can require hydrogen-related assessment even without naming the fuel. An implementation route may use risk assessment, OEM instructions, competent engineering and suitable standards within the applicable legal framework. A specific amendment may still be needed, but that conclusion must follow a clause-level analysis.

Several source records illustrate the need for careful scope review. GAP-134 concerns a wide-cut-fuel provision; hydrogen should not be classified as wide-cut fuel merely because the row is included. GAP-136 concerns supplemental oxygen in flight; a ground-handling relevance argument must be established before retaining a separate aviation-safety scenario. GAP-040 should not be read as excluding hydrogen events from occurrence reporting solely because the fuel is not named.

Phase 3 thus preserves the earlier work while sharpening its decision logic. The retained output is the requirement-to-change trace. The validation task is to confirm applicability, the physical or organisational mechanism of harm, the control needed, and the evidence that closes the local question. This approach allows useful general requirements to be retained and genuine gaps to receive a proportionate remedy.

6. Demand scenarios and handling exposure

6.1. Scheduled aviation assumptions

The WP 1.2.1 demand report provides a planning context for aircraft handling. It deliberately describes scenarios rather than a definitive forecast. Its scheduled-flight method starts with routes identified by partner airports and combines annual departures, sector distance and an assumed fuel-consumption factor. This is useful for WP 1.3 because the number and pattern of movements determine how often people and equipment encounter the assessed tasks.

The detailed route section identifies 69 routes from 21 origin airports for the 2030 scenario, including 24 reactivated routes and 15 new routes, with an average length of 170 nautical miles. The corresponding table reports 42,216 annual departures in 2030 and 61,740 in 2035. These are partner planning assumptions and are not airline commitments. The source explicitly states that the routes were not established through route-specific feasibility calculations or agreements with airlines.

Scheduled-flight assumption	Value in S6	Relevance to handling
Smaller reference aircraft	10 seats, Grand Caravan example	Lower uplift per movement does not remove connection or coordination hazards
Larger reference aircraft	Assumed 30-seat type similar in size to Saab 340	More passengers and potentially different equipment and evacuation interfaces
Consumption factors	0.20 and 0.36 kg per nautical mile respectively	Inputs to scenario demand, not certified aircraft performance
Hamburg departures	1,566 in 2030 and 5,976 in 2035	Possible increase in task repetition and stand demand
Hamburg annual GH_2 demand	211,506 kg in 2030 and 386,335 kg in 2035	Planning quantities requiring reconciliation to the route model before design use

The tankering assumption doubles the route demand at the origin where both outward and return flights are fuelled there. The model neglects additional consumption from carrying extra fuel because reliable GH_2 tankering data were unavailable. For handling assessment, tankering changes the uplift, fill duration and aircraft fuel state on arrival. It also changes what an alternate airport may need to do even if no normal uplift is planned there.

6.2. General and business aviation assumptions

The non-scheduled-flight analysis uses Hamburg Airport's 2024 General Aviation Terminal activity as its starting point. It describes approximately 18,000 movement records, reduced to around 9,100 outbound movements, then around 8,600 after a 1,500-kilometre distance filter, and finally around 6,600 after excluding helicopters, military activity and large commercial jets. These rounded values describe the study funnel; they are not a current traffic count.

For the retained flights, the model combines aircraft categories with route distances. Table 7 gives assumed GH_2 factors of 0.40 kg/nm for jets, 0.30 kg/nm for the source's "Large Aircraft" category, and 0.15 kg/nm for small aircraft. These broad modelling categories should not be read as certification categories. In particular, they do not establish that all examples in a category can use the same ground interface.

The resulting 495,391 kg annual hydrogen quantity is a theoretical full-replacement potential for the analysed outbound flights. It is not expected initial demand. The adoption model uses aircraft life and replacement assumptions, with a stated annual replacement rate of 3.42%, then applies progressively increasing hydrogen shares among replacement aircraft. The scenarios also compare zero growth with 1.5% annual growth in nautical miles flown.

Hamburg GAT scenario	2030 GH_2 demand	2050 GH_2 demand
Low uptake with 1.5% growth	4,563 kg/year	110,621 kg/year
High uptake with 1.5% growth	9,126 kg/year	184,368 kg/year
Low uptake with zero growth	4,236 kg/year	76,241 kg/year
High uptake with zero growth	8,471 kg/year	127,068 kg/year

The source's seasonal analysis indicates higher activity in summer, with June and July approximately twice the lowest-month level.

For WP 1.3, the important consequence is that competence, equipment availability and stand coordination cannot be sized around an annual average alone. Initial low-volume operation also creates a different challenge: long gaps between tasks can reduce practical familiarity and conceal maintenance or documentation weaknesses.

Scheduled and GAT scenarios should remain separately identified until their populations and assumptions have been reconciled. Adding them without checking aircraft, movements, tankering and year definitions could double-count demand or mix incompatible cases. The purpose of carrying these figures into Phase 3 is to define credible handling scenarios and review triggers, not to create a new demand forecast or imply that the model confirms aircraft availability.

6.3. Translating demand into risk exposure

Annual hydrogen demand is not sufficient to describe the exposure of the handling system. The same annual quantity could be delivered in a few large uplifts or many small ones. Each connection and disconnection introduces tasks, opportunities for error and equipment cycles. A local Phase 3 assessment should therefore supplement the demand scenarios with movements by operating day, peak periods, uplift distribution, expected transfer duration and the number of equipment changes.

A simple planning example illustrates the distinction. At the scheduled-study factor of 0.20 kg/nm, a 200-nm sector gives a nominal 40-kg consumption input. Doubling for the study's simplified tankering case gives 80 kg at the origin. These are arithmetic illustrations using WP 1.2.1 report assumptions. Actual uplift must account for approved performance, fuel already on board, reserves and operational limitations. Neither value defines a safe filling rate or a maximum quantity for a stand.

Exposure variable	Why it matters	Local evidence needed
Connections per shift	Repeated coupling, verification and disconnect tasks	Task sequence and expected cycle counts
Peak simultaneous activity	Shared space, supervisors, response access and alarms	Stand schedule and compatibility assessment
Uplift and transfer duration	Time at risk, equipment use and turnaround pressure	Aircraft and refueller envelope with measured trial data
Supply replenishment	Additional vehicles and custody-transfer interfaces	Delivery routes and separation of depot and aircraft tasks
Long inactive periods	Loss of task familiarity and unnoticed deterioration	Recommissioning checks and competence refresh criteria
Tankering and diversion	Different arrival inventory and emergency needs	Aircraft information and alternate-airport arrangements

The recommended local scenario set includes low-volume introduction, a busy operating period, a delayed movement that overlaps another operation, and a supply or equipment disruption. Each should identify which controls remain available and which operational restrictions apply. Increased frequency must not be accommodated simply by shortening hold points or relying on unassessed simultaneous work.

Demand changes are also MoC triggers. A larger aircraft, higher uplift, additional refuelling vehicle, extended operating hours or a second stand can change the credible release, the number of exposed people and the ability of responders to reach the site. These effects require screening even if the fuel state and general procedure remain unchanged. GAP-154 already identifies the potential influence of multiple mobile fuelling vehicles on other ground activities.

Risk probability should be tied to a stated exposure basis, such as a transfer cycle or defined operational period. Without that basis, a rating can appear unchanged while activity increases substantially. Where quantitative reliability data are not available, the workshop should record the qualitative basis, uncertainty and conditions that require reassessment. Demand scenarios support that judgement; they do not supply failure probabilities.

7. Phase 3 assessment framework

7.1. Method derived from the AEROTHRIVE proposal

The proposal describes Phase 3 as the risk assessment of significant changes between conventional and gaseous-hydrogen aircraft handling within a Management of Change process. It envisages a hazard log, a risk register, severity/probability classification, subject-matter-expert involvement and initial scenario analysis. Coordination with aircraft developers and project partners is identified as a possible part of the assessment. The current framework develops that method into a traceable set of working records.

The first Phase 3 activity is change definition. The project manager/ process owner should obtain a clear description of the proposed aircraft, fuel state, stand, equipment and operating envelope. The second is applicability and gap validation, using the Phase 1–2 register to identify affected duties and assumptions. The third is HAZID, which translates those issues into credible scenarios with threats, top events and consequences.

Initial risk is then assessed against an explicitly described baseline. Preventive and recovery controls are selected and tested against each scenario. The MoC action programme turns missing controls and evidence into deliverables with owners, dependencies and review points. Residual risk is estimated during design and confirmed against implementation evidence before operational acceptance. Safety assurance then checks whether the accepted basis continues to hold.

This sequence is iterative. A design review may identify a new vent location that affects passenger routes. A drill may show that a shutdown indication is ambiguous. An OEM update may change a permitted filling condition. Each can reopen an earlier assessment. The report's Gates 0–6 provide decision points without suggesting that the work always moves once through a linear sequence.

The proposal's broad low, medium and high categories are implemented in v3 as Acceptable, Tolerable with mitigation and Intolerable. These labels are decision categories, not interchangeable numerical scores. The actual 5×5 lookup (ICAO safety management risk matrix) must be used, because the same apparent numerical severity can remain conditional at very low qualitative probability. Unassessed is a fourth status and cannot be treated as low risk.

The current evidence demonstrates the establishment and partial population of the framework. It does not demonstrate that joint validation workshops, commissioning tests or authority reviews have all occurred. Proposed activities in the following chapters should therefore be entered into the local programme and supported by records of attendance, assumptions, decisions and evidence. This preserves the distinction between preparing an assessment method and completing the safety demonstration for a real operation.

7.2. Workbook structure and traceability

The v3 workbook organises the assessment across 14 sheets. Its intended trace is requirement, gap, hazard, top event, threats and consequences, controls, risk classification, MoC action, evidence and acceptance. The structure is useful because an auditor can start with a requirement or an operational scenario and follow it towards the implementation decision.

Workbook component	Content and role
Source GAP Extract and Integrated Gap Register	Source preservation and 154 mapped requirement/gap records
Risk Assessment	83 assessment rows: 77 linked by GAP ID and 6 PART-IS rows, with initial and residual coding
Bowtie Library	22 threat/control/consequence records across 12 distinct top-event texts
Control Library	44 identified preventive and recovery controls with suggested assurance and owners
HAZID Library	10 generic hazard groups supporting scenario development
MOC Register	71 actions with trigger GAP ID and an intended review gate
MOC Gate Checklist	12 evidence questions distributed across Gates 0–6
Matrix and acceptance criteria	Classification and decision rules
Traceability and Dashboard	Cross-reference and portfolio views requiring validated source links
Bowtie View and Lists	Selected scenario presentation and supporting terminology

The workbook contains several different populations. Eleven proposed hazard-family labels are used in the Integrated Gap Register, while the HAZID Library has ten generic groups and the Bowtie Library has twelve distinct top-event texts. These figures need not match because they describe different levels of the model. They should nevertheless be governed by a common taxonomy so that a new scenario is intentionally linked rather than accidentally duplicated.

The Risk Assessment sheet uses GAP ID as its primary identifier. That is convenient for requirement traceability but creates a limitation when one gap needs several scenarios or several gaps concern one physical event. We recommend adding a stable risk or scenario identifier within the controlled implementation system, while retaining every contributing GAP ID. Similarly, top events should have identifiers independent of their editable description.

A record should distinguish the existence of a control in the catalogue from its applicability, implementation and verification at a specific location. The Control Library's "Active" field currently describes catalogue status. It is not evidence that all 44 controls are installed or effective. Suggested owners likewise identify functions for allocation, not accepted assignments.

The workbook can remain the common project baseline, while a local change package records aircraft, stand and organisation-specific evidence. The link between the two should retain the source revision and the exact scope of acceptance. A later change to a generic library entry should prompt an impact review for affected local packages instead of silently changing their accepted basis.

7.3. Reconciled populations and maturity

The numerical reconciliation confirms 154 integrated entries, with 80 positive gap flags. The gap-status field contains 75 In Progress, 74 Open, four Closed and one On Hold. These are administrative record states. They do not by themselves show whether a requirement has been met or a risk has been accepted.

Comparison	Reconciled result	Interpretation
Risk assessment required	73 YES, 7 NO, 74 CHECK	A separate screening field from the gap flag
Actual risk rows	83	All 73 YES entries are present, plus four NO entries and six PART-IS rows
Additional GAP-ID risk rows	GAP-002, GAP-057, GAP-060, GAP-136	Retention or removal requires a documented screening decision
MoC required	95 YES, 58 CHECK, 1 NO	Current gap-level change trigger population
Actions linked to YES entries	70	Leaves 25 YES entries without direct actions
Other action	MOC-010 for GAP-012	Trigger is now MoC NO; action remains Open

The three unassessed initial rows are GAP-057, GAP-060 and GAP-136. The first two have status Closed and have no hazard, top event, threat or consequence populated. GAP-136 is On Hold. These may ultimately be resolved as administrative issues or outside the defined handling scenario, but that requires a recorded rationale. Closing a status cell does not resolve the absence of a risk assessment when the record remains in the active portfolio.

GAP-001 is the only row with a residual code, 3E, and is marked Accepted. Its verification/assurance field, review date and comments are blank. The gap record remains In Progress and its MoC action remains Open. The report therefore recognises the recorded acceptance status but does not treat it as substantiated operational acceptance. The evidence supporting the severity reduction and the identity and scope of the decision must be retrieved or completed.

All 83 risk rows lack verification/assurance evidence and review dates. All 71 MoC actions lack an accountable owner, due date, mitigation package, residual-risk acceptance and closure reference. The 12 gate questions are Open and have no owner or evidence reference. This is a consistent indication that the material is an assessment and action baseline awaiting implementation evidence.

The appropriate management response is to assign and validate the work, not to alter status labels to improve the dashboard. Progress should be measured by demonstrable completion of evidence packages and reduction of unresolved safety questions. Counts remain useful for workload control, provided the population and the meaning of completion are stated explicitly.

8. Hazard identification and operational baseline

8.1. Hydrogen states and combined energy systems

The starting point for HAZID is the energy and material present in the defined operation.

GH_2 stores energy in a pressurised gas system. A failure can create a high-energy jet, hose movement, damaged equipment and a flammable release. LH_2 introduces cryogenic liquid and its transition to gas as heat enters the system. Both require containment and ignition control, but their release mechanisms and protective measures must be assessed separately.

Configuration	Distinct assessment emphasis	Ground-interface evidence
GH_2	Pressure compatibility, filling temperature, pressure transients and controlled depressurisation	Validated filling envelope, compatible connection and protective functions
LH_2	Cryogenic exposure, insulation, boil-off, trapped liquid and vent behaviour	Conditioning, drain/purge and relief arrangements defined for the equipment
Fuel-cell aircraft	Hydrogen together with high voltage, batteries, stored electrical energy and cooling	OEM safe states and coordinated fuelling, maintenance and emergency instructions
Mixed-energy apron	Hydrogen alongside conventional fuel, SAF, electric charging and other ignition sources	Stand-specific simultaneous-operation restrictions and emergency access

Hydrogen flame visibility can be poor in daylight. Personnel should not rely on visible flame or smell to determine whether an area is safe. Warm hydrogen is buoyant, but rapid dispersion does not guarantee that a release is harmless. Roofs, equipment, aircraft geometry, wind and the initial condition of a cold release can affect accumulation and movement. Detection and exclusion arrangements must therefore be based on the actual configuration.

Oxygen deficiency and, in relevant cryogenic conditions, oxygen enrichment are distinct concerns. Hydrogen gas detection does not replace oxygen monitoring where the scenario requires it. Conversely, oxygen monitoring does not reliably establish the absence of flammable hydrogen concentration. Detector purpose, location and response should be specified for the hazard being controlled.

Material suitability must consider the actual pressure, temperature, purity and service conditions. A generic description such as “hydrogen compatible” is insufficient without the equipment’s qualified application envelope. The same applies to personal protective equipment: protection for cryogenic contact does not establish protection from a high-pressure release or an electrical hazard.

The workbook’s generic hazard families are prompts for this assessment, not a complete inventory of every aircraft configuration. Fuel-cell/HV and mixed-energy interfaces require deliberate review because they are not separately represented as comprehensive scenario groups in the current risk portfolio. Their inclusion here responds to a hydrogen aircraft manufacturer’s technical review and should lead to additional local records where the defined operation creates exposure.

8.2. HAZID workshop method

The HAZID should be a structured examination of the defined handling system by people who understand its different parts. The proposed core participants are airport operations, the aircraft operator, the OEM or its authorised technical representative, the ground handler, hydrogen supply and infrastructure specialists, maintenance, HSE, SMS/compliance and RFFS. ATC or apron management should participate where movement or emergency interfaces are affected. Attendance alone is insufficient; the record should identify which assumptions each participant is competent to validate.

Before the workshop, the project manager should circulate the change description, stand layout, operating sequence, equipment interfaces, applicable OEM information and current gap/risk records. Missing information should be logged as an assumption or open question. A workshop cannot validate a pressure limit, emergency response capability or national permission that has not been established by the responsible party.

The discussion should follow each operating stage and ask what could fail, why it could fail, how loss of control would be detected, and what consequences could follow. Normal, abnormal and emergency states should be distinguished. Useful prompts include incorrect connection, interrupted power, failed communications, delayed aircraft departure, blocked vent, detector impairment, vehicle incursion and an unexpected aircraft technical condition.

Each scenario should record a hazard, one clearly defined top event, causal threats and credible consequences. A hazard is a condition, situation, activity or object that could cause or contribute to an aircraft incident or accident. A top event is the point at which control of that hazard is lost. A consequence is the potential event resulting from the release of a Hazard, which directly results in loss or damage. “No procedure” is usually a threat or organisational weakness; it needs a causal link to a physical or operational outcome before it can be scored as an aviation-safety scenario.

The participants then identify existing barriers and the evidence that supports them. Proposed barriers are recorded separately. The group should challenge dependencies, shared power or communications, maintenance assumptions, human workload and control degradation. A disagreement over severity, probability or applicability should be documented with its reason and the information needed to resolve it rather than removed through unsupported consensus.

The output is a validated scenario set with traceability to all relevant gaps, a list of actions and unresolved assumptions, and a record of the agreed scope. GH_2 and LH_2 should be reviewed in separate technical branches before the common apron and organisational interfaces are examined. The workshop chair should ensure that lower-frequency, severe-consequence events and indirect interfaces receive attention even when the most numerous register entries concern routine fuelling.

8.3. Hazard families in the integrated register

The Integrated Gap Register maps every entry to a proposed hazard family. The distribution is useful for organising specialist review, especially where several regulatory sources point to the same operational issue. It does not express event frequency, probability or independent risk exposure. The 36 fuelling mappings, for example, include multiple source clauses that may ultimately be addressed by the same validated operating scenario.

Proposed hazard family	Mapped entries
Aircraft H_2 fuelling operation	36
Regulatory and compliance gap	34
Procedure and documentation gap	22
Competence and training gap	16
Emergency response not adapted to H_2	13
SMS and MoC integration gap	10
H_2 infrastructure integration	7
H_2 fuel quality and verification	7
Cryogenic and boil-off release	4
High-pressure hydrogen release	3
Hydrogen leak not detected	2
Total mapped entries	154

Fuelling, procedures, competence and emergency response should be examined together where they affect the same task. A procedure may define a hold point, training may enable the person to apply it, and supervision may detect a missed step. These are connected functions. Counting them separately does not establish three independent barriers.

The regulatory/compliance family requires particular care. An unresolved requirement can be significant for permission to operate even where its immediate consequence is administrative. The reviewer should identify whether there is also a physical safety scenario, such as unverified equipment or an untrained person. Legal compliance and safety risk should remain linked but should not be collapsed into one severity label without explanation.

The smaller families must not be deprioritised solely because they have fewer entries. A single detector impairment or pressure-protection failure can affect several scenarios. The current HAZID Library also omits a separate comprehensive HV group and does not resolve all simultaneous-operation combinations. The local assessment should add records for material exposures rather than force them into an unsuitable generic family.

For reporting, we recommend retaining the mapped-family count as a workload measure and developing a separate count of validated scenarios by configuration and operating stage. That second measure should be created only after the scenario reconciliation, so that apparent reductions in risk records do not hide the removal of useful traceability.

8.4. Normal GH_2 handling sequence

The normal GH_2 sequence should be developed from the aircraft operator's instructions, OEM limitations and the fuel system's validated operating envelope. The following narrative identifies the required coordination and evidence. It is not a substitute for the approved task procedure or a generic instruction for connecting equipment. [refer to S2, GAP-017, GAP-081 to GAP-084 and GAP-150 to GAP-151]

Before arrival, the coordinating organisation confirms the aircraft configuration, expected uplift, compatible stand and equipment, operating restrictions and emergency coverage. The aircraft's technical state must be understood, including any defect or limitation affecting fuelling, venting, electrical systems or movement. A mismatch between the planned and actual configuration should trigger a stop and reassessment before the operation is committed.

At the stand, the team establishes the agreed aircraft and refueller safe states, verifies the equipment condition and protects access and escape routes. A pre-task briefing allocates the transfer supervisor, aircraft contact, stop-work responsibilities and communications method. It also confirms how an abnormal condition will be reported to airport operations and RFFS. Everyone involved must know which person coordinates a normal stop and who can initiate an emergency stop.

Connection proceeds only after the required hold points have been satisfied. These include positive interface identification, equipment compatibility, the specified bonding or earthing arrangement, and the applicable leak-tightness, purge or inerting checks. Any pressure ramp, temperature conditioning or communications handshake must follow the validated configuration. Familiarity with conventional fuelling equipment does not establish competence for these steps.

During transfer, the responsible personnel monitor the parameters and indications specified by the system design and procedure. The supervisor maintains awareness of the whole stand, including adjacent activities, personnel entry, vehicle movement, changing weather and emergency access. An alarm, abnormal trend, communication failure or loss of a required protective function should lead to the defined safe response. Restart requires a positive diagnosis and authorisation, not merely the disappearance of an alarm.

Completion includes controlled stop, the specified management of residual pressure, safe disconnection, interface inspection and positive release of the aircraft and equipment. Hydrogen-safe conditions should be demonstrated by the defined monitoring and acceptance criteria; a vague assertion that the area is "gas-free" is not an adequate record. The operator receives the fuel quantity, quality and deviation information needed for aircraft release.

The final handling record should identify the configuration, personnel, equipment, quantity, relevant checks, alarms and deviations. It should also confirm that no temporary restraint, connection, damaged component or unresolved defect affects departure. The objective is a controlled transfer with an auditable handover, including when the planned sequence is interrupted.

8.5. LH_2 and simultaneous operation interfaces

LH_2 handling requires a separate technical procedure because cryogenic transfer adds conditions that the GH_2 sequence does not resolve. The assessment should consider temperature conditioning, insulation performance, boil-off, vent or return arrangements, trapped liquid, drain and purge requirements, and the safe condition of disconnected equipment. The aircraft and infrastructure providers must define their respective responsibilities at each interface. [refer to S2, GAP-148 and GAP-153]

A delay after arrival or during fuelling can alter the thermal and pressure state of an LH_2 system. The change package should therefore define what happens during extended stand occupancy, equipment unavailability or an interrupted transfer. Venting and relief functions must be considered in both normal and abnormal states. A temporary storage or maintenance arrangement should not be treated as a routine extension of a turnaround approval.

Mixed-energy operations add a common interface challenge for GH_2 and LH_2. Conventional fuel transfer, electric charging, running APUs or engines, aircraft electrical work, de-icing and vehicle movements may introduce ignition sources, block access or change the exposure of people. Permission for each combination should follow a stand-specific assessment rather than an assumption that separately approved tasks can safely occur together.

Simultaneous activity	Proposed initial planning treatment	Evidence needed to relax a restriction
Boarding or passengers on board during H_2 transfer	Hold outside the initial trial envelope	Operator/OEM basis, evacuation assessment and joint validation
Running engine or APU near transfer or vent areas	Exclude unless specifically justified	Ignition, ingestion, exhaust and safe-state assessment
Electrical charging or HV maintenance	Separate from transfer pending assessment	Compatible electrical state, zoning and isolation controls
Adjacent conventional-fuel operation	Assess the shared stand environment	Overlapping zones, escape routes and combined response capability
Unrelated vehicle or contractor movement	Restrict within the controlled area	Segregation, access rules and supervision

These are recommended planning restrictions for an initial local trial, not declarations of universal legal prohibitions. Where the aircraft design requires a particular system to remain active, the OEM-defined safe state must be assessed explicitly rather than replaced by an arbitrary “everything off” rule.

Maintenance handovers should identify residual hydrogen, pressure, temperature and electrical energy. The responsible authorised personnel must establish and communicate the safe state before others approach or resume handling. Return to service after maintenance or an emergency requires a defined release route. A passed gas measurement or a reset emergency stop alone does not establish that the aircraft, equipment and operating area are fit to resume service.

9. Risk assessment and acceptance

9.1. The project risk matrix

The v3 matrix combines severity from 1 to 5 with probability from A to E. The code is a lookup address, not a product. A 5C assessment means Catastrophic severity and Remote probability under the project definitions. The matrix is described as ICAO/EASA-style in the workbook; its precise cell boundaries are the project's selected convention and require adoption within the local SMS.

Severity	A Frequent	B Occasional	C Remote	D Improbable	E Extremely improbable
5 Catastrophic	5A I	5B I	5C I	5D T	5E T
4 Hazardous	4A I	4B I	4C T	4D T	4E T
3 Major	3A I	3B T	3C T	3D T	3E A
2 Minor	2A T	2B T	2C T	2D A	2E A
1 Negligible	1A T	1B A	1C A	1D A	1E A

I = Intolerable T = Tolerable with mitigation A = Acceptable

Severity 5 is Catastrophic, with examples including multiple fatalities or loss of aircraft. Severity 4 is Hazardous, including serious injury, major damage or a major reduction in safety margin. Severity 3 is Major; severity 2 is Minor; severity 1 is Negligible. The workbook also uses disruption and procedural-failure examples. The local assessment should define the concrete consequence and apply the severity descriptor consistently, rather than score the label "compliance gap" without an operational mechanism.

Probability A is Frequent, B is Occasional, C is Remote, D is Improbable and E is Extremely Improbable. These are qualitative terms in the supplied matrix. They do not contain numerical event-rate thresholds. An assessor should state the operating exposure and the evidence or expert reasoning used to select a category.

The matrix has three classified outcomes. Intolerable requires risk reduction before the affected operation or change is released. Tolerable with mitigation requires documented controls, justification, assurance and authorised acceptance. Acceptable permits normal SMS acceptance with continued maintenance of the controls. A missing severity or probability remains unassessed and prevents a dependable acceptance decision.

Two boundaries are particularly important: 4E and 3D are both Tolerable with mitigation. The earlier draft labelled these as Acceptable in its 15-scenario tables. Those labels are corrected in this report. The classification of the code must follow the matrix even where the wording "Extremely Improbable" appears reassuring.

9.2. Initial risk and residual risk reasoning

An initial-risk assessment describes a defined scenario under a stated baseline. The assessor should identify which controls are already present and supported by evidence, and which are proposed. The term “inherent risk” should be reserved for a deliberately defined assessment without selected controls. Mixing an uncontrolled inherent case with an initial case that credits existing barriers makes comparisons unreliable.

For each scenario, the assessor should describe the initiating conditions, the top event, the people or assets exposed and the credible consequence being rated. If one top event has materially different consequences, the assessment should distinguish them or explain which governs the overall rating. A minor unignited release and an ignited release affecting an occupied aircraft should not share an unexplained severity judgement simply because both involve a hose.

The probability argument should consider task frequency, equipment reliability, environmental conditions and human performance. Where experience is limited, the record should state the uncertainty. Expert judgement can be useful, but the reviewer needs to understand why one configuration is judged Remote and another Improbable. A category change based only on a workshop preference is weak evidence for operational acceptance.

Controls should be linked to the part of the scenario they affect. A preventive measure may reduce the probability of loss of containment. A recovery measure may limit release duration or reduce exposure after it occurs. A control can have more than one effect, but each should be explained. Training should not automatically reduce the severity of a catastrophic physical event; a lower severity requires a defensible change to the credible consequence.

During design, residual ratings may be recorded as targets or predictions conditional on a defined control package. At readiness review, the assessors should confirm the ratings against installation, test, competence and exercise evidence. A proposed detector, interlock or procedure should not be credited as available merely because its name is present in the catalogue. If implementation differs from the assumptions, the residual assessment must be revisited.

The acceptance record should identify the risk owner, reviewers, evidence, limitations, acceptance authority and review trigger. A risk owner is responsible for maintaining the basis of the decision; the assessor may be a different person. Independent challenge is particularly valuable where controls share dependencies, consequences are severe, or the implementation organisation is under schedule pressure.

This process gives the rating an auditable explanation. It also allows the organisation to distinguish a change in the actual risk from a change in the quality of knowledge about that risk. Both can justify revisiting an earlier decision, but they should not be represented as the same event.

9.3. Application of the ALARP principle

The ALARP principle requires aviation safety risks to be reduced to a level that is “as low as reasonably practicable”. It provides the decision-making bridge between identifying a risk, selecting appropriate controls and accepting the remaining residual risk. ALARP does not mean that every conceivable control must be implemented, nor does it mean that a risk becomes acceptable merely because it falls within a particular matrix cell. It requires a reasoned and documented demonstration that suitable additional risk-reduction measures have been identified and implemented unless their implementation would be clearly disproportionate to the additional safety benefit achieved.

For the purposes of this project, ALARP is applied as a safety-management principle rather than as a separate risk classification. The risk matrix continues to determine whether a scenario is Intolerable, Tolerable with mitigation or Acceptable. An Intolerable risk cannot be justified by an ALARP argument: the affected operation or change must not be released until the risk has been reduced. A risk classified as Tolerable with mitigation may be accepted only where the required controls have been implemented, their effectiveness has been verified and the organisation can demonstrate that further reasonably practicable risk reduction has been considered. An Acceptable rating permits acceptance through the normal SMS process, but it does not justify the removal of established controls or the rejection of an obvious, effective and proportionate safety improvement.

The ALARP assessment should begin with a systematic search for further controls. Preference should normally be given to measures that eliminate the hazard or prevent the top event, followed by engineered safeguards, detection and automatic protection, procedural and organisational controls, competence and training measures, and emergency-response provisions. Measures that depend primarily on human performance should not automatically be treated as equivalent to inherently safe design or reliable engineered protection. For hydrogen aircraft handling, this means considering, for example, whether separation distances, equipment design, breakaway devices, automatic isolation, hydrogen detection, ventilation, bonding and grounding arrangements or access controls can prevent or limit a release before relying principally on procedures, warnings or personal protective equipment.

Reasonable practicability should be assessed by comparing the expected safety benefit of a measure with the resources, time, operational difficulty and additional risk associated with implementing it. Cost may form part of this consideration, but cost alone is not sufficient justification for rejecting a material safety improvement. The higher the potential severity, the greater the uncertainty, or the weaker the existing barriers, the stronger the justification required for deciding that an additional measure is not reasonably practicable. In particular, where a credible consequence is catastrophic or hazardous, inconvenience, schedule pressure or ordinary implementation cost should not be treated as sufficient reasons for declining an effective control.

An ALARP demonstration should therefore record the control options considered, the expected effect of each option on probability, exposure or severity, and the reasons for implementation or rejection. The assessment should also examine whether the proposed controls are independent, sufficiently reliable and effective under foreseeable abnormal conditions. Common dependencies must be identified. For example, several controls may appear independent while all relying on the same power supply, detector, communication channel, contractor, procedure or trained individual. The number of controls alone is not evidence that the risk has been reduced ALARP.

Compliance with applicable legal and regulatory requirements, certification specifications, operational rules and mandatory technical standards constitutes the minimum baseline. ALARP cannot be used to justify non-compliance or to trade a mandatory requirement against cost or operational convenience. Conversely, compliance with minimum requirements does not automatically establish that the risk is ALARP

where the specific hydrogen-handling configuration presents additional hazards or where further proportionate controls are reasonably available. ICAO guidance similarly treats compliance as the foundation of safety management and requires safety risks to be mitigated to an acceptable level through appropriate controls.

The residual-risk rating used for acceptance must reflect the control package actually implemented and available at the time of operation. A proposed detector, interlock, procedure, training course or emergency arrangement may support a predicted residual-risk target during design, but it cannot support final ALARP acceptance until its installation, functionality, competence requirements and operational effectiveness have been demonstrated. Evidence may include design verification, commissioning and functional tests, training and competence records, emergency exercises, inspection results, interface agreements and confirmation that operating procedures reflect the assessed configuration.

ALARP is not a one-time declaration. The conclusion remains valid only while the assumptions, operating environment, exposure, interfaces and credited controls remain valid. The assessment must therefore identify review triggers, including equipment or procedural changes, increased handling frequency, new aircraft types, contractor changes, control failures, incidents, abnormal events, audit findings or new technical knowledge. Where such a trigger occurs, the organisation should reconsider both the residual-risk rating and whether further risk reduction has become reasonably practicable.

Accordingly, an ALARP conclusion should be expressed as a substantiated acceptance statement rather than as a simple matrix result. It should confirm that mandatory requirements have been met, suitable control options have been considered, selected measures have been implemented and verified, rejected measures have been justified, uncertainties and dependencies have been addressed, and the residual risk has been accepted by the authorised risk owner. This provides an auditable basis for determining that the proposed hydrogen aircraft-handling activity may proceed without compromising the objective of maintaining a high level of aviation safety.

9.4. Initial risk portfolio and prioritisation

The 83 risk rows contain 80 initial codes. Fourteen are Intolerable, 66 are Tolerable with mitigation and none are Acceptable. Three are unassessed. The intolerable population consists of nine rows coded 5C and five coded 4B. These are counts of assessment rows, not 14 independent accident scenarios.

Initial classification	Rows	Share of 83 rows
Intolerable	14	16.9%
Tolerable with mitigation	66	79.5%
Acceptable	0	0.0%
Not assessed	3	3.6%

The intolerable rows concern emergency response under JIG 4, depot layout, aircraft servicing under ICAO Annex 14, several fuelling provisions, and passenger-related or special fuelling questions. GAP-081 to GAP-084, for example, link four rule or AMC records to the same principal fuelling top event. A consolidated technical assessment can address them, provided all four requirements and their individual implementation details remain traceable.

The present portfolio should be prioritised in two ways. First, severe and unresolved scenarios require prompt technical attention before the operating envelope can be defined. Second, controls that serve several scenarios deserve early design and assurance work because their absence can block many assessments. Detection, shutdown, connector compatibility, stand segregation, competence and emergency coordination are examples of these shared dependencies.

Amber rows should not be treated as a completed second tier. Fourteen initial rows have code 5D and three have code 5E, both with Catastrophic severity. Their lower qualitative probability does not remove the need for a supported control package and acceptance rationale. Likewise, the seven rows at 3D and six at 4E remain conditional under the project matrix. A low-probability descriptor is not evidence that the conditions for acceptance have been met.

The three blank initial assessments need an explicit disposition. GAP-057 and GAP-060 may be administrative change records rather than safety scenarios. GAP-136 may require a narrower interface rationale or exclusion from the defined ground-handling case. The preferred approach is to document that decision and maintain traceability. Entering arbitrary scores solely to remove blanks would weaken the assessment.

Appendix A identifies the fourteen intolerable rows and the outstanding initial assessments. The narrative chapters that follow group them by operational mechanism so that the implementation programme can address shared controls without losing the source links. The priority order remains provisional until local configuration and exposure have been validated.

9.5. Residual risk and conditional acceptance

The residual portfolio is substantially incomplete. GAP-001 is the sole row with a residual assessment, moving from 4E to 3E. The remaining 82 rows have no residual severity, probability or code. The row status Accepted for GAP-001 records a decision label, but its supporting assurance field and review date are empty. The appropriate conclusion is that one residual classification has been entered and that the evidence basis for acceptance has not been demonstrated in the record. Consistent with ICAO safety management principles, risk mitigation may use avoidance, reduction and segregation strategies, supported by technical, training, regulatory and procedural controls. Any claimed reduction in severity, likelihood or exposure should be linked to the specific scenario and supported by evidence demonstrating how the selected controls achieve that reduction.

The change from severity 4 to severity 3 in GAP-001 deserves specific review. The stated controls include a role-based competence matrix, refresher training, drills, role descriptions and supervisory stop-work authority. These can improve performance and reduce error likelihood. Whether they also change the credible consequence requires a scenario-specific explanation. The report neither endorses nor replaces the recorded 3E value; it identifies the reasoning and evidence needed to support it.

The earlier Word draft contains a separate 15-scenario set with proposed residual targets. Those targets are retained in Appendix C as workshop inputs. Applying the v3 matrix gives seven intolerable and eight amber initial scenarios, followed by fourteen amber residual targets and one acceptable target. The draft's claim of six amber residuals is inconsistent with its codes and the matrix. No achieved risk reduction should be inferred from that illustrative set.

Decision condition	Minimum treatment
Residual risk unassessed	Complete the scenario or document an approved scope disposition before release
Residual risk intolerable	Reduce risk and reassess; an accountable manager cannot waive the project rule through a status change
Residual risk tolerable with mitigation	Demonstrate controls, document ALARP or equivalent local justification, accept conditions and monitor
Residual risk acceptable	Record acceptance and maintain the controls and review arrangements

ALARP in the workbook means that the chosen risk reduction must be justified, including consideration of further practicable measures. The record should show the options considered, the safety benefit, technical constraints and reasons for the decision. This report contains no financial analysis, so it does not claim to establish an economic gross-disproportion argument. Any legally required local test must be addressed by the responsible organisation.

Acceptance should be bounded by configuration, location and operating conditions. A residual rating accepted for one stand, aircraft variant or trial volume is not automatically valid for another. Temporary restrictions and compensating measures should have an owner, expiry, verification requirement and restoration plan. If a critical assumption fails, the operation returns to the relevant review point.

10. Priority operational risk assessments

10.1. Fuelling and passenger exposure

The largest coherent priority group is the transfer of hydrogen to the aircraft. GAP-017 and GAP-081 to GAP-084 are initially rated 4B. GAP-109, GAP-113, GAP-143 and GAP-144 are rated 5C, while GAP-133 and GAP-134 also carry 5C and are On Hold in the risk sheet. These rows address overlapping physical tasks and regulatory questions, but their different severities and probabilities require explanation through scenario scope and exposure.

The core top event is uncontrolled hydrogen release during fuelling. Credible causes include hose or coupling failure, incorrect connection, a sequence error and vehicle impact. The consequence depends on released inventory, duration, ignition, nearby people, aircraft occupancy and the effectiveness of isolation and evacuation. The local assessment should therefore specify the transfer system and exposed population before confirming the score.

Prevention should address equipment integrity, positive connection identification, controlled sequence, movement restraint and protection of the transfer area. The selected functions need measurable acceptance criteria. For example, an equipment inspection should identify what condition is unacceptable, who performs the check and how defective equipment is prevented from use. An interlock should define the unsafe condition it detects and the safe response on loss of its inputs.

Recovery should consider detection, emergency shutdown, isolation of the relevant inventories, warning and movement of people, and responder access. Several ESD-related controls may be different parts of one protective function. Their number should not be treated as proof of independence. A common loss of power or communications could affect several apparently separate controls.

Passenger exposure requires a specific operating decision. Boarding, passengers remaining on board, persons with reduced mobility and activity on an adjacent stand can change the consequence and evacuation requirements. The project should not assume that a conventional-fuel permission extends automatically to hydrogen. For an initial trial, we recommend excluding these combinations unless the aircraft operator and other duty holders establish a supported case within the applicable framework.

GAP-134 needs a distinct legal-applicability review because its source concerns wide-cut fuel. Its inclusion in the workbook identifies a question; it does not classify hydrogen as that fuel type. The safety concern can still be assessed through a properly defined hydrogen scenario without using an inapplicable fuel label. GAP-133 and GAP-134 also lack both preventive and recovery control text in their current risk rows, making them unsuitable for a residual-risk decision as recorded.

The closure package for this group should combine the validated transfer envelope, operator/OEM instructions, stand plan, passenger restrictions, test records and competence evidence. It should map each source clause to the relevant procedure and protective function and explain any remaining differences in risk ratings.

10.2. Emergency response and facility segregation

GAP-005, GAP-008 and GAP-011 are all initially rated 5C. They address the emergency response procedure, depot layout and aircraft servicing/fire response interfaces. Their common issue is that the consequences of a hydrogen event depend on more than the immediate actions of the fuelling team. Access, information, command, equipment and surrounding activities determine whether the incident remains controlled.

For emergency planning, the assessment should distinguish an unignited release, an ignited release, a pressure-system failure, an LH_2 event where applicable, and an aircraft emergency arriving from flight. The airport must understand what information the aircraft can provide and what actions remain possible. RFFS should validate response arrangements against the actual fuel system and ground isolation provisions, including limitations where the source cannot be safely isolated.

The relevant detection method must match the scenario. A gas alarm, a flame indication and an oxygen alarm communicate different hazards. The response plan should identify how those indications reach the fuelling supervisor, airport operations and RFFS and what each recipient does. Reliance on visible flame alone is inadequate where flame visibility may be poor. The technical specification of detection equipment belongs in the local engineering and response evidence.

Facility segregation needs a defined release case and an operational layout. The assessment should examine occupied buildings, air intakes, vehicle routes, adjacent aircraft, passenger paths, vents, temporary equipment and responder approach. A small layout change can affect several of these simultaneously. The workbook's references to hazardous-area assessment and separation-distance assessment are appropriate starting points, but they are distinct analyses and should not be represented by a single arbitrary circle on a stand plan.

GAP-018 is rated 5D and has been developed in the risk sheet as delayed or inadequate firefighting response. It should be linked to the same interface review where water supplies, access or other response resources are relevant. The different top-event text from the generic library needs an intentional mapping. A changed description should improve the scenario's clarity without breaking its control links.

The closure evidence should include the configuration-specific ERP, validated response capability, access checks, communications tests and exercise results. Any failed safety-critical exercise objective should remain open until corrected and retested. A plan's publication date or a high overall exercise score cannot compensate for failure to warn, isolate, evacuate or establish command where those functions are required.

No site-specific emergency plan or engineered segregation assessment is completed by the generic workbook. The Phase 3 programme should make those deliverables explicit and assign them to the organisations with the competence and authority to provide and accept them.

10.3. Fuel quality and control system interfaces

Fuel quality is an aircraft safety interface as well as a supply-chain process. GAP-021, GAP-022 and GAP-029 are rated 5D, while GAP-125 and GAP-139 address aerodrome verification and fueller loading/quality control. The local assessment should define the applicable aircraft fuel specification, how conformity is demonstrated through the supply chain and where responsibility transfers between supplier, infrastructure operator, into-plane provider and aircraft operator.

A supplier certificate is useful only when it can be linked to the delivered product and the conditions that preserve its quality. The package should address sampling or verification where required, analytical methods, contamination risks, equipment cleanliness, batch identification and the disposition of non-conforming fuel. It should also define what happens if a certificate is missing, a test is inconclusive or the delivered fuel cannot be traced to the accepted batch.

The Control Library proposes fuel quality specifications, supplier assurance, sampling/testing, quarantine and stop-supply measures through PC-017, PC-018, RC-017 and RC-018. These are sensible functions to develop, but their effectiveness depends on aircraft-specific acceptance criteria and the actual supply arrangement. A road-vehicle or industrial hydrogen specification should not be assumed sufficient without examining the aircraft requirement and the intended process.

Control-system information is another important interface. Transfer permissives, pressure/temperature indications, ESD signals, equipment configuration and quantity records may depend on software and communications. GAP-064 recognises software at the fuelling interface, but is marked Risk Assessment Required NO. That decision should be reviewed if the local system uses software for a safety function or safety-relevant data exchange.

The assessment should consider loss, delay, corruption or misinterpretation of a control signal and the system’s response. It should identify which functions remain safe without the network, how a restart is authorised and whether changes to software or settings require retesting. Information security is relevant where compromise could alter a safety function or operating data. This is an interface review, not a claim that the current workbook contains a completed Part-IS assessment.

GAP-131 illustrates the need to align the scenario with its source. Its source concerns portable electronic devices, its risk-sheet top event concerns uncontrolled hydrogen release, and its controls are blank. The link may be defensible through ignition, electromagnetic or procedural effects, but the causal chain must be stated. A broad reference to electronics should not replace analysis of the actual device, location and failure mechanism.

For fuel-cell aircraft, the same discipline applies to HV isolation, residual electrical energy, batteries and cooling. The OEM-defined safe state must be translated into actions and handovers that each ground organisation can understand, perform and verify.

11. Bow tie analysis and control assurance

11.1. Causal structure and barrier placement

A bow-tie connects the causes of a loss-of-control event to its consequences and shows the barriers that interrupt those pathways. Its value is explanatory: it shows why a control is needed and what must be true for the control to work. A diagram that simply lists equipment and procedures does not demonstrate a complete barrier strategy.

The v3 Bowtie Library contains 22 scenario-path records and 44 identified controls. Each record includes a top event, threat, preventive control, consequence, recovery control, escalation factor, escalation control, verification method and suggested owner. This provides a useful structure for local development. The relationships nevertheless require technical review, particularly where generic descriptions have been applied across different configurations.

For an uncontrolled-release top event, hose integrity, correct connection and protection from vehicle impact can act before loss of containment. Ignition-source control primarily prevents ignition of a release and therefore normally acts on a consequence pathway rather than preventing the release itself. PC-004 is currently placed on the preventive side of the fuelling-release bow-tie. Its function should be retained, but its placement or the top-event definition should be corrected to preserve causal logic.

Similarly, absence of cryogenic PPE does not normally cause a loss of containment. It changes the exposure or injury consequence after contact with the hazard. PC-012 should be reviewed in that context. A relief device can prevent rupture while also creating a controlled discharge; its appropriate position depends on whether the assessed top event is overpressure, rupture or uncontrolled release. These distinctions affect which severity or probability reduction can be claimed.

A barrier should have a defined function and a way of showing that it is available. Supporting activities such as training, maintenance and document control help sustain barriers but should not automatically be counted as independent physical layers. An accessible emergency-stop button, its circuit and the isolation valve may form one end-to-end function. The assessment must consider the complete chain and its failure modes.

Escalation factors describe conditions that degrade the control, such as overdue calibration, bypassed interlocks, blocked routes or untrained contractors. The escalation control should specifically address that degradation. A generic “audit” is insufficient without identifying what is checked, how often, by whom and what happens when the result is unsatisfactory.

The proposed local bow-tie review should therefore validate the top event, place barriers on the correct causal side, identify dependencies and define performance and impairment rules. This can preserve the workbook’s control identifiers while improving the reasoning that supports risk reduction. It is more useful than adding control names solely to make the diagram appear complete.

11.2. Worked physical bow tie

The example below develops the workbook's fuelling-release scenario. It separates prevention of loss of containment from control of ignition and exposure after release. The diagram is a proposed refinement for local validation. It does not represent a commissioned installation or an accepted residual risk.

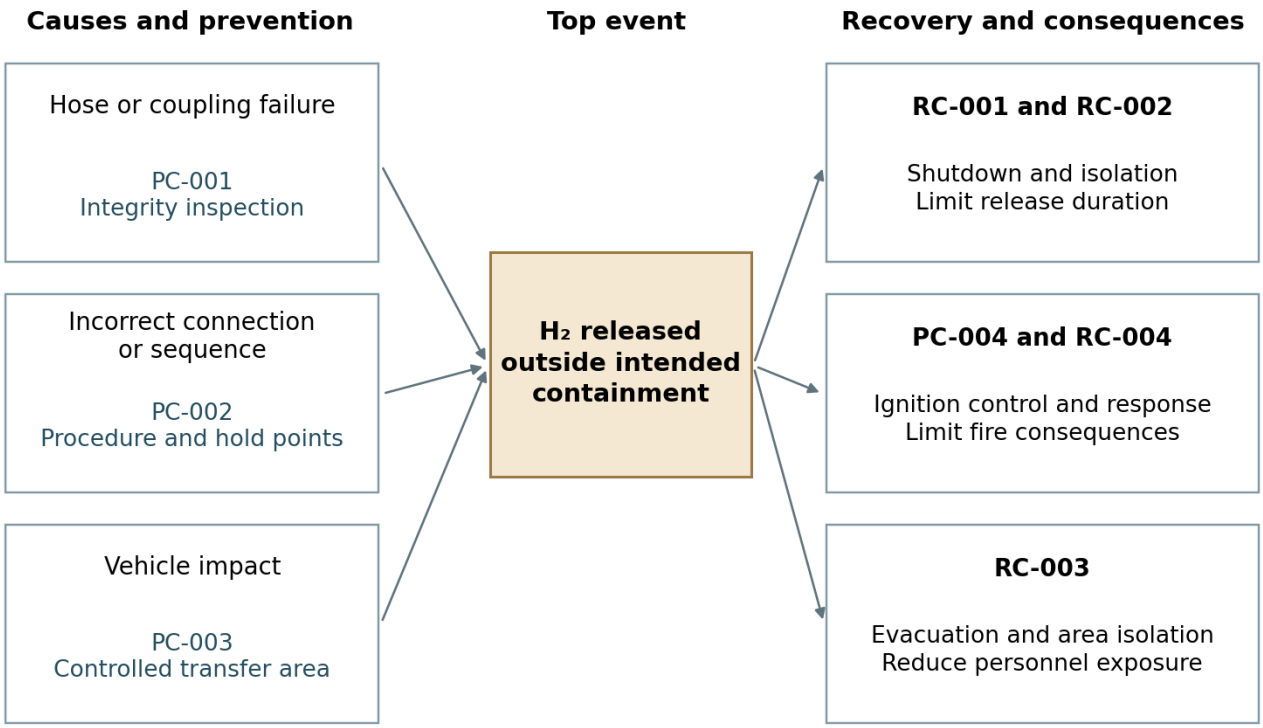


Figure 1 Proposed refinement of the fuelling release bow tie

The pre-use inspection in PC-001 needs a defined scope, rejection criteria and a method of preventing use of defective equipment. PC-002 requires an executable sequence with hold points appropriate to the actual connection and transfer system. PC-003 requires effective control of vehicle movement and the transfer area, including effects from an adjacent stand.

After release, the protective functions must limit the event before the credible consequences develop. Detection and shutdown should be assessed end to end, including the time and conditions required to reach the specified safe state. Ignition control and evacuation address different pathways and should have their own assurance evidence. The response plan should reflect what remains possible if isolation fails or release continues.

A credible challenge is a vehicle incursion while the transfer system is connected. The review should establish whether physical or operational segregation prevents contact, what happens if the hose is damaged, whether the shutdown function remains available and whether people can leave without crossing the release area. This single challenge tests several interfaces more effectively than reviewing each control in isolation.

The residual assessment must explain which pathway has changed after the controls are implemented. Reducing the release probability does not necessarily reduce the consequence severity. Limiting inventory or separating people may change the consequence, but the effect must be supported by engineering and operational evidence. The resulting reasoning should be recorded with the risk row and all contributing GAP IDs.

11.3. Governance bow tie and a worked trace

The active Bowtie View selects "H_2 change not adequately assessed or controlled". This governance top event concerns a failure of the change process. Its consequence is the introduction of an operation with missing controls or assurance. It is different from the physical release scenario and should be maintained as a separate organisational assessment.

The workbook links this top event to MoC screening and risk gates through PC-019 and to the hazard log/bow-tie relationship through PC-020. Late design changes and pressure to close actions are identified as escalation factors. The recovery functions, RC-019 and RC-020, involve review before operation and residual-risk acceptance. Their protective value depends on the ability and authority of the reviewer to withhold release when evidence is inadequate.

Trace element	Worked example using GAP-030
Source issue	ICAO Doc 9977 section 6.3 change management requires consideration of hydrogen-specific changes
Current initial rating	4E, Tolerable with mitigation
Governance top event	H_2 change not adequately assessed or controlled
Prevention	PC-019 screening/risk gates and PC-020 current hazard-log links
Recovery before operational consequence	RC-019 review before operation and RC-020 accountable acceptance
Evidence to establish	Change scope, linked risk/control records, independent challenge and authorised release

This trace illustrates the purpose of Phase 3. The regulatory reference starts a change question. The scenario identifies how the process could fail. Controls define what prevents or detects the failure. Evidence demonstrates that the controls were actually used. The acceptance record then states what can proceed and under which conditions. A signed approval with no underlying evidence breaks that chain.

Governance controls must also have impairment rules. If a late OEM change invalidates the interface assumptions, the project manager should reopen the relevant gate. If a risk owner is unavailable, the organisation must identify a suitably authorised substitute rather than allow the task to proceed without ownership. If the workbook cannot reliably display links, the review must use a verified evidence index until the tool is corrected.

The project manager coordinates this process but does not replace the statutory responsibilities of the aerodrome, operator, maintenance organisation, supplier or authority. A common Safety Review Board can provide coordinated challenge, provided each participating organisation records the decisions within its own powers. The governance bow-tie is effective only when that allocation is clear and the operational release can genuinely be stopped.

11.4. Control performance and continuing assurance

The 44 controls comprise 22 preventive and 22 recovery records, with 30 labelled Critical and 14 Important. All are marked Active in the library. These labels establish an intended assurance priority, but the workbook does not contain evidence that the controls have been implemented at a particular airport. Each selected control should therefore receive a local performance standard and an accountable owner.

Control function	Performance question	Suitable evidence type
Detection and alarm	Does the system detect the defined condition and communicate an actionable indication in the required environment?	Design assessment, calibration, functional test and alarm-response exercise
ESD and isolation	Does the complete chain achieve the defined safe state, including loss of power or communication?	Integrated cause-and-effect test and isolation verification
Connector and transfer sequence	Are incompatible connections prevented and hold points reliably completed?	Interface qualification, inspection and witnessed task demonstration
Stand segregation and access	Are people, vehicles and emergency routes protected during actual operations?	Approved layout and operational observation
Competence and supervision	Can assigned personnel perform normal and abnormal tasks correctly?	Practical assessment and current task authorisation
Fuel quality	Is the delivered product within the aircraft specification and traceable?	Batch/quality records and non-conformance disposition

The standard should state operating limits, availability, dependencies, test method, acceptance criteria and actions on failure. Test intervals should follow applicable requirements and the equipment's degradation mechanisms, manufacturer instructions and operational experience. The report does not prescribe a universal interval because the source material does not establish one.

Evidence examples in the library are generic. "Pre-use checklist" may show that an inspection was signed but not that an ESD function operates within its specification. A training attendance record may show participation but not competence. The verifier should select evidence that demonstrates the function claimed in the risk assessment and, where necessary, observe the task under representative conditions.

Critical-control impairment should be visible to the people who decide whether an operation can proceed. A failed detector, bypassed interlock or blocked route needs a defined stop or restricted-operation rule. Any compensating measure should be specific, authorised, time-limited and reassessed. A temporary measure should not become the normal process through repeated informal extension.

Common-cause failures require particular attention. Shared electrical supply, communications, sensors, software or maintenance arrangements may defeat several controls at once. The local safety argument should identify those dependencies and avoid unsupported multiplication of reliability claims. Where the potential consequences warrant more detailed analysis, the project should obtain competent engineering review or a quantitative assessment rather than imply precision from the qualitative matrix.

12. Management of Change programme

12.1. Trigger and action reconciliation

The gap-level MoC decision should govern the change programme. In v3, 95 records are marked YES, 58 CHECK and one NO. The action register contains 71 actions, each linked to one trigger GAP ID. Direct reconciliation shows that 70 actions relate to the YES population and one relates to the NO entry, GAP-012. This leaves 25 YES entries without a direct action.

The exact calculation is therefore 95 YES triggers less 70 matching actions, giving 25 unmatched triggers. The net population difference, 95 less 71, is 24, but it is not the missing-action count. The earlier Word draft's 96-versus-71 comparison should not be carried forward as the v3 position. Appendix B lists all 25 unmatched IDs and groups them by the implementation question they raise.

The unmatched records include air-operator interfaces, passenger fuelling, fuel quality, vehicle positioning, bonding, APU/GPU/engine coexistence and the SAE GH_2/LH_2 transfer topics. Several are operationally important and some are already rated intolerable. The absence of a direct action does not prove that no work has been done elsewhere, but the workbook provides no explicit consolidated link or closure reference that demonstrates coverage.

Many-to-one consolidation is legitimate when a single deliverable addresses several gaps. For example, a validated aircraft-fuelling procedure may cover several rule and AMC references. The consolidated action should list every contributing GAP ID, identify each acceptance criterion and show how the final evidence meets them. A general reference to a workstream is insufficient where a specific requirement or configuration remains unresolved.

MOC-010 should be reviewed separately. Its trigger, GAP-012, concerns isolated aircraft parking and is now marked MoC NO and Closed in the gap register. The action remains Open. The owner should determine whether the action is obsolete, whether the screening decision needs reconsideration, or whether the action supports another gap. The resolution should preserve the historical reason and avoid silent deletion of evidence.

The 58 CHECK entries need screening as well. They include general management, oversight and national requirements that may apply even without a positive hydrogen gap flag. Resolution of the 95 YES triggers does not automatically resolve those entries. The local scope review should decide which general duties require new implementation evidence and which can remain covered by existing arrangements.

Each retained action should identify the deliverable, accountable organisation, delivery owner, due date, dependencies, control IDs, required verification, closure evidence and acceptance conditions. The present 71 actions have those key implementation fields blank. Assignment and evidence definition should therefore precede any claim that the programme is ready for gate closure.

12.2. Workstreams and implementation dependencies

We recommend organising the actions into workstreams that correspond to complete operational outputs. This allows related requirements to be addressed together while retaining their individual links. The workstreams are proposed programme arrangements and do not create new assignments or completion claims for the project partners.

Workstream	Principal output	Main dependency
Applicability and governance	Local requirement map, duty holders and decision route	Defined aircraft, airport and organisational scope
Aircraft and transfer interface	Agreed technical envelope and handover specification	OEM and equipment-provider information
Stand and equipment readiness	Compatible layout, protective functions and maintenance baseline	Release cases and permitted simultaneous activities
Procedures and coordination	Controlled normal, abnormal and emergency task sequences	Validated interface and stand restrictions
Competence and contractor control	Assessed, authorised personnel with adequate coverage	Final task roles and procedures
Emergency preparedness	Coordinated response plan and demonstrated capability	Aircraft/system information and local access/resources
Assurance and acceptance	Verified controls, residual assessments and release records	Evidence from all preceding workstreams

The dependency order matters. Detailed training should follow sufficiently stable procedures. Integrated testing should follow installation and component acceptance. Residual-risk confirmation should follow the evidence on which the reduction depends. Some activities can proceed in parallel, but a deliverable should not be finalised on assumptions that another workstream has yet to validate.

A project manager should maintain an integrated evidence index and a decision log. The index links deliverables to GAP IDs, scenarios, controls and gates. The decision log records changes to scope, assumptions, restrictions and responsibilities. Together, they allow a reviewer to see why an action was closed and whether a later change has affected its basis.

Action closure should distinguish production from verification. Producing a procedure is a delivery milestone. Demonstrating that personnel can use it correctly is an implementation milestone. Confirming its effectiveness under representative conditions is an assurance milestone. These can be recorded within one action if the acceptance criteria make the distinction clear.

Temporary arrangements deserve the same discipline. A trial may use a mobile supply unit, restricted operating hours or a dedicated stand that differs from the intended permanent configuration. The trial's evidence and acceptance should identify those conditions. A permanent arrangement should not inherit approval simply because the trial was completed without an occurrence.

The workstream structure should also support transfer between airports. Common technical lessons can be reused, while each airport confirms local requirements, stand geometry, weather exposure, response capability and organisational arrangements. Differences should be recorded in a local annex and assessed for their effects on the common control argument.

13. MoC gates and evidence decisions

13.1. Gates 0 to 2

The workbook contains 12 questions across Gates 0–6. All are Open and the owner and evidence fields are blank. The gate framework is therefore an intended decision process awaiting implementation. A gate should be passed only for a defined scope and on the basis of specified evidence, with any conditions recorded. [refer to S2, MOC Gate Checklist]

Gate 0 screens the change. The output should identify what is changing, where, for which aircraft and fuel state, and which organisations are affected. It should nominate the MoC lead and identify preliminary constraints, including whether the case is a test, limited trial or intended routine operation. A screening decision of “not applicable” should state its reasoning rather than remove the issue from the record.

Gate 1 confirms applicability and HAZID. Its two questions require affected requirements to be linked to the gap register and hazards/top events to be validated with the relevant functions. The evidence should include the local requirement map, operational boundary, workshop record, scenario identifiers, open assumptions and interface responsibilities. Technical uncertainties that prevent a safe design decision should be resolved before they are embedded in procedures or equipment specifications.

Gate 2 reviews bow-ties, risk and the mitigation rationale. The selected barriers should be technically credible, owned and linked to a verification plan. Initial ratings must be complete or subject to an approved scope disposition. Predicted residual ratings may be used to determine whether the proposed design is worth implementing, but they must be explicitly conditional on the control package and later verification.

Gate	Decision at this stage	Evidence required before passing
0 Screening	Is the change sufficiently defined to assess?	Scope, affected organisations, configuration and nominated lead
1 Applicability and HAZID	Are the relevant duties and scenarios understood?	Validated requirements, workshop record and disposition of exclusions
2 Risk and control design	Can the proposed control strategy support an acceptable operating case?	Initial assessment, barrier logic, predicted residual rationale and verification plan

The sequence resolves an ambiguity in the earlier draft: final residual-risk acceptance cannot normally be completed before implementation evidence exists. Gate 2 establishes a justified design target. Gate 5 confirms operational acceptance after Gates 3 and 4 provide the evidence. If an existing installation already supplies valid evidence, it may be reviewed earlier, but that should be documented rather than assumed.

Passing these gates permits the next assessed development stage. It does not itself authorise hydrogen transfer. Commissioning and live testing can introduce their own hazards and require a separately defined safe test envelope. A project should be able to continue controlled engineering work while withholding operational release for unresolved risks.

13.2. Gates 3 to 6

Gate 3 establishes that the selected controls have been implemented. Its questions address procedures, competence and infrastructure. The operating and maintenance documents should match the actual configuration. Personnel should have completed the practical assessments required for their tasks. The stand, detection, ESD, signage, access controls and equipment should have passed their relevant acceptance checks. A planned completion date is not implementation evidence.

Gate 4 examines integrated readiness. Component certificates and individual training records are necessary inputs, but the system must also work across organisational boundaries. The review should include representative task demonstrations, abnormal-condition tests, communications checks and emergency exercises. Any safety-critical failure should be corrected and retested before the affected operating case proceeds.

Gate 5 is the operational acceptance decision. The authorised organisations should review the completed evidence, confirm residual risk and state the permitted operating envelope. The record should identify aircraft configuration, fuel state, location, equipment, operating restrictions, validity and review triggers. It should also confirm that required authority decisions and other permissions have been obtained. A project-level approval does not replace those decisions.

Gate 6 addresses post-implementation assurance. The workbook asks whether monitoring, occurrence reporting and audits are scheduled. That planning question can be answered before implementation. Actual post-implementation closure, however, can occur only after operating evidence has been reviewed. The local system should distinguish approval of the monitoring plan from completion of the later review.

Gate	Principal evidence	Decision outcome
3 Implementation	Controlled procedures, competence records and technical acceptance	Ready for integrated demonstration within an assessed test scope
4 Readiness	Tests, drills, findings and verified corrective actions	Ready for final operational decision
5 Acceptance	Confirmed residual risk, permissions and signed operating conditions	Authorised defined operation, restriction or refusal
6 Assurance	Monitoring plan followed by operational evidence and review	Close, extend, modify or suspend the change

A failed gate should identify what evidence is missing and which activities remain permitted. This avoids both uncontrolled continuation and an unnecessarily vague suspension of all project work. The decision should be communicated to affected teams so that planned activities cannot be mistaken for authorised operations.

Regression rules are equally important. Changes in aircraft type, connector, control software, stand layout, supplier, operating volume or emergency capability should trigger screening and reopen the affected gates. A critical-control impairment during operation should activate the relevant stop or restriction rule immediately, followed by assessment of the wider change implications.

14. Governance and responsibility

Hydrogen aircraft handling crosses several legally and technically distinct responsibilities. The governance model should make each decision owner visible and prevent a shared committee from obscuring individual duties. The allocation below is a proposed functional model for local agreement. Named organisations and authorised individuals must be entered in the controlled change package.

Function	Principal responsibility in the change
Aerodrome operator	Integrate the activity into aerodrome operations, local safety management, stand arrangements and emergency planning
Aircraft operator	Define aircraft operational requirements, ground-handling instructions, crew interfaces and operational acceptance
OEM and design approval holder	Provide the relevant approved or controlled aircraft limitations, technical interface and emergency information
Ground handling organisation	Implement safe task procedures, personnel competence, supervision and handling records
Hydrogen supplier and infrastructure operator	Establish product quality, system suitability, operating limits, maintenance and supply-side isolation
CAMO and maintenance organisation	Manage continuing-airworthiness and maintenance interfaces, safe-state and technical release responsibilities within their scope
RFFS and emergency partners	Validate response capability, command, access, information and joint exercises
Competent authorities	Exercise applicable approval, permitting and oversight functions within their legal remit
AEROTHRIVE project management	Coordinate methodology, traceability, issues, deliverables and review preparation

For each important deliverable, the project should identify who produces it, who accepts it and who must be consulted. Stand segregation, for example, needs engineering input, operational validation, emergency-service review and acceptance through the applicable local route. The party drawing the plan should not be assumed to hold every required decision right.

The Safety Review Board can coordinate cross-organisational review, but its terms of reference should define membership, authority, quorum, escalation and the handling of dissent. The accountable managers retain the decisions assigned to them by their own systems and applicable law. An authority representative's participation in a workshop should not be described as formal approval unless an actual decision has been issued.

Risk-assessment competence should be matched to the question. Operational specialists can validate task feasibility and human factors. Pressure-system, cryogenic, electrical and dispersion questions require suitable technical expertise. National legal applicability may require local regulatory input. An aviation safety facilitator can integrate these contributions without claiming competence to certify every engineering calculation.

The final responsibility record should include handovers and stop-work rights. Any person observing an unsafe condition should be able to raise it and invoke the applicable stop process. Restart authority should be more specific and should depend on the technical and operational cause of the interruption. These arrangements should be understood by contractors as well as permanent staff.

15. Procedures competence and human factors

The procedure set should cover the full handling sequence and its abnormal branches. A master procedure can define common coordination, while configuration-specific instructions address GH_2, LH_2 and aircraft differences. The controlled documents should identify the limits and hold points that matter to the user, including when to stop, who to contact and what evidence permits restart. They should not rely on personnel inferring those decisions from the risk register.

A practical document hierarchy includes the aerodrome and operator manuals, the handler's task procedures, equipment operating and maintenance instructions, emergency plans and concise task checklists. Each should have a defined owner and revision relationship. Where two organisations use different instructions for the same interface, the conflict must be resolved before operation rather than left to the person carrying out the task. [refer to S2, GAP-067 and GAP-085 to GAP-088]

Training should follow the task and the consequence of error. General apron awareness should explain the hazards, restricted areas, alarms and reporting route. Fuelling personnel require practical competence in the actual equipment and sequence. Supervisors need abnormal-operation judgement, coordination and stop/restart control. Maintenance personnel need the relevant pressure, cryogenic or electrical competence and safe-state procedures. RFFS and operations control need the aircraft and installation information required for their response roles.

The competence record should identify the configuration, assessed tasks, limitations, assessor, date and currency requirement. Attendance at a general hydrogen course is not sufficient evidence of task authorisation. Recurrent practice should reflect actual exposure, especially where low operating volume creates long gaps between tasks. Contractor turnover and temporary staff require the same role-specific checks before assignment. [refer to S2, PC-009, PC-010 and associated escalation controls]

Human factors should be tested in the real work setting. The review should examine alarm clarity, language, workload, visibility, access to controls, protective clothing, handover quality and the pressure to recover a delayed turnaround. A checklist should be short enough to use but explicit about the critical checks. Duplicated confirmation steps should have a reason, particularly where independence is claimed.

The local programme should also protect the reporting culture. Personnel need a clear route to report a near miss, equipment anomaly or procedural conflict without waiting for an injury or release. Reports should lead to feedback and, where needed, changes to the task or control. Training can then incorporate observed failure modes rather than repeat a generic awareness package.

Closure evidence should include controlled documents, practical assessments and observed task demonstrations. The assessor should verify that the procedure can be performed with the available team, equipment and stand layout. If a critical step is impractical, the remedy is to change the design or procedure and reassess it, rather than rely on repeated reminders to staff.

16. Emergency validation and operational trials

Emergency validation should test the whole response chain, from recognition of an abnormal condition to a stable safe state and controlled recovery. The scenarios should be selected from the HAZID and risk records and adapted to the actual aircraft, stand and equipment. The purpose is to demonstrate critical functions and identify weaknesses before routine exposure increases. [refer to S2, GAP-005, GAP-011, GAP-018 and GAP-049; S5]

The initial exercise programme should include an unignited leak during connection or transfer, an ignited release with uncertain flame visibility, a hose or coupling failure, vehicle movement while connected and loss of a required detector or ESD function. Where LH_2 is in scope, cryogenic exposure and abnormal boil-off/vent conditions need their own scenarios. Fuel-cell aircraft require coordinated hydrogen and electrical safe-state information.

Aircraft events beyond the stand also matter. An emergency return, go-around, decompression report, diversion or emergency landing can place a hydrogen aircraft at an airport without normal fuelling support. ATC, operations, the aircraft operator and RFFS should agree what information is exchanged and how the aircraft is positioned and supported. A diversion airport may need emergency capability even where it has no planned hydrogen uplift activity.

Exercise objectives should be observable. Examples include correct recognition and communication of the condition, successful operation of the relevant isolation function, preservation of evacuation and response routes, establishment of command and use of current aircraft information. Acceptance criteria should be agreed before the exercise. All safety-critical objectives must pass; an aggregate percentage should not hide a failed essential function.

Trials require their own approved envelope. The project should define the activity, personnel, aircraft or test article, fuel state, inventory, location, restrictions, observers and abort criteria. Preparatory simulation and non-live demonstrations can identify interface problems before live hydrogen activity. Each later stage should proceed only after the preceding evidence has been reviewed and the hazards of that stage have been assessed.

An occurrence-free trial is useful evidence but does not prove a low failure probability. The review should examine whether controls were actually challenged, whether the operating conditions were representative and whether personnel used undocumented workarounds. Findings should be linked back to risk and MoC records, with corrective actions and retest requirements.

A hydrogen aircraft manufacturer asked about the ALBATROS emergency-response outputs. Their technical findings are not part of the eight-source evidence set and no reliance is placed on them for control effectiveness. They remain a proposed input for the RFFS workstream, subject to review of configuration and scenario applicability. The completed local evidence package should record their use if they are subsequently adopted.

17. Safety assurance and monitoring

After implementation, safety assurance should test whether the accepted assumptions remain valid and the controls remain effective. Monitoring needs both event information and evidence of protective-function availability. A low occurrence count can coexist with overdue tests, unreported deviations or repeated compensating measures. The assurance programme should therefore examine the mechanisms that keep risk controlled.

Proposed indicator	Definition and management use
Hydrogen releases	Confirmed releases by source, fuel state, duration and detection route; normalise by a stated exposure measure
Detector and ESD availability	Failed tests, unavailable periods, bypasses and unsuccessful demands on the protective function
Critical procedure deviations	Missed hold points, unauthorised restart or incompatible simultaneous activity
Competence coverage	Required task authorisations current for the actual assigned personnel and configuration
Quality exceptions	Missing batch evidence, rejected fuel, contamination concerns and disposition effectiveness
Emergency readiness	Availability of required response capability and completion of corrective actions from exercises
MoC discipline	Unassessed changes, unresolved conditions, overdue critical actions and expiring temporary measures

The local SMS should set alert levels and review intervals appropriate to the operation. This report does not adopt the earlier draft's proposed numerical thresholds as validated targets. A small initial operation may generate too little data for a stable rate. In that case, each event and control failure should be reviewed in detail, with a clear exposure denominator and recognition of uncertainty.

Pre-operation checks should verify the aircraft/stand match, personnel authorisation, equipment status, critical protective functions and restrictions. Supervisory review should identify defects, deviations and open temporary measures. During introduction, a regular management review should examine the evidence and decide whether to maintain the envelope, tighten restrictions or permit an assessed expansion.

Occurrence reporting should use the applicable organisational and legal routes. Hydrogen should be included in local reporting taxonomy so that relevant events can be recognised and trended; the absence of a dedicated fuel label does not by itself remove reporting obligations. Safety information should reach affected aircraft, ground and infrastructure organisations through defined interfaces. [refer to S2, GAP-016, GAP-040 and GAP-046; R6]

The post-implementation review should compare observed work with the accepted change package. It should examine incidents, near misses, control demand, maintenance, training, procedure use and configuration changes. The decision can be to close the change, continue enhanced monitoring, modify the operation or suspend it. Closure should retain the ongoing controls in the normal management system rather than remove their assurance obligations.

Lessons intended for other BSR airports should describe the configuration and conditions under which they were observed. This allows others to assess transferability and prevents a local success or failure from being generalised beyond the evidence.

18. Implementation sequence and release criteria

The implementation programme should progress by demonstrated capability. The first milestone is a reconciled and locally scoped baseline. It should resolve the 25 unmatched MoC triggers, the inconsistent GAP-012 action, the 58 CHECK decisions and the three unassessed initial rows. It should also establish reliable risk classifications and traceability outputs, while preserving the source record and the reasons for changes.

The second milestone is a validated scenario and control design. This requires the relevant OEM and equipment data, agreed stand and operating assumptions, a documented HAZID and initial-risk reasoning. Bow-ties should have correct causal placement and clearly defined controls. Predicted residual risk should be conditional on the selected package and supported by a plan to verify every critical function.

The third milestone is implementation and integrated demonstration. Procedures, competent personnel, equipment, maintenance and emergency arrangements should match the agreed configuration. Tests and exercises should resolve safety-critical findings and supply the evidence needed to confirm residual risk. Required local permissions and authority decisions should be tracked separately from internal project approval.

Release domain	Minimum evidence	Reason to withhold release
Scope and permissions	Defined operating envelope and applicable decisions obtained	Unknown configuration or unmet mandatory requirement
Risk assessment	All applicable scenarios resolved with supported residual ratings	Unassessed or intolerable residual risk
Critical controls	Implemented, verified and available	Failed, absent or unsupported essential barrier
People and procedures	Competent team using controlled, configuration-specific instructions	Missing authorisation or unresolved procedural conflict
Emergency readiness	Demonstrated response and current aircraft/system information	Failed critical objective or unavailable response capability
Acceptance and assurance	Signed conditions and an active monitoring plan	Unclear decision authority or incomplete evidence basis

The final milestone is controlled operational introduction with a defined review period or exposure. The accepted envelope should identify any limits on passengers, simultaneous activities, aircraft variants, stand use, weather or equipment. Expansion should follow review of both operating experience and the new exposure created by the proposed change.

The project end date in the programme context is not an operational safety deadline. If an evidence item is incomplete, the project can document the result, responsible function and next decision without declaring an unsubstantiated readiness status. A clear handover of remaining work is a legitimate project output; an unsupported go-live conclusion is not.

The decision record should state precisely what may proceed and what remains restricted. It should be accessible to the people planning and performing the operation, and it should identify the event or change that requires renewed review. This makes the report's assessment method usable in day-to-day control.

19. Conclusions and recommended decisions

Phases 1 and 2 established a regulatory and operational baseline for hydrogen aircraft handling. Their lasting contribution is the traceable connection between requirements, implementation gaps and significant changes. Phase 3 extends that connection into scenarios, initial risk classifications, bow-tie controls, MoC actions and evidence gates. The framework is sufficiently developed to organise the next validation programme, while the current records show that operational acceptance remains incomplete.

The v3 portfolio contains 154 gap entries and 83 risk rows. Fourteen initial rows are intolerable under the selected matrix, 66 require mitigation and three have not been assessed. Only GAP-001 has a residual code, and its acceptance label lacks supporting assurance evidence in the record. All 71 MoC actions and all 12 gate questions remain Open. These are the material facts on which the management recommendation rests.

We recommend that the project partners agree the local operating cases and nominate the responsible organisations for each evidence package. GH_2 should remain the primary project case, with LH_2 and fuel-cell/HV interfaces separately identified wherever applicable. Demand scenarios should be used to test peak activity, task repetition, tankering and growth assumptions, while aircraft-specific limits and site engineering remain the basis for actual operating parameters.

The project should reconcile the register before using its summary views for acceptance. The 95 MoC YES entries have 70 direct matching actions, leaving 25 without direct links. MOC-010 refers to a trigger now marked NO. The saved traceability outputs and risk-label logic also need a controlled correction. These issues should be resolved together with the content review so that a reliable spreadsheet does not merely reproduce an unsuitable scenario or control mapping.

The next technical priority is validation of the severe fuelling, passenger, emergency and segregation scenarios and of the controls that support several risks. Each critical barrier needs a defined function, owner, performance standard, verification method and impairment response. Procedures, competence and emergency exercises should demonstrate the actual interfaces between airport, aircraft operator, ground handler, supplier, infrastructure operator and responders.

Operational release should occur only after the relevant gates establish the required permissions, implemented controls, supported residual assessments and authorised acceptance. The post-implementation programme should then test whether those assumptions remain valid and provide a route to restrict, modify or expand the operation.

The intended Phase 3 outcome is a controlled change package that an accountable organisation can examine and maintain: every relevant obligation has a disposition, every material scenario has a justified assessment, every critical control has evidence, and every acceptance decision has a defined scope. This report provides the narrative and reconciliation needed to progress towards that outcome.

20. Appendix A Initial risks requiring priority review

20.1. Intolerable rows in the first part of the register

The table reproduces the current identifiers and initial codes for the first seven of the fourteen intolerable rows. Source descriptions are shortened for readability. The action column shows a direct match in the MOC Register; it does not imply implementation or closure. All listed residual codes are blank.

GAP ID	Source and subject	Code	MoC action
GAP-005	JIG 4 section 2.4 Emergency response procedures	5C	MOC-005
GAP-008	JIG 4 section 4.0 Depot facilities and design	5C	MOC-007
GAP-011	ICAO Annex 14 section 9.6 Ground servicing of aircraft	5C	MOC-009
GAP-017	ICAO Doc 9137 cited section 10.6.2 Aircraft refuelling	4B	MOC-012
GAP-081	GH.OPS.310 Aircraft refuelling and defuelling	4B	MOC-054
GAP-082	AMC1 GH.OPS.310 Fuelling procedures	4B	MOC-055
GAP-083	AMC2 GH.OPS.310 Fuelling interfaces	4B	MOC-056

GAP-005, GAP-008 and GAP-011 should be reviewed together where the emergency scenario and surrounding layout interact. Their 5C classifications express potentially catastrophic consequences under a Remote qualitative probability assumption. The local assessment needs to define the actual event, exposed population and response conditions before that judgement can be confirmed.

GAP-017 and GAP-081 to GAP-083 share the fuelling-release mechanism. The report recommends a consolidated technical assessment of the transfer system, with a separate compliance mapping for each contributing reference. Consolidation should retain the differences between a task procedure, its supervision and the organisational interface obligations.

Priority evidence includes the agreed aircraft and equipment envelope, site layout, transfer sequence, effective detection and isolation, emergency arrangements and demonstrated competence. The control package should explain which barriers reduce release likelihood and which limit the consequences. Evidence from one aircraft/stand configuration should be reused only after checking its applicability to the proposed local case.

The recorded initial class prevents release of the affected operation at that assessed level. It does not prevent controlled design work or appropriately assessed testing intended to develop and verify the risk reduction. The project manager should identify the permitted development activities and the prerequisites for each stage.

20.2. Remaining intolerable rows and unassessed cases

The remaining seven intolerable rows include four without a direct MoC action. This highlights the need to reconcile severity priorities with the action programme. A row can have a high initial rating while its required implementation work is absent from the direct action map.

GAP ID	Source and subject	Code	MoC action
GAP-084	AMC1 GH.OPS.310(b) Responsibilities and supervision	4B	MOC-057
GAP-109	ICAO Doc 10121 section 5.3.7 Fuelling activities	5C	MOC-066
GAP-113	ICAO Doc 10121 Appendix B section 7 Fuel and oil handling	5C	MOC-069
GAP-133	CAT.OP.MPA.195 Passenger interface during fuelling	5C	No direct action
GAP-134	CAT.OP.MPA.200 Wide-cut-fuel applicability question	5C	No direct action
GAP-143	JIG 4 section 10.5 Fuelling procedures	5C	No direct action
GAP-144	JIG 4 section 10.6 Fuelling with passengers	5C	No direct action

GAP-133 and GAP-134 are On Hold in the Risk Assessment sheet and have no preventive or recovery controls entered there. GAP-143 and GAP-144 are In Progress but likewise lack direct MoC actions. The local owner should establish whether a consolidated action already exists outside the workbook and record it, or create the required action with explicit acceptance criteria.

Unassessed initial row	Recorded status	Required disposition
GAP-057	Closed	Confirm administrative scope or complete the missing scenario and assessment
GAP-060	Closed	Confirm administrative scope or complete the missing scenario and assessment
GAP-136	On Hold	Establish relevance of the supplemental-oxygen reference to the handling case or document exclusion

GAP-057 and GAP-060 have no hazard, top event, threat or consequence entered. Their Closed status is therefore not a substitute for a justified screening decision. GAP-136 has a generic compliance scenario but no initial score. These records should remain visible until the responsible reviewer documents a consistent disposition across the gap, risk and action records.

21. Appendix B MoC triggers without direct actions

The groups below contain all 25 GAP IDs marked MoC YES without a matching trigger in the 71-row MOC Register. The grouping is proposed for programme organisation; it does not create consolidated links in the workbook. Each ID still requires an explicit action or a justified many-to-one mapping.

Unmatched GAP IDs	Proposed subject for action allocation
GAP-122, GAP-124, GAP-132	Operator competence, fuel/energy management and self-handling interfaces
GAP-125, GAP-139	Fuel quality verification and fueller loading/quality control
GAP-126, GAP-137	Load control process and hydrogen-specific information
GAP-129	Operator and ground-handler procedure coordination
GAP-131	Portable electronic devices and the actual safety mechanism
GAP-133, GAP-144	Passenger exposure during fuelling
GAP-134	Applicability of the wide-cut-fuel reference and hydrogen scenario
GAP-136	Scope decision on supplemental oxygen
GAP-138	Aircraft fire-extinguisher and emergency interface
GAP-141	Vehicle positioning and stand procedure
GAP-142, GAP-145, GAP-146, GAP-147	Bonding and coexistence with APU, GPU or engine operation
GAP-143	Hydrogen fuelling procedure
GAP-148, GAP-150, GAP-151	GH_2 target envelope, filling protocol and personnel requirements
GAP-153	LH_2 transfer requirements and operating limits
GAP-154	Mobile and stationary fuelling arrangements

The reconciliation should also review MOC-010, which is linked to GAP-012 although that gap is now MoC NO. The 25 missing direct links and this additional action explain why the net difference between 95 YES triggers and 71 actions is 24. These are different measures and should not be interchanged.

All 71 existing actions are Open. Their trigger risk code, mitigation package, owner, due date, residual-risk acceptance and closure-reference fields are blank. A completed mapping therefore resolves traceability only. Implementation, verification and acceptance remain separate tasks.

22. Appendix C Earlier scenario targets reconciled

The following 15 scenarios come from the earlier Word draft. Initial and target codes are retained as proposed workshop inputs. Target classifications are corrected to the v3 matrix. “Amber” means Tolerable with mitigation and “Green” means Acceptable. None of these targets is evidence of achieved or accepted residual risk.

Scenario	Initial	Target	Target class
1 Hydrogen leak during refuelling	5C	4D	Amber
2 Poorly visible hydrogen flame	5C	4D	Amber
3 Overpressure of aircraft hydrogen tanks	5D	4E	Amber
4 GSE collision with hydrogen refueller	4C	3D	Amber
5 Personnel unfamiliarity with hydrogen tasks	4B	3D	Amber
6 RFFS unfamiliarity with hydrogen fires	5C	4D	Amber
7 Lightning affecting hydrogen system	5D	4E	Amber
8 Improper purge or commissioning	5C	4D	Amber
9 Unauthorised persons in safety zone	3C	2D	Green
10 Refuelling hose failure	5C	4D	Amber
11 Nozzle failure during refuelling	4C	3D	Amber
12 Refueller movement while connected	4C	3D	Amber
13 Blocked pressure relief valve	5D	4E	Amber
14 Electrical spark during hydrogen operation	5C	4D	Amber
15 Hydrogen emergency at diversion airport	4C	3D	Amber

The initial codes give seven Intolerable and eight Tolerable with mitigation scenarios. The target codes give fourteen Tolerable with mitigation and one Acceptable. In particular, all 4E and 3D targets remain amber. The sole green target is 2D for unauthorised persons within the safety zone.

The proposed code reductions must be justified against the actual consequences and control evidence. Measures such as training, detection or improved procedures should not automatically reduce severity. Some proposed technical measures in the earlier draft, including pressure-relief arrangements, also require OEM and engineering validation before inclusion in an operating procedure.

23. Appendix E Project references

S1. AEROTHRIVE, WP 1.3 Aircraft Handling, Phase 1–2 report. Supplied file: 251211_BSR Hy Airport - WP 1.3 Aircraft Handling_AEROTHRIVE_clean version_Revision1(3).pdf. Cover dated 4 December 2025; filename dated 11 December 2025. Principal use: methodology on pages 5–22, gap themes on pages 23–28 and recommendations on pages 29–35.

S2. AEROTHRIVE, H_2 Integrated Gap Risk Bowtie MoC Audit workbook v3. Supplied file: AEROTHRIVE_H2_Working_RiskAssessment(3).xlsx. Primary numerical and record baseline. Key ranges are Integrated Gap Register A2:M155; Risk Assessment A2:V84; Bowtie Library A2:L23; Control Library A2:I45; MOC Register A2:N72; Traceability A2:J155; and MOC Gate Checklist A2:G13.

S3. AEROTHRIVE, WP 1.3 Aircraft Ground Handling Preliminary Results, 1 September 2026. Supplied file: AEROTHRIVE_BSR_HyAirport_WP1.3_Preliminary_Results_2026-09-01.pdf. Principal use: portfolio and readiness cross-check on pages 5–14. Authors shown in the source: Tobias Westen and Henrik Baark.

S4. AEROTHRIVE, WP 1.3 Management of Change and Risk Assessment Phase 3 Report, draft dated 23 August 2026. Supplied file: BSR_HyAirport_WP1.3_Phase3_MoC_Risk_Assessment_AEROTHRIVE_DRAFT(1).docx. Principal use: narrative baseline, governance and implementation concepts, and the preliminary 15-scenario set. Its v2 counts and inconsistent target classifications are superseded by the reconciled treatment in this report.

S5. AEROTHRIVE, Regulatory and Safety Framework for Hydrogen Aircraft Handling, BSR HyAirport, Revision 1 proposal dated 17 June 2025. Supplied file: 2025_06_17 CON BSR HyAirport Rev 1.pdf. Principal use: technical scope and Phase 1–4 methodology on pages 2–4.

23.1. Regulatory references and terminology

The references below identify the regulatory framework and institutional context. The controlled local applicability register should retain the relevant edition, amendment, application date and authority interpretation for the actual implementation. The report does not assert acknowledgement of a particular hydrogen standard or completion of a country-specific permit review.

R1. Commission Delegated Regulation (EU) 2025/20, requirements for safe provision of ground handling services and organisations providing them. Relevant references include ORGH.GEN.125, ORGH.GEN.130 and GH.OPS.310.

R2. Commission Implementing Regulation (EU) 2025/23, oversight of ground handling services and organisations. Industry-standard evaluation should be reviewed with the applicable authority framework, including ARGH.OVS.310.

R3. Commission Regulation (EU) No 139/2014, aerodromes, including the applicable change, management-system, emergency-planning and operational provisions.

R4. Commission Regulation (EU) No 965/2012, air operations, including the applicable Part-ORO and Part-CAT requirements and amendments.

R5. Commission Regulation (EU) No 1321/2014, continuing airworthiness, including applicable Part-CAMO and Part-145 interfaces.

R6. Regulation (EU) No 376/2014, occurrence reporting, analysis and follow-up in civil aviation.

Term	Meaning
ALARP	As low as reasonably practicable
GH_2 and LH_2	Gaseous hydrogen and liquid hydrogen
HAZID and MoC	Hazard identification and Management of Change
ESD and GSE	Emergency shutdown and ground support equipment
OEM and HV	Original equipment manufacturer and high voltage
SMS and SRB	Safety management system and Safety Review Board
RFFS and ERP	Rescue and Fire Fighting Services and Emergency Response Plan
AMC and SARPs	Acceptable Means of Compliance and Standards and Recommended Practices