Project Acorn

The UK's First Airside Hydrogen Refuelling and Operational Trial

Project Acorn led by:

easyJet   Bristol Airport   Jacobs

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Project Acorn Technical Report

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Acronyms and Abbreviations

ADR	Agreement Concerning the International Carriage of Dangerous Goods by Road
ANSI	American National Standards Institute
APRR	Average Pressure Ramp Rate
APU	Auxiliary Power Units
ATEX	Atmospheres Explosives
BRS	Bristol Airport
BS EN	British Standard Implementations of English Language Versions of European Standards
CAA	Civil Aviation Authority (UK)
CAeS	Cranfield Aerospace Solutions
CCTV	Closed Circuit Television
CDG	The Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations
cm	Centimetre
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
COMAH	Control of Major Accident Hazards
CSA	Canadian Standards Association
DSEAR	Dangerous Substances and Explosive Atmosphere Regulations
EU	European Union
EV	Electric Vehicle
g	Grams
GB	The United Kingdom of Great Britain and Northern Ireland
kW	Kilowatt
kWh	Kilowatt-hour
LEL	Lower Explosion Limit
LH_2	Liquid Hydrogen
MCP	Manifold Cylinder Pallet
MIE	Minimum Ignition Energy
MJ	Megajoules
MJ_{lhv}	Megajoules Lower Heating Value
mJ	Millijoules
mph	Miles per Hour
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Authority
NWP	Nominal Working Pressure
O_2	Oxygen
PED	Pressure Equipment Directive
PEM	Proton Exchange Membrane
PGS	Publicatiereeks Gevaarlijke Stoffen (*Publication Series Hazardous Substances*)
PPE	Personal Protective Equipment
PRD	Pressure Relief Device
PV	Photovoltaic
RFFS	Rescue and Firefighting Services

GH_2	Gaseous Hydrogen
GSE	Ground Support Equipment
H_2	Hydrogen
H_2O	Water
HBT	Hydrogen Baggage Tractor
HGV	Heavy Goods Vehicle
HIA	Hydrogen in Aviation Alliance
HSE	Health and Safety Executive
IAAPS	Institute of Advanced Automotive Propulsion Systems
ICAO	International Civil Aviation Organization
IEC	International Electrotechnical Commission
ISO	International Organization for Standardisation
kg	Kilograms
kg/hour	Kilograms per Hour

SAE	Society of Automotive Engineers
SMR	Steam Methane Reforming
SSoW	Safe System of Work
TAI	Temporary Airport Instruction
TPE	Transportable Pressure Equipment
TPED	Transportable Pressure Equipment Directive
TR	Technical Report
TÜV SÜD	Technischer Überwachungsverein (*Technical Inspection Association*)
UK	United Kingdom
UN	United Nations
UNE	Spanish Association for Standardisation
US	United States
USD	United States Dollars

1 Executive Summary

Green hydrogen offers enormous potential as a zero-carbon emission fuel and an enabler of aviation's transition towards net zero. Progressing hydrogen fuel from its current stage of research and development to full-scale commercial flight will require many hurdles to be overcome, including the establishment of a robust network of hydrogen-ready airports to service new types of aircraft.

Despite hydrogen being regulated and used safely across different industries for decades, a critical challenge to the current delivery of hydrogen-ready airports is the lack of a comprehensive regulatory framework and operational guidance. Any use of hydrogen at airports in the UK requires navigating complex and fragmented legislation, regulation, codes of practice, standards and industry guidance - since the existing regulatory framework was established long before the emergence of hydrogen as a potential fuel source for aviation.

This lack of regulatory framework, combined with the hope of building confidence and encouraging other airports to work towards becoming hydrogen ready, were the key drivers of *easyJet,* with support from *Bristol Airport, Jacobs* and other leading partners to establish Project Acorn. Formed as a collaborative initiative, the project's aim was to demonstrate safe hydrogen storage, refuelling and operations via the first ever airside trial at a major UK airport – which was successfully achieved in March 2024.

This report shares the knowledge gained from Project Acorn, together with recommendations to enrich hydrogen research, develop industry best practice and standards, as well as providing guidance to airports, airlines, government, and aviation authorities, on required future infrastructure changes and a potential airside hydrogen regulatory framework.

The trial combined airside storage of gaseous hydrogen with refuelling and operation of a hydrogen-powered baggage tug (HBT) to support commercial aircraft turnarounds. While small-scale, the trial demonstrated the potential impact of hydrogen fuel in facilitating airport decarbonisation. Ground Support Equipment (GSE) is often one of the sources of carbon emissions under an airport's direct control and in that context some studies suggest consumption of fossil fuels for GSE contributes up to 13% of airport energy and 15% of carbon emissions.[1]

Project Acorn's successful gaseous hydrogen ground trial also represents the completion of a foundational step towards establishing hydrogen more widely across airport ground operations, on a possible pathway to hydrogen-ready airports as shown in Figure 1. The trial was dubbed Project Acorn, reflecting the potential for this small-scale trial's outcomes to inform the uptake of hydrogen infrastructure across airport operations to support the wider vision for hydrogen-powered flight.

To enable this landmark ground trial, Project Acorn commenced in mid-2023, initially focussing on identifying the relevant safety considerations associated with the properties of hydrogen (Chapter 3), the corresponding safety and regulatory landscape (Chapter 4), and the technologies and equipment necessary to safely facilitate the trial (Chapter 5).

This preliminary work conducted as part of Project Acorn also involved targeted industry and academic engagement, identification of relevant safety and risk considerations, and implementation of mitigation measures for each risk area - culminating in the development of a Safety and Risk Assessment (Chapter 6). This was submitted to the CAA for review and having oversight of the safety case, the CAA deemed mitigations addressed the trial's potential risks sufficiently to enable the demonstration to proceed.

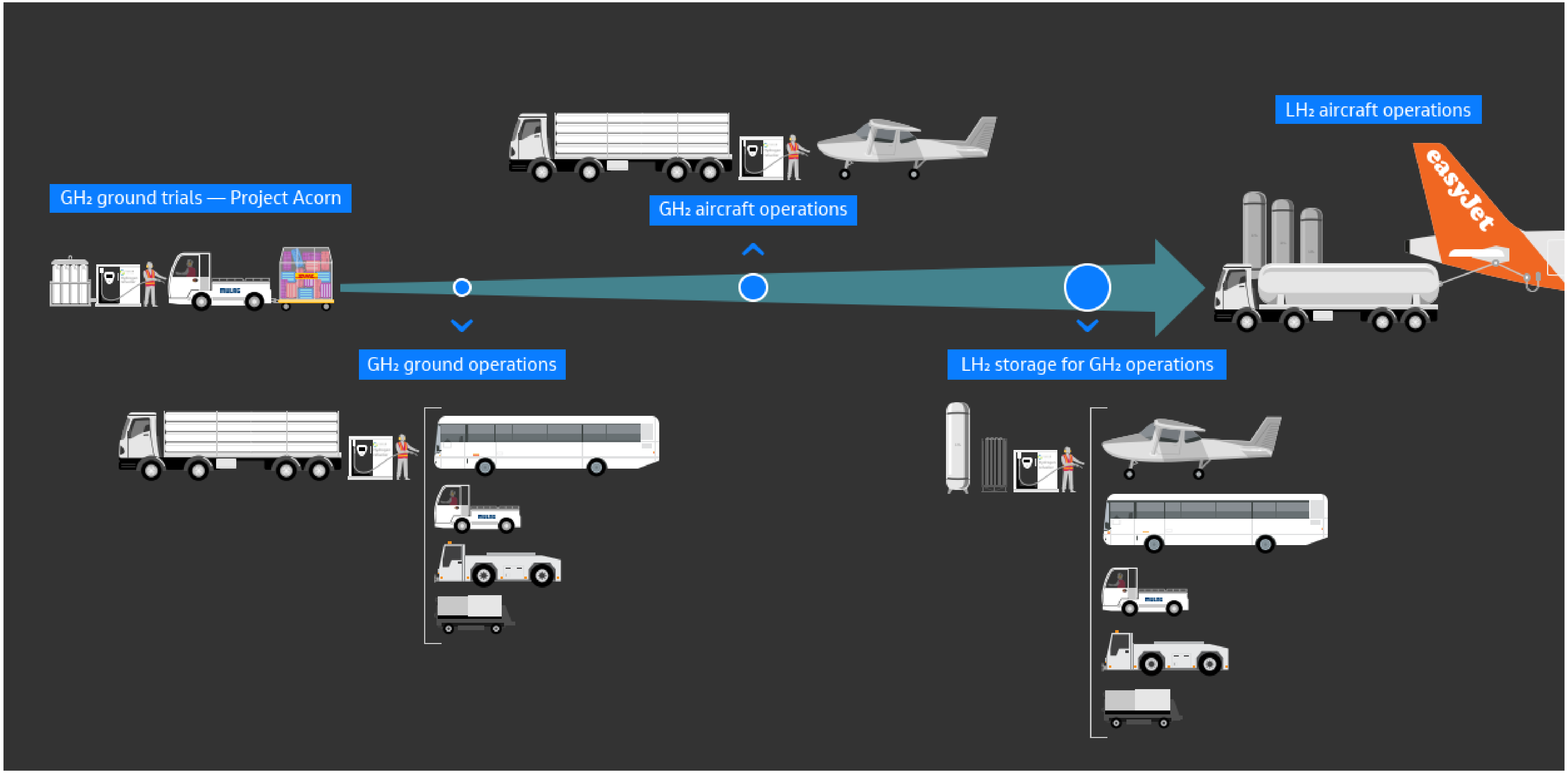


Figure 1: Potential Wider Scale-up of Hydrogen's Role in Decarbonising Aviation

Phase 1 of the trial focused on landside preparation. This phase included testing of key technology and equipment by Cranfield University, landside safety briefings and operational staff and emergency services training at the university's *Centre for Propulsion and Thermal Power Engineering* (CPTPE) (Chapter 7). Phase 2 of the trial included full integration of airside hydrogen storage, refuelling and operations at Bristol Airport with the HBT under load to service easyJet aircraft turnarounds (Chapter 8).

Importantly, over the five days of trial in a live operational environment there were no near misses and zero incidents. The only user system warning issued during the trial related to the HBT's EV battery being low. Feedback obtained from the baggage handlers' experience both in training and during the trial was positive and indicated that the use of the HBT had been effective by enabling them to carry out their shifts as normal (Chapter 9).

In terms of project learning, a great deal of knowledge was obtained across the collaboration partners and the many other industry stakeholders involved in the trial. The data collected from Project Acorn will be analysed by Cranfield University for later publication, providing key input into modelling and forecasting around the use of hydrogen in GSE. This report focuses instead on key learning and recommendations related to development and delivery of the trial, regulatory framework, hydrogen supply and storage, refuelling and operations (Chapter 10).

Project Acorn's collaboration partners hope this report will assist in the development of a standardised set of procedures and processes for conducting hydrogen trials in live environments. To that end, a checklist and summary of the critical steps for future trials has been formulated (Chapter 11). This checklist includes but is not limited to issues related to risk assessments, training and safety provisions for operators.

Project Acorn demonstrated the complex and fragmented landscape of hydrogen safety regulations, codes and standards for hydrogen refuelling, both in the UK and internationally. To enable hydrogen-ready airports, there must be further streamlining and development of an airside hydrogen regulatory framework (Chapter 12). There is no reason to wait until hydrogen aircraft have arrive to lay the foundations for safe hydrogen airport operations.

While widespread decarbonisation of aviation is still many years away, Project Acorn as a small-scale gaseous hydrogen trial has already made a vital contribution towards understanding the safety and risk management necessary to enable hydrogen infrastructure. The knowledge from Project Acorn and the trials that follow will underpin the future safe working procedures necessary for hydrogen-ready airports.

2 Hydrogen's Role in Decarbonising Aviation

Although the global aviation sector accounts for a relatively small share of worldwide energy-related carbon dioxide emissions today (~2.5%), it is a growing industry with demand expected to increase rapidly in the future. [2] While solutions to reduce emissions for other sectors like power or road transport have been identified and now require scale up, aviation remains one of the most technologically challenging areas to decarbonise.[3] Although both the International Civil Aviation Organization (ICAO) and UK Government's Jet Zero Strategy commit to delivering net zero flying by 2050, the industry is still a long way from reaching this goal – in terms of net zero technology, capability and regulatory frameworks.[4] [5]

Aircraft operations contribute to around 95% of aviation emissions so as an aircraft fuel, hydrogen could play a vital role in the decarbonisation of the aviation industry.[6] Unlike JET A-1 kerosene fuel or Sustainable Aviation Fuels (SAFs), hydrogen does not emit carbon dioxide (CO_2) emissions when burned. The Aerospace Technology Institute's (ATI) FlyZero project assessed the feasibility of zero-carbon emission flight and concluded that while more research was needed, there is a viable technical and commercial case for hydrogen fuel in aviation.[7]

In 2020, Airbus announced their ZEROe project and ambition to commence hydrogen-powered aircraft services by 2035, while Rolls Royce and easyJet conducted the world's first run of a modern aero engine on hydrogen in 2022.[8] [9] Similarly, ZeroAvia are building hydrogen-electric powertrains for aircraft and in 2023, they successfully flew the largest hydrogen-electric aircraft in the world.[10]

Hydrogen production via electrolysis (using renewable electricity) provides a potential opportunity for zero carbon flying. While expensive today, green hydrogen production has the potential to be more cost-effective than other aviation fuels. Declining costs for solar photovoltaic (PV) and wind generation mean building electrolysers at locations with excellent renewable resource conditions could become a low-cost supply option for hydrogen.[11] By 2050, it's anticipated the cost of green hydrogen production could reach levels of almost USD 0.65/kg for the best locations in the most optimistic scenario.[12]

To mitigate some of the upfront investment cost of transition, hydrogen could be adopted more widely across airport ground operations. The FlyZero project suggested the potential to use hydrogen fuel for cars, buses, trains, trucks, as well as Ground Support Equipment (GSE).[13] FedEx in collaboration with the US Department of Energy, Plug Power and Charlatte America, pioneered the development of hydrogen fuel cell GSE in 2014 before Albany International Airport began operating hydrogen Fuel Cell Hydrogen Baggage Tractors (HBTs) in 2019.[14] [15] [16] These trials found hydrogen-powered baggage tugs and cargo vehicles could offer greater operational range, less maintenance and quicker refuelling times than pure-battery electric vehicles.

In 2019 the US Airforce Research Laboratory deployed a hydrogen fuel cell U-30 aircraft tow tractor in a first-of-a-kind at the Joint Base Pearl Harbor-Hickam in Honolulu, on behalf of the Hawaii Center for Advanced Transportation Technologies.[17] This was the first demonstration using hydrogen fuel cell equipment on a large Air Force aircraft. Similarly, in 2021 Tees Valley hydrogen transport hub announced its intention to convert GSE at Teeside International Airport to hydrogen as part of Project ZeHyDA.[18]

In 2023, ENGIE Solutions and the Occitanie region's Energy and Climate Agency unveiled HYPORT, Europe's first airside green hydrogen production, storage and distribution station at Toulouse-Blagnac Airport.[19] Groningen Airport Elde followed with the first proof-of-concept for a hydrogen Ground Power Unit (GPU) in late 2023 and announced its intention to become Europe's first hydrogen Valley Airport.[20] Finally, in March 2024 Wellington Airport reported that they were collaborating with Air New Zealand, Toyota and Hiringa Energy to trial hydrogen fuel cells to charge the airport's electric GSE.[21]

2.1 Hydrogen-Ready Aviation

Hydrogen in Aviation Alliance (HIA) and other initiatives like the FlyZero project, highlight a critical need to develop the regulatory landscape, certification frameworks, infrastructure, incentives, skills and safety procedures for future uptake of hydrogen for aircraft and airport operations. As shown in Table 1, HIA's Milestone Delivery Report lists six critical steps for the UK to be the leader in hydrogen aviation globally:

Table 1: HIA's Six Critical Steps for Hydrogen-Ready Aviation

Steps	Description
1	**Hydrogen-ready technology research and development:** HIA recommends that measures are taken to support the transition from research to development, and ultimately industrialisation, of world leading propulsion and flight technologies in the UK.
2	**A hydrogen-ready CAA:** HIA recommends that the Civil Aviation Authority (CAA) is appropriately resourced and funded with the capacity to lead on certification, standard-setting, and new regulation – working in co-ordination with other relevant bodies and the academic community to support a hydrogen-ready future.
3	**Hydrogen-ready airports:** HIA recommends building a well-developed network of hydrogen-ready airports both in the UK and overseas.
4	**Transition fund and incentives:** HIA recommends the government provide the necessary support and incentives needed to get the sector over the hurdle of transition costs and investment in new infrastructure.
5	**Plan to deliver aviation's hydrogen requirements:** Given the significant rise in demand for hydrogen that's expected over the next several decades, HIA recommends scaling up both hydrogen production capacity as well as renewable power, carbon capture and low carbon hydrogen generation to ensure the UK can secure sufficient hydrogen for all sectors that need to decarbonise, including aviation.
6	**A hydrogen-ready skill force:** HIA recommends government and industry work together to equip the UK's workforce with the appropriate skills and ensure industry-readiness to support the transition to this new technology.

Underpinning all these recommendations is a focus on safety as the highest priority. The aviation industry is already governed by stringent safety regulations and comprehensive industry-wide operational frameworks developed over many decades. Notwithstanding, more research and testing opportunities are needed so that lack of operational experience with hydrogen energy systems does not become a barrier to future adoption.[22]

While there are risks to handling hydrogen airside, aviation along with many other industries already manage other hazardous substances safely in day-to-day operations in accordance with national and international requirements. While there is no specific hydrogen legislation in the UK, hydrogen is defined as a 'gas' under the Gas Act 1986 and multiple chapters of safety legislation and regulation currently apply to hydrogen.[23] These include but are not limited to:

- Planning (Hazardous Substances) Act 1990 and Planning (Hazardous Substances) Regulations 2015.
- Dangerous Substances and Explosive Atmosphere Regulations (DSEAR) 2002. DSEAR also gives effect to the two EU directives for controlling explosive atmospheres, together known as ATEX.
- Gas Safety (Management) Regulations (GSMR) 1996.
- Control of Major Accident Hazards Regulations (COMAH) 2015.

- Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2004.
- Alternative Fuels Infrastructure Regulations SI 2017/825.
- Health and Safety at Work etc. Act 1974.

Notably, airside hydrogen projects must comply with these regulations and those that cover airports and aviation specifically. There is, however, no regulatory precedent or framework for airside storage and refuelling with hydrogen.

2.2 Project Acorn Overview

Project Acorn was a collaborative hydrogen initiative led by easyJet with support from Bristol Airport, Jacobs and other leading partners. The project aimed to develop capability and gather data to aid the process of establishing standards and procedures for the safe airside use of hydrogen, which is a key requirement to progress hydrogen uptake in aviation. This was accomplished by demonstrating small-scale airside gaseous hydrogen storage and refuelling of hydrogen-powered GSE to support commercial aircraft turnarounds. The project consisted of a comprehensive risk and safety assessment, equipment training and familiarisation in a controlled landside environment, and an operational trial airside at Bristol Airport (BRS) in March 2024.

As the founder of the HIA and a core member of Hydrogen South West (HSW) - an infrastructure ecosystem that brings the benefits of hydrogen to the southwest of England, easyJet and their Project Acorn partners aim to help inform future hydrogen data and standards in aviation through showcasing the practical application of hydrogen in an operational environment.[24] Project Acorn was designed to support the significant steps still required towards a more sustainable aviation future in the southwest of England and beyond.

In addition to demonstrating the use of hydrogen in airside refuelling, Project Acorn explored the potential for hydrogen to support the transition of GSE away from fossil fuels. GSE is one of the sources of carbon emissions that is often under an airport's direct control. In that context a 2023 study published in the Journal of Air Transport Management cited fossil fuel-powered GSE contributed up to 13% of total airport energy and 15% of total airport carbon emissions.[25]

While battery electric GSE (e-GSE) are well established at some airports, these cannot be easily supported in all airside circumstances at present. Hydrogen-powered GSE offers a potential alternative to electrical GSE that can offer an additional path to accelerate the aviation industry's transition to net zero.[26]

2.3 Aim and Objectives

A regulatory framework for airside refuelling is a critical step to enable vital trials that will pave the way to future hydrogen uptake and broader aviation decarbonisation. As shown in Figure 2, Project Acorn aims to help inform a future UK and international regulatory framework, and in doing so to inspire and assist in the development of further ground trials that pave the way to aircraft trials and ultimately help accelerate the widespread adoption of hydrogen in aviation.

Figure 2: Driver and Aim of Project Acorn

Alongside the overarching driver and aim of the project were several additional objectives, as follows:

- Demonstrate collaboration and the extent of the cross-industry collaboration and a new way of engaging with the UK CAA to achieve net zero aviation and support the hydrogen-transition.
- Share data and insights from trial findings and share recommendations to enrich hydrogen research and develop industry best practice, standards as well as provide guidance to airports, airlines, local authorities, and regulators on required infrastructure changes.
- Build stakeholder confidence through contributing to a potential future airside hydrogen regulatory framework.

These objectives collectively align with the broader aim of advancing sustainable aviation practices and establishing the foundations for hydrogen's future integration into the sector by readying the airport for further trials, the potential permanent deployment of hydrogen-powered GSE and potential longer-term commercial operations of hydrogen-fuelled aircraft.

2.4 Trial Outline

The Project Acorn trial involved two key phases to demonstrate the safe operation of hydrogen-powered GSE, as outlined in Table 2 below. Prior to delivering these two key phases, the Project Acorn team identified all safety and risk considerations associated with the trial and implemented mitigations for each identified risk area. This safety and risk assessment required consultation with industry, academia and regulatory bodies and is further outlined in Chapter 6.

Table 2: The Two Key Phases of Project Acorn

Phase 1	Phase 2
Cranfield University: Landside Training The HBT underwent landside testing at Cranfield University, to train and familiarise operational and emergency services with the HBT, refuelling equipment and associated safety procedures as well as troubleshoot any potential issues.	**Bristol Airport: Airside Trial** The refuelling equipment was sited at a remote stand (Stand 17) where the HBT was refuelled airside at necessary intervals. The HBT was then operated airside under load to service easyJet aircraft turnarounds.

2.5 Industry Collaboration

Project Acorn involved a cross-industry effort involving collaboration between 12 organisations, indicative of the strong co-operation that will be required to accelerate the hydrogen and net zero transition in the future. Each of the organisations involved and their area of participation are shown in Figure 3.

Further details about these industry and academic collaborators, as well as their specific roles and responsibilities within Project Acorn are outlined in Appendix A.

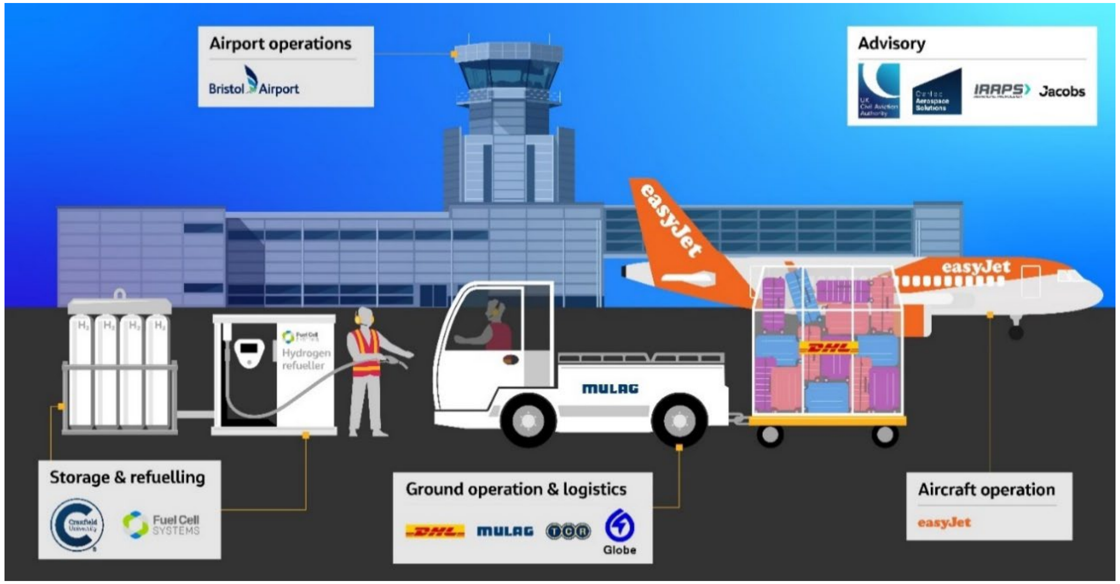


Figure 3: Project Acorn Collaboration Partners and their Area of Involvement

3 Hydrogen Properties

Though hydrogen has recently gained prominence as a potential low carbon energy source, it has already been used safely across a variety of industries for generations.[27]

While many of the unique properties of hydrogen still require specific safety considerations for airside use, significant effort amongst international bodies to date has resulted in the development of a wide range of regulatory responses that cover hydrogen related risks, as detailed in the following Chapter 3.1.

To understand the necessary airside regulation for hydrogen use, the risks associated with its properties must also be understood and mitigated against to reduce the net risk to a level that aligns with existing aviation regulation and operational frameworks, as discussed in Chapter 6.

3.1 Hydrogen Properties and Safety Considerations

All fuels pose risks and hydrogen is no exception. The 'combustion triangle' (Figure 4; left) explains the need for three elements (fuel, ignition, oxygen) to be present for a fire to ignite and burn (combustion). If one or more of these elements is absent combustion cannot occur. Therefore, as with other fuels, mitigation measures should focus on minimising or eliminating scenarios where hydrogen interacts with either oxygen and/or ignition sources.

The 'explosion pentagon' (Figure 4; right) builds on the basic fire triangle concept, to include two additional factors needed to cause an explosion. The mixture of the fuel (hydrogen dispersion) and oxygen must be in a specific concentration range, as well as confinement of this mixture (either partial or complete) which enables pressure to build up to enable a fast-burning flame to become an explosion. Again, mitigation should focus on eliminating elements of the fire triangle and pentagon, in particular hydrogen fuel availability (leakage).

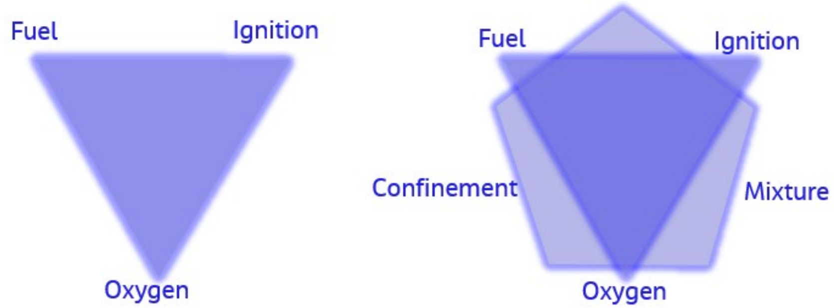


Figure 4: Combustion Triangle and Explosion Pentagon[28]

When compared to conventional fuels like gasoline, propane and diesel, hydrogen requires more stringent controls to enable its safe use and mitigate the risks of fire or explosion.[29]

However, in the event of a leak, hydrogen disperses faster given it is 14 times lighter than air and rises at a rate of 45 miles per hour (mph) or 20 metres per second (m/s). Hydrogen also has a lower radiant heat than conventional gasoline, reducing the risk of injury when detected and managed.

Additional hydrogen specific properties with safety implications include:

- No natural detectable odour, nor can artificial odorants be added due to the potential damage they can cause to a fuel cell's proton-exchange membranes (PEMs).
- Almost invisible when burning during daylight and has low thermal radiation making it difficult for humans and traditional heat or thermal/flame sensors to detect.
- Non-corrosive but can cause embrittlement (induced/assisted cracking) in some metals.

Table 3 summarises the high-level chemical properties, risks and advantages of gaseous hydrogen compared to other typical gaseous fuels (i.e., propane, natural gas) in the context of the fire triangle elements.

Table 3: GH_2 Properties, Risks and Advantages Compared to Other Gaseous Fuels

Properties of GH_2	Associated Risks	Advantages over Other Gaseous Fuels
Lighter than air	Propensity to leak which may lead to ignition and/or explosion.	Rises and disperses rapidly. Fire consumes itself faster than other fuels.
Very low ignition energy and fast detonation	Propensity to ignite and/or explode.	Higher oxygen requirement before risk of explosion.
Higher flame temperature and wide flammability	Propensity to ignite and/or explode, when mixed with oxygen.	Fire consumes itself faster than other fuels.

As shown above in Table 3, hydrogen's properties mean that the main risks associated with this fuel include propensity to leak, propensity to ignite and propensity to explode. However, hydrogen also has advantages over other similar fuels, which are outlined in greater detail in Chapters 3.1.1-3.1.3.

3.1.1 Propensity to Leak

A key risk given hydrogen's small molecular size and gas permeation properties, is its propensity to leak and hydrogen movement can cause friction (and heat) which could also cause ignition. In outdoor unconfined spaces, hydrogen leaks are less of a concern given hydrogen dissipates quickly. While hydrogen is non-toxic and non-poisonous, any accumulation in certain concentrations (particularly in confined spaces), can lead to potential asphyxiation or flammability. To mitigate these risks, technological solutions involving leak prevention (through equipment and component design), detection and ventilation systems are essential. These solutions include fixed or portable hydrogen detectors, thermal/flame detectors and audio monitors to detect the high-pitch sound of a gas leak - all of which can be linked to emergency alarm systems.

3.1.2 Propensity to Ignite

Hydrogen's propensity to ignite is dependent on two of its key characteristics - Minimum Ignition Energy (MIE) and flammability range.[30]

The MIE refers to the minimum amount of energy required to ignite a fuel-air mixture without the presence of an external flame or spark. While the MIE varies between fuels and at different temperatures, the typical MIE of a hydrogen–air mixture is approximately 0.02 mJ, which is lower than other comparable fuels (gaseous) – shown in Figure 5.

Hydrogen's MIE is one order of magnitude lower than that of most hydrocarbon fuels MIE, which means it can ignite easily even with minimal energy input. As shown in Figure 5, an ignition source with the energy of approximately 0.02 mJ could ignite hydrogen in air if the ratio of hydrogen to air met a specific concentration (vapour) threshold. Ignition sources could be thermal (open flame, smoking, hot surfaces, vehicle exhaust or chemical reactions), electrical (electric discharge from nearby equipment or static electricity), or mechanical (friction, impact or metal fracture).

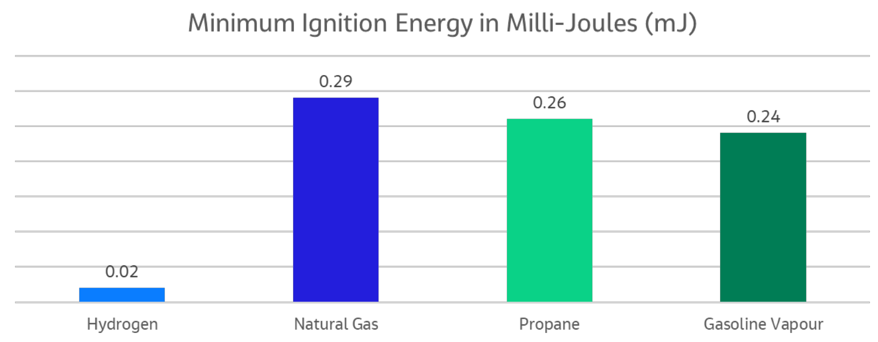


Figure 5: Minimum Ignition Energy (mJ) for Hydrogen Compared to Other Fuels[31]

Flammability range, the second characteristic influencing the propensity to ignite, represents the concentration of a fuel in the air where combustion can occur. Hydrogen's flammability range is between 4% and 75%, which is very wide compared to other fuels, as shown in Figure 6. This means hydrogen can burn over a broad range of concentrations. However, at low concentrations of hydrogen in air, the energy required to initiate combustion is comparable to other gaseous fuels.

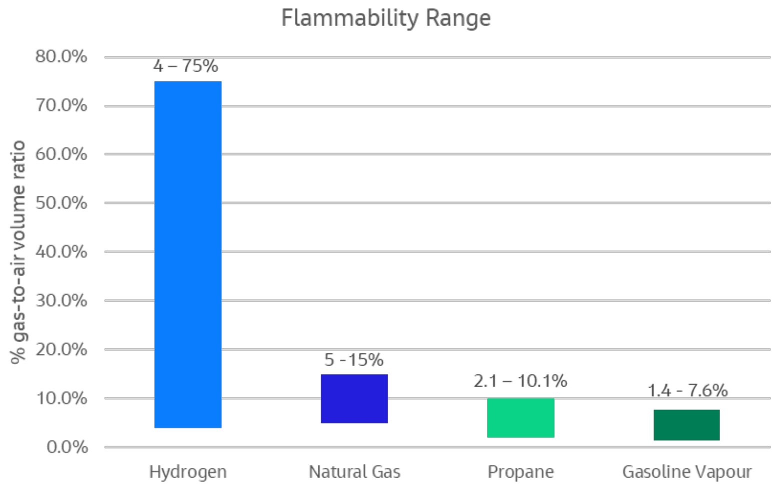


Figure 6: Flammability Range of Hydrogen Compared to Other Gaseous Fuels[32]

By contrast, kerosene (which forms the basis of most jet fuels) has a higher MIE than hydrogen. This means more energy is required to initiate combustion. According to a 2004 Aviation Fuels Technical Review, kerosene-type jet fuels lower and upper flammability limits are 0.6% - 4.7% vapour in the air.[33]

While wide-cut jet fuels (mixtures of gasoline and kerosene), are 1.3% to 8% - noting kerosene's flash point is much higher than hydrogen (the temperature at which liquid begins to give off vapours) at between 37°C - 65°C.

Given these characteristics, hydrogen fires generally burn themselves out relatively quickly and in an upwards direction. Hydrogen burns with an invisible flame, has a high flame temperature and low thermal radiation (lower than natural gas).[34] This means even in proximity to a flame, the presence of a hydrogen fire flame may not be felt until you are very close to it.[35] Since hydrogen is also lighter than air, the gas is likely to diffuse upwards quickly if unobstructed.[36] These factors mean that while hydrogen fire and burns can still lead to serious or potentially fatal consequences, the risk of secondary fires is generally lower than other hydrocarbon fuels.[37]

These risks can generally be mitigated through the positioning of hydrogen storage. For instance, placing hydrogen fuel containers either at the top of a hydrogen-powered vehicle, or at the rear, significantly reduces the risk of passenger injury. However, as hydrogen also burns with an almost invisible flame in daylight, this key safety risk needs to be mitigated through appropriately designated ATEX zones (see Table 4 and Chapter 5.2.2.) and there are visual cues like thermal waves or combustible probes that can be utilised to signal the presence and location of a hydrogen flame or fire.

3.1.3 Propensity to Explode

Hydrogen explosions are uncommon. As illustrated by the 'explosion pentagon' (Figure 4; right) explosions would only typically occur because of a catastrophic crash, combined with a ventilation failure, inadequate fire management measures and/or lack of safety training. For example, the incorrect use of water to extinguish liquid hydrogen (cryogenic) fires could form an ice layer over the tank causing pressure build-up, eventually leading to an explosion. While the release of large volumes of liquid hydrogen causes air to cool rapidly, condensing to solid air enriched with oxygen, which can eventually lead to explosion or fire – though both are rare. The risk of explosions can be mitigated against through safe storage and handling, detection equipment, monitoring and ATEX zoning. The most effective way to enforce these mitigations is via regulation, safety standards and codes of practice.

4 Safety and Regulatory Landscape

4.1 Hydrogen Safety Regulations

There is currently no comprehensive regulatory framework for hydrogen production, transportation and storage in the UK. Nor is there a specific regulatory framework designed for hydrogen in aviation. Any party undertaking a hydrogen project in England, such as Project Acorn, currently requires consideration of fragmented legislation and regulation since the existing rules and policies were enacted before the emergence of hydrogen as a realistic fuel source.[38]

Notwithstanding this, hydrogen has been regulated and safely handled nationally and internationally for decades. 2021 marked the 40th anniversary of the STS-1 Space Shuttle when liquid hydrogen was first successfully used as a rocket propellant on a crewed spacecraft.[39] Hydrogen is regularly handled and processed in the UK in many sectors, such as petroleum refining, glass purification, semi-conductor manufacturing, fertiliser production and as a coolant in powerplant generators.

The following Chapters 4.1.1-4.1.3 outline relevant and general UK hydrogen safety regulations, codes of practice, and standards (RCS), as well as guidelines. Although originally developed for other sectors, they remain relevant to Project Acorn and span applications such as storage, transportation, and the use of hydrogen. Where regulations or codes for a specific hydrogen process were not located, other standards and guidelines were identified and referenced according to the hierarchy illustrated in Figure 7.

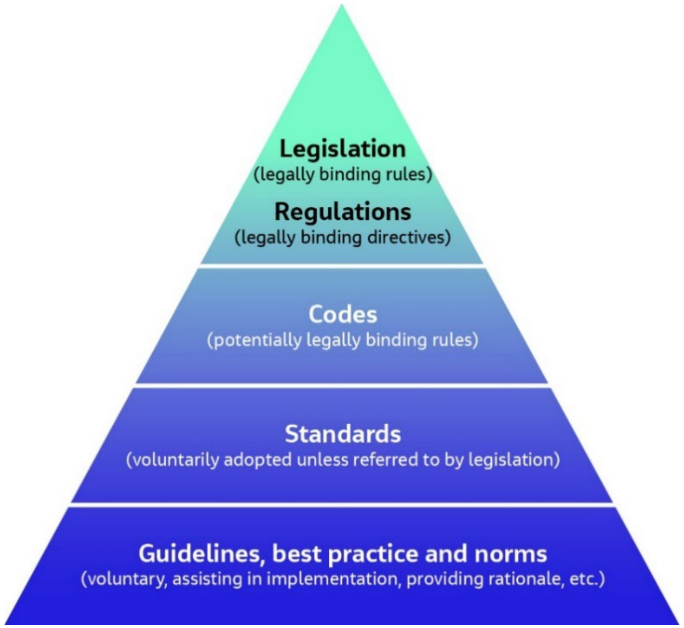


Figure 7: Hierarchy of the Legislative and Regulatory Structure

4.1.1 Hydrogen Regulations, Codes, Standards and Guidelines

A literature review was undertaken to identify regulations, codes of practice, standards, and guidelines for the safe handling of hydrogen in the context of Project Acorn. The results of the literature review are synthesised in Table 4 according to the hierarchy of the legislative and regulatory structure and areas of hydrogen application, as follows: hydrogen fuel quality; hydrogen transport; refuelling; fuel cell vehicle; storage, equipment, or systems; and fire and explosion (prevention).

A more detailed breakdown of the results is also provided in Appendix B, which further categorises the literature identified as follows: compressed gaseous hydrogen; liquid hydrogen; area control; environment; type of vehicle; safety measures and equipment use.

Table 4: Overview of Hydrogen Regulations, Standards and Guidelines from High-Level Literature Review in the Context of Project Acorn

	Fuel Quality	Transport	Fuelling	Fuel Cell Vehicle	Storage, Equipment or Systems	Fire and Explosion
Regulations	Gas Act 1986	ADR (European Agreement Concerning the International Carriage of Dangerous Goods by Road	Alternative Fuels Infrastructure Regulations 2017 (UK)	UN Regulation No 134 – (HFCV) (2019/795)	Pressure Equipment (Safety) Regulations	ATEX 137 (ATEX Workplace Directive)
		Transportable Pressure Equipment Directive 2010/35/EU (TPED)		Implementing Regulation (EU) 2021/535	Pressure Systems Safety Regulations (PSSR)	ATEX 114 (ATEX Equipment Directive)
		Dangerous Goods Directive 2008/68/EC			The Simple Pressure Vessels (Safety) Regulations	DSEAR (The Dangerous Substances and Explosive Atmospheres Regulations)
		CDG 2009 Regulations / CDG 2020 Regulations (EU Exit)			Pressure Equipment Directive (PED) 2014/68/EU	COMAH (Control of Major Accident Hazards)
					Regulation (EC) No 1907/2006 Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)	The Planning (Hazardous Substances) Regulations 2015
Codes of Practice						2021 International Fire Code (IFC)
						NFPA 2
						NFPA 55
Standards	ISO 14687	PGS 35 Guidelines	SAE J2601	ANSI/CSA CHMC 1	BS EN 17533	ISO/IEC 80079
	SAE J2719	ISO 11114-4	SAE J2799	CSA/ANSI CHMC 2	BS EN 17339	IEC 60079
	BS EN 17124		BS EN 17127	ISO 11114-1	EN 60079-29-1	BS EN 1127
	TÜV SÜD CMS 77		ISO 17268		BS EN ISO 10961	ISO/TR 15916
	TÜV SÜD CMS 70		ISO 19885			BS EN IEC 60079

	Fuel Quality	Transport	Fuelling	Fuel Cell Vehicle	Storage, Equipment or Systems	Fire and Explosion
			ISO 19880	UNE EN 50271		NASA NSS1740.16
			SAE J2600			EN ISO 11999
				BS EN 13445		
				CSA/ANSI HGV 2		
				BS EN ISO 21009		
				ISO 19881		
				IEC 62282		
Key:						
	Hydrogen Specific		**General**			

As shown in the more detailed breakdown in Appendix B, the literature identified largely focused on the use of gaseous hydrogen in a road environment, either for Light Goods Vehicles (LGVs) or Heavy Goods Vehicles (HGVs). While two of the standards were applicable to an airport environment and aircraft turnaround operations, none were specifically published for hydrogen in the context of the aviation industry.

Additionally, many of the standards relevant to hydrogen refuelling focused on stationary fuelling stations, with little information specific to mobile refuelling applications, except for NFPA-2, which gave safety measures and location restrictions. Whilst the dispensing procedures were similar for both mobile and stationary refuelling, there are inherently different risks associated with each.

This analysis is reinforced by the *2023 Zero Emission Flight Instructure – Standards Action Plan*, which made the following observations – of which the refuelling operation standards needs are particularly relevant to Project Acorn, as shown in Table 5.[40]

Table 5: Standard Needs Identified Relevant to Project Acorn, taken from Zero Emission Flight Infrastructure – Standards Action Plan

Refuelling operations standard needs	Hydrogen infrastructure standards needs
▪ Fire, rescue, and emergency response ▪ Safety monitoring systems ▪ Billing and metering ▪ Safety zoning in an airport environment	▪ Standardisation of refuelling nozzles ▪ Storage of hydrogen in an airport environment ▪ Data protocols ▪ Planning procedure for hydrogen storage and infrastructure

Refuelling operations standard needs	Hydrogen infrastructure standards needs
▪ Building changes ▪ PPE ▪ Training/guidance for ground handling ▪ Training for non-fuel handlers ▪ Quality measurement processes ▪ Minimum standards of service/maintenance of equipment ▪ Maintenance procedures for hydrogen aircraft ▪ Remote aircraft refuelling ▪ Liability during refuelling operations	▪ Metering technologies and standards ▪ Communication protocol for refuelling ▪ Fuel unloading at the airport ▪ Fuel quality and testing ▪ Defueling equipment ▪ Minimum airport system requirements for diversions

4.1.2 Hazardous Fuel & Fuel Cell Regulation

General safety regulations exist for hazardous fuels, land vehicles and fuel infrastructure. In terms of fuels, existing regulations can and should be enforced to protect both workers and equipment from any risks (e.g., fires, explosions, or the release of dangerous substances). These can be seen in Table 6.

In terms of land vehicles powered by hydrogen fuel cells, international and European technical regulations exist for a combination of compressed gaseous and liquid hydrogen, which are shown in Table 7. The regulatory bodies in the UK are outlined in Table 8.

Finally, the *Alternative Fuels Infrastructure Regulations (AFIR) 2017* requires adherence to ISO 17268 Gaseous Hydrogen Land Vehicle Refuelling Connection Devices. While this regulation only applies to publicly accessible stationary hydrogen vehicle refuelling points in the UK, it has been detailed for completeness in Table 4 and Appendix B.

Table 6: High-Level Summary for General Safety Regulation for Hazardous Fuels

Application	Regulation	Region	Description	Summary of Requirements for Compliance
Explosive Atmospheres	Atmospheres Explosives (ATEX)	European	ATEX is the name given to the two European Directives for controlling explosive atmospheres: 1) Directive 99/92/EC (ATEX 137) on health and safety of workers, 2) Directive 2014/34/EU (ATEX 114) on equipment and protective systems for use in explosive atmospheres.	1. Carry out a risk assessment identifying fire and explosion hazards, classify places of risk, implement risk mitigation measures, communicate them with workers, and draw an explosion protection document. 2. Manufacturers must carry out a safety and conformity assessment and provide technical documentation as well as safety instructions to obtain CE marking. Devices and systems must be controlled by national notification bodies.

Application	Regulation	Region	Description	Summary of Requirements for Compliance
	Dangerous Substances and explosive Atmospheres Regulations (DSEAR)	UK	DSEAR regulations place duties on employers to eliminate or control all the risks from explosive atmospheres in the workplace. Regulation 7 and 11 of DSEAR are the interpretation and implementation of the EU directives ATEX in the UK.	1. Carry out a risk assessment and implement risk mitigation measures (e.g., elimination, reduction, compartmentalisation, etc.) 2. Undertake a Hazardous Area Classification based on the likelihood of an explosive atmosphere occurring in different areas.
	Control of Major Accident Hazards Regulations 2015 (COMAH)	UK	This regulation provides requirements to prevent major accidents involving dangerous substances and minimise consequences to the environment and people. It applies to site storing and handling sufficient hazardous substances.	Based on the weight of dangerous substances handled: 1. Lower tier: 5 tonnes - establishments must consider the potential for a major accident and describe the approach of controlling the risks in a major accident prevention policy. 2. Upper tier: 50 tonnes - establishments must prepare a safety report and send it to the Competent Authority as part of their demonstration that all measures necessary have been taken to prevent major accidents. 3. For an airport storing kerosene and hydrogen, aggregation rules apply to the combined storage to determine whether applicable limits have been exceeded.
Hydrogen Transport	European Agreement Concerning the International Carriage of Dangerous Goods by Road 2017 (ADR)	European	Requirements for the construction, testing and use of Transportable Pressure Equipment (TPE) derive from ADR and the Regulations concerning the International Carriage of Dangerous Goods by Rail (RID). RID is not covered in this report since not applicable to Project Acorn. In the EU, RID and ADR are implemented via the Inland Transport of Dangerous Goods Directive 2008/68/EC. ADR provides a classification system for categorising dangerous goods based on their inherent hazards. The ADR agreement allows dangerous goods travelling by road through more than one country to be exempt from the domestic	1. Classification of Dangerous Goods. 2. Packaging and Tank Provisions. 3. Consignment procedures, including documentation and vehicle marking. 4. Construction and testing of packaging, Intermediate Bulk Containers (IBC), large packaging and tanks. 5. Carriage, loading, unloading and handling. 6. Vehicle crews, equipment, operation and documentation (including driver training). 7. Construction and approval of vehicles. 8. Many duty holders are required to have a Dangerous Goods Safety Adviser (DGSA) who should have the training and knowledge to deal with the matter.

Application	Regulation	Region	Description	Summary of Requirements for Compliance
			legislation in force in those countries, as long as the requirements of ADR are met in full.	ADR contains no provisions for enforcement, and therefore, if a vehicle travelling under ADR does not comply in full, the vehicle becomes subject to all domestic requirements. As such, any enforcement action would be framed in terms of the relevant domestic regulations.
	Transportable Pressure Equipment Directive 2010/35/EU (TPED)	European	TPED is a European Directive that applies within the European Economic Area (EEA) to manufacturers, authorised representatives, importers, distributors, operators and owners of certain types of transportable pressure equipment used for the transport of dangerous goods by road, rail and inland waterway.	The TPE directive sets out the responsibilities of various parties and requires that, before being placed on the market, TPE is conformity-assessed by an EU-notified body and affixed with a ‘Pi’ conformity marking. The Directive defines three categories of pressure equipment based on pressure volume in bar litres and, hence its stored energy. Assessment and conformity procedures are different for each category, ranging from occasional auditing of test procedures for the lowest (category I) hazard up to full ISO 9001 quality management and/or notified body type examination for category 3 equipment.
	Dangerous Goods Directive	European	This Directive establishes a common regime for all aspects of the inland transport of dangerous goods by road, rail, and inland waterway. This Directive enforces ADR.	See ADR for compliance requirements.
	The Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2009 (CDG)	UK	CDG Regs implement the requirements of ADR. It sets the legal framework in Great Britain (GB), as ADR itself has no provision for enforcement. Intended to remove technical barriers to trade within the EU for certain types of TPE and is linked to the ADR. It achieves this by ensuring that all relevant products entering the marketplace meet specified Design & Manufacturing & Testing requirements.	CDG Regs cross-refer almost totally to ADR, and it is ADR that contains the detailed requirements. The regulations do allow certain exemptions that arise from the way the EU Dangerous Goods Directive is worded, and the UK has several derogations from that directive.
	Carriage of Dangerous Goods and Use of	UK	In 2020, the CGD “2009 Regulations” were updated with the “2020 Regulations”. These maintained the dangerous goods regulatory	The 2020 regulations provided for the continued recognition of TPE approved by a notified body established in the EU or Northern Ireland. The 2020 regulations also established an alternative process to

Application	Regulation	Region	Description	Summary of Requirements for Compliance
	Transportable Pressure Equipment (Amendment) (EU Exit) Regulations 2020 (the "2020 regulations")		framework in GB but made necessary amendments to reflect the UK's departure from the EU. Entities based in GB that had been EU-notified bodies were appointed by the GB competent authority as appointed bodies.	allow TPE to be assessed by a GB-appointed body and marked with a 'Rho' conformity marking.
Hydrogen Storage	Pressure Equipment (Safety) Regulations 2016	UK	This regulation applies to the design, manufacture and conformity assessment of stationary pressure equipment with a maximum allowable pressure greater than 0.5 bar.	Manufacturers must classify the high-pressure vessels and perform a conformity assessment, which involves design examination, material certification, and final product inspection.
	The Pressure System Safety Regulations (PSSR) 2000	UK	This regulation provides requirements for pressure systems for use at work to minimise risks of injury from the hazard of stored energy in case of a system failure. They cover the design, construction and testing requirements of such a system and its components.	Employers and operators of high-pressure vessels should prepare a Written Schemes of Examination (WSE), complete a thorough examination of the pressure vessels by competent examiners at a pre-determined frequency and report the examination findings to the relevant authorities.
	The Simple Pressure Vessels (Safety) Regulations	UK	This regulation sets out 'essential requirements' (for example, for safety), written in general terms, which must be met before products are placed on the market in the UK.	Standards fill in the detail and are the main way for businesses to meet the 'essential requirements'. The Regulations also say how manufacturers are to show that products meet the 'essential requirements'. Products meeting the requirements are to be appropriately marked and carry the UKCA marking which should mean that they can be supplied in the UK, provided they are safe.
	Pressure Equipment Directive (PED) 2014/68/EU	European	This regulation applies to the design, manufacture and conformity assessment of stationary pressure equipment with a maximum allowable pressure greater than 0.5 bar.	Under the Directive, pressure equipment must be safe, meet essential safety requirements covering design, manufacture and testing, satisfy appropriate conformity assessment procedures and carry the CE marking and other required information.

Table 7: Hydrogen Fuel Cell Vehicle Regulations

	Region of applicability	Description	Compressed Gaseous Hydrogen	Liquid Hydrogen
UN Regulation No. 134	Worldwide	Lists the legal safety requirements for hydrogen vehicles. It covers different components of the vehicle such as hydrogen containers, PRDs, automatic shut-off valves, and valves, and it partly covers refuelling connections, receptacles, and sensors for hydrogen systems.	✓	
Regulation (EU) 2021/535	European	Provides safety-related regulation on vehicles of category M (cars, buses), N (heavy goods vehicles) and O (trailers and semi-trailers). Annex XIV focuses on H_2-powered vehicles.	✓	✓

Table 8: UK Regulatory Bodies and their Responsibilities Regarding Different Hydrogen Activities

Regulatory Body	Role
Local Authority / Town and Country Planning Authority	▪ Signs off local decisions ▪ Undertakes the role of a hazardous storage authority ▪ Carries out Environmental Impact Assessments ▪ Authority regarding land use
Health & Safety Executive	▪ Provider of national regulations ▪ Regulates local authority decisions. ▪ Certifies drivers training
UK Vehicle Certification Agency	▪ Certifies hydrogen transport vehicles

4.1.3 UK Regulatory Training Requirements

As identified in Table 6 and defined by the *UK's Health and Safety Executive (HSE),* DSEAR are goal-setting regulations which set minimum requirements for the protection of workers from fire and explosion risks related to dangerous substances and potentially explosive atmospheres and from gases under pressure and substances corrosive to metals - which require employers to control the risks to the safety of employees and others from these hazards.[41] DSEAR are supported by an Approved Codes of Practice (ACOP) that provides practical advice on how to comply with them.

These dangerous substances can be found in nearly all workplaces and include things such as solvents, paints, varnishes, and flammable gases, such as liquid petroleum gas, dust, and pressurised gases. HSE states that DSEAR employers must: [42]

1. Find out what dangerous substances are in their workplace and what the risks are.
2. Put control measures in place to either remove those risks or, where this is not possible, control them.
3. Put controls in place to reduce the effects of any incidents involving dangerous substances.
4. Prepare plans and procedures to deal with accidents, incidents and emergencies involving dangerous substances.
5. Make sure employees are properly informed about and trained to control or deal with the risks of the dangerous substances.
6. Identify and classify areas of the workplace where explosive atmospheres may occur and avoid ignition sources (from unprotected equipment, for example) in those areas.

These requirements were integral to the safety assessment undertaken prior to Project Acorn (see Chapter 6). In terms of requirement 5 above, Table 9 provides a high-level summary of the training requirements for different airside roles aligned to DSEAR for the purposes of Project Acorn. They encompass the intricacies of hydrogen-fuelled systems, safety protocols, emergency response procedures, and the unique considerations associated with hydrogen storage.

Table 9: Summary of General DSEAR Training Requirements for Roles Working Relevant to Project Acorn.

Role	Training Requirements
Hydrogen-powered GSE Driver	Training for potential incidents they may encounter in a moving vehicle environment, including the risk of crush injuries and fatalities, as well as the potential for explosion and fire incidents.
Mobile Refueller Operators	Training on essential safety elements, including efficient and safe use of dispensers and filling of vehicles with hydrogen.
Maintenance Staff and Operators	Training in correct manual handling techniques, correct use of PPE, awareness of protective structures around equipment to prevent collisions during refuelling and the installation and use of leak testing equipment on the unit. Operatives should be trained in responding to wearable hydrogen gas detectors, ensuring an enhanced level of safety and preparedness for potential incidents.
Fire Departments	Fire departments dealing with hydrogen-related incidents require comprehensive training to ensure they are well informed about key safety features of all vehicles and infrastructure. This training is crucial where traditional firefighting methods involving water are not suitable. Moreover, fire department personnel need to be equipped with anti-static (EN ISO 11999) and flame-retardant PPE (personal protective equipment) to enhance safety during response and mitigate the risk of injuries.

5 Hydrogen Technology and Equipment

Project Acorn engaged with various technologies and equipment in the delivery of the trial. The technology utilised is described in the following chapters according to hydrogen lifecycle stages: landside (production and distribution) and airside (storage, refuelling and end use) as shown in Figure 8. All relevant equipment was compliant with ATEX and rated appropriately, as discussed in the following Chapters 5.1-5.2.[43]

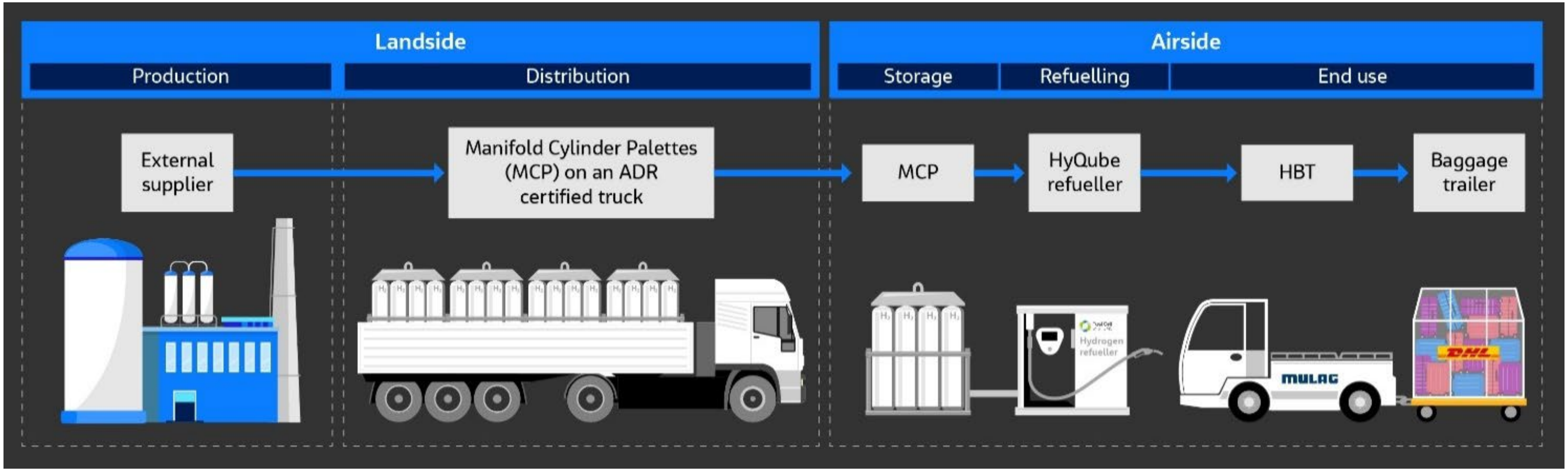


Figure 8: Landside and Airside Hydrogen Lifecycle Stages Relevant to Project Acorn

5.1 Landside Lifecycle Stages

5.1.1 Production

The gaseous hydrogen was produced, stored and transported to BRS by an external supplier according to the specifications shown in Table 10. The gaseous hydrogen was stored in pressurised gas cylinders at 99.999% purity. The total amount of hydrogen required for Project Acorn (27 – 30kg) was stored for distribution at a pressure of 175 bar within three Manifold Cylinder Pallets (MCPs), as discussed in Chapter 5.1.2 and shown in Figure 9.

The gaseous hydrogen cylinders were certified in accordance with *BS EN ISO 10961 Gas cylinders. Cylinder bundles. Design, manufacture, testing and inspection*. This standard specifies the requirements for design, manufacture, identification and testing of Multiple-Element Gas Containers (MEGCs) containing cylinders, tubes or bundles of cylinders.

The MCPs also conformed with the TPED Directive and were Type III classified – meaning that the vessels comprised a fully wrapped composite cylinder with a metal liner that serves as the hydrogen permeation barrier. This metal liner was made of aluminium (Al), which mitigates against embrittlement and contributes >5% to the mechanical resistance.[44]

Table 10: MCP Hydrogen Specification

Specification	Value
Hydrogen Purity	99.999%
Nominal Hydrogen Pressure (at 15°C)	175 bar
MCP Hydrogen Mass	9 -10 kg
MCP Quantity	3
Total Hydrogen Mass	27 - 30 kg

5.1.2 Distribution

The MCPs were transported from the gaseous hydrogen supplier to BRS on a flatbed truck certified under the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR). This certification enabled the transportation of the hydrogen on public roads, if driven by a Certificate of Professional Competence (CPC) certified driver – which the gaseous hydrogen supplier provided as part of its routine operations.

Figure 9: Three MCPs each storing 9 – 10kg of Hydrogen

5.2 Airside Lifecycle Stages

5.2.1 Storage

The hydrogen was stored in three MCPs at BRS in a designated area on a remote stand. Each MCP stored 9 - 10kg of hydrogen as far from aircraft and buildings as reasonably practicable as shown in Figure 10, and further discussed in Chapter 6 (Safety and Risk Assessment).

Figure 10: MCPs Stored Airside at BRS Remote Stand 17

5.2.2 Refuelling

Gaseous hydrogen refuelling of the HBT was undertaken using Fuel Cell Systems' HyQube 350 refueller (HyQube 350) as shown in Figure 11. The HyQube 350 is a modular, scalable and re-deployable hydrogen refuelling system, which provides high energy efficiency and a compact design for space optimisation at required refuelling locations – highly suitable for BRS's airfield.

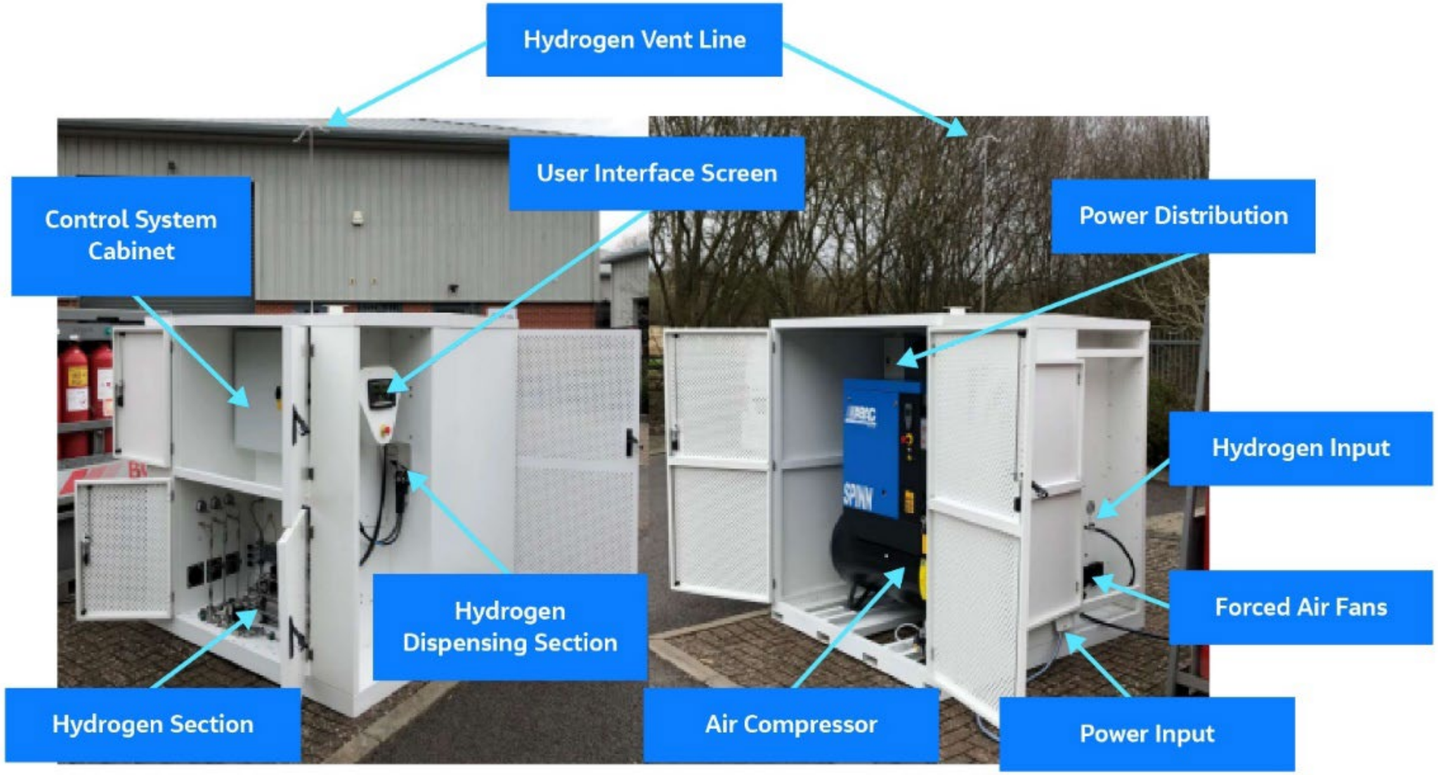


Figure 11: Fuel Cell Systems HyQube 350 (Refueller) [45]

The gaseous hydrogen MCPs were connected to the HyQube 350 via an input hose, and when the cylinder outlet valves are opened, hydrogen could flow from an MCP into the refueller. The HyQube itself has multiple filters in the hydrogen line which eliminates any solid impurities, further increasing the hydrogen purity. A three-phase electrical connection was required for the HyQube operation, which was identified specifically for the trial as part of the safety assessment, outlined in Chapter Safety and Risk Assessment.

5.2.2.1 Refueller Technical Specifications

The technical specifications for the refueller are provided in Table 11.

Table 11: Refueller Specifications

Specification	Value
Dimensions	1.8m x 1.8m x 1.8m
Operating Temperature	-10 to 50°C
Operating Pressure	50 – 400 bar
Maximum Allowable Pressure	413 bar
Maximum Compression Ratio	4:1
Hydrogen Output	350 bar

5.2.2.2 Hydrogen Compression and Dispensing

The HyQube 350 refueller compressed hydrogen from the MCPs to a pressure of 350 bar using a *Maximator* double acting piston booster which was driven by a three-phase 15 kW air compression system, including air compressor, receiver, and dryer. The refueller used a *WEH TK16* hydrogen fuelling nozzle, compliant with *Society of Automotive Engineers (SAE) J2600 Compressed Hydrogen Surface Vehicle Fueling Connection Devices Standard.*

Connection was made with the hydrogen HBT vehicle receptacle using the supply hose, fuelling was initiated by the operator via its control panel. The refueller automatically determined the required Average Pressure Ramp Rate (APRR) based on the ambient temperature and pressure inside the vehicle tank in accordance with the *SAE J2601* fuelling protocols, to achieve an output of 350 bar. Once the APRR was confirmed, the booster and nozzle inlet valves opened, along with the air compressor valves.

The air compressor drove the booster to compress the hydrogen at a maximum compression ratio of 4:1, until the pressure sensor at the nozzle inlet confirmed that the pressure had reached 350 bar. At this point, the refuelling nozzle opened to enable hydrogen to flow into the HBT fuel tank. The fuel flowrate, pressure, and quantity were all monitored via the control panel. The nozzle remained connected to the receptacle until the pressure in the vehicle tank had reached 350 bar, at which point the valve closed and refuelling automatically terminated. The fill rate varies depending on the supply pressure and fill level of the vehicle; the compression rate can range between 2.55kg/hr and 1.20kg/hr and the overall fill time ranged between 15 minutes and 55 minutes.

5.2.2.3 Refueller Safety Features

The HyQube 350 was also designed to promote safe operation and incorporates several key safety features as shown in Figure 12 and outlined in the following Table 12.

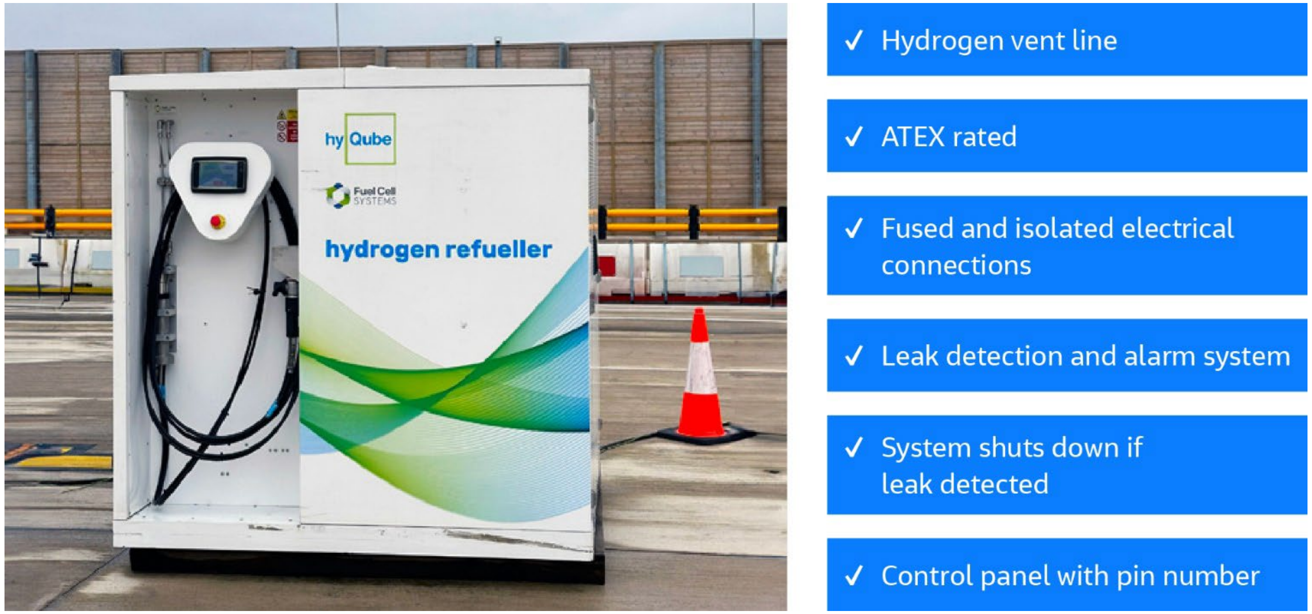


Figure 12: Fuel Cell Systems HyQube 350 Key Safety Features

Table 12: Refueller Safety Feature Specifications

Safety Feature	Description
Leak Detection and Alarm System	The refueller was fitted with multiple hydrogen sensors to identify leaks, as well as pressure sensors and heat sensors to detect any excess heat or pressure. If any alarms were raised from the system these would appear on the control panel and require acknowledgement from an operator. Any alarms such as a sensor fault or hydrogen detection at a concentration of 100ppm indicating a leak would cause the system to enter lockout mode, preventing the refueller from operating. In the event of a leak, the system shuts off the hydrogen supply preventing any additional gas entering the system and the air supply is shut off to stop the boosters from operating.

Safety Feature	Description
System shuts down if leak detected	Following installation of the refueller, all joints and fittings were confirmed as leak-tight using a suitable hydrogen gas leak detector and leak detection spray. All tubing was made from 316 Stainless Steel designed to be compatible with GH_2 and operated at above the working pressure at 415 bar. If the nozzle pressure was detected as above 400 bar, the system will enter lockout mode. In the unlikely event that this did not occur, a pressure relief valve would open to vent discharge hydrogen at a pressure of 413 bar. The hydrogen will vent through a high vent line, 1m from the refueller, seen in Figure 12.
Operational requirements	The control panel required a pin number to unlock operative functionality, meaning only trained personnel were able to use the refueller. Trained personnel were equipped with the correct PPE, including gloves, ear protection, goggles, and anti-static high-vis overalls. Additionally, refuelling was only initiated once the nozzle was locked in place with the receptacle; upon which an audible click would be heard. In the event the vehicle should move whilst dispensing, the breakaway connector is designed to seal immediately so minimal GH_2 would be released.
Hazardous event mitigation	All electrical equipment in the area surrounding the refueller was ATEX rated as required. The ATEX zones surrounding the refueller are outlined in Table 13 and shown in Figure 13. There were warning signals on the refueller to alert nearby personnel of any potential risk, and there was an emergency stop button which could be triggered by personnel for an emergency shut down if any hazardous event is observed. The Bristol Fire & Rescue Service was also equipped with a dry powder extinguisher to respond to any potential fire from electrical components. Further to this, the refueller was earthed so in the event of a lightning strike or if there is any static discharge, the electrical energy would be transmitted to the earth via a low resistance wire and would not travel through the refueller itself. This protects the equipment and reduces the likelihood of ignition. To reduce residual risk, work would be stopped altogether if lightning or electrical storms are forecast. Additional electrical safety features are also built into the system including fused and isolated electrical connections, as well as an isolated air compressor with a circuit breaker and a Residual Current Device (RCD) for protection.

Table 13: Refueller ATEX Zones

Location	ATEX Zone	Extent
Vent line on roof (Figure 13)	1	3.2m diameter, 11.2m upwards
Breakaway connector	2	0.5m from connector
Input connectors	2	0.5m from connector

Figure 13: Refueller ATEX Zones from Vent Line

5.2.3 End Use

5.2.3.1 Hydrogen Baggage Tractor (HBT)

The HBT used in the trial to load, transport, and unload passenger baggage was the *MULAG Comet 4 Electric Towing Tractor*, which was integrated with a *GLOBE XLP80* hydrogen fuel cell system. This vehicle was manufactured, and factory acceptance tested by MULAG. The following Chapter 5.2.3.2 gives details on the hydrogen vehicle including how the fuel cell system works, the specifications of the vehicle, and the refuelling mechanisms. The chapter concludes with a discussion of the safety design features within the HBT, to enable its safe operation in an airport environment. An image of the HBT and its features are shown in Figure 14.

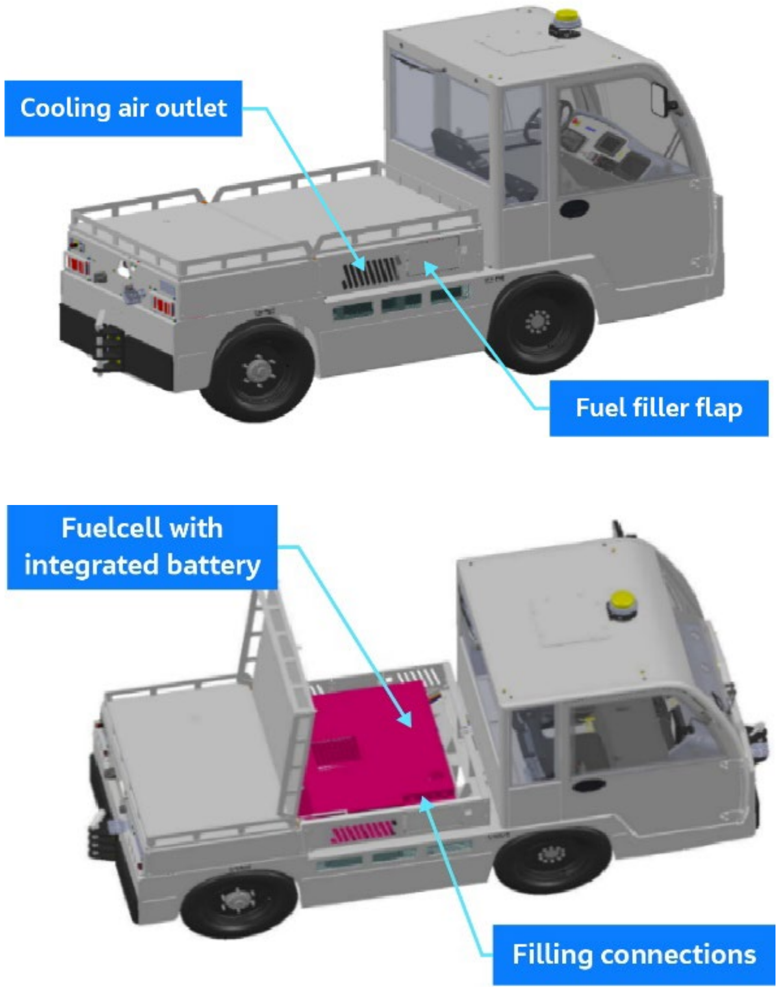


Figure 14: Hydrogen Baggage Tractor Key Features[46]

5.2.3.2 Fuel Cell Operation

The *Globe XLP80* fuel cell system utilises a stack of individual proton-exchange membrane fuel cells, which were each made up of two electrodes, a cathode and an anode, an electrolyte in between, and a metal plate which allowed for gas supply and cooling channels. Once the fuel cell system was started from the HBT control panel, the fuel supply valve on the storage tank opened and hydrogen was fed into the anode, where the molecules were split to produce protons (H^+) and electrons (e^-). The protons passed through the electrolyte towards the cathode, whilst the electrons passed through an external circuit to generate electricity, which was supplied to the battery to power the electric motor of the vehicle. At the cathode, air from the surrounding environment, containing oxygen, was supplied and the oxygen molecules reacted with the protons and electrons to produce water as the only by-product.

The fuel cell stack was fitted with an air filter to remove the impurities and pollutants from the ambient air to ensure only clear air enters the fuel cell and the water produced as a by-product was collected in a tank inside the fuel cell system, which had to be emptied when the HBT was refuelled. The overall reaction that occurs is: $2H_2 + O_2 \rightarrow 2H_2O$; this process is demonstrated in Figure 15.[47]

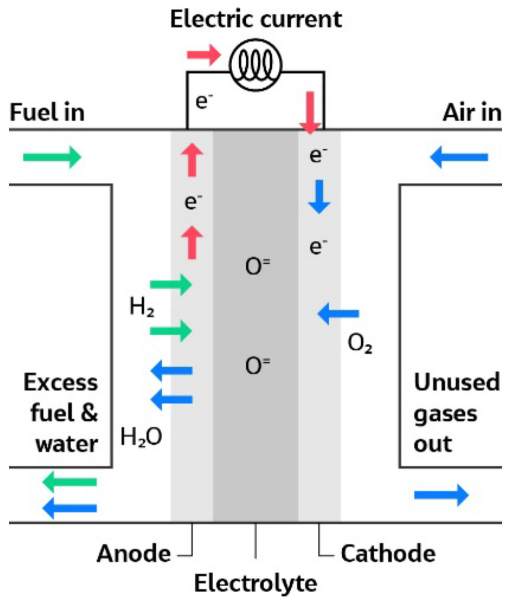


Figure 15: Fuel Cell Components

5.2.3.3 Hydrogen Baggage Tractor Specifications

The fuel cell system consisted of a hydrogen storage tank, a fuel cell stack, a battery, an air filter, and a water tank, which were all housed in a 15 mm thick stainless-steel casing and installed in the centre of the vehicle. The detailed specifications of the MULAG HBT are shown in Table 14 below:

Table 14: Hydrogen Baggage Tractor Specifications

Specification	Value
Maximum Power	70 kW (for 5 seconds) / 35 kW (for 300 seconds) *
Continuous Power	9 kW
Maximum Speed	30 km/h
Maximum Efficiency	63%
Hydrogen Tank Material	ISO 9809-1 Certified Stainless-Steel
Hydrogen Tank Quantity	1.631 kg
Hydrogen Pressure	350 bar

Specification	Value
Hydrogen Temperature	15°C
Refuelling Time	**From 3 minutes (depending on hydrogen refueller)
Battery Type	Lithium Nickel Manganese Cobalt (NMC)
Battery Energy Storage Capacity	11.88 kWh
Fuel Cell System	1,880 kg
Fuel Cell System Dimensions	102.5 x 85.2 x 75.9 cm

** The range in maximum power is attributable to different operating strategies. **~3 minutes is possible with HyQube 500*

As the HBT was a prototype, it could not be stored below 0°C as at this temperature the membrane in the fuel cell was at risk of freezing and would need replacing. Hence, the HBT was stored in a warm building overnight when freezing conditions were forecast to prevent this from occurring. Globe and MULAG are currently developing a solution to protect the fuel cell membrane from the cold weather, however this was not yet available at the time of the trial.

5.2.3.4 HBT Refuelling

The HBT control panel had a dual hydrogen and wastewater indicator light, which when activated indicated that either the hydrogen tank is less than 30% full and requires refuelling or that the water tank is full and requires emptying. In either case, the HBT was taken to the refueller immediately. Prior to refuelling, the data connection cable from the refueller was connected to the fuel cell system to enable the transfer of safety-critical information, and then the water extraction nozzle was connected to the water tank to empty the wastewater. Following this, the refuelling process could be initiated once the hydrogen nozzle was correctly attached to the fuel tank receptacle, which minimised the risk of hydrogen leakage during the refuelling process. Once the hydrogen tank had reached its pre-determined storage limit, the refuelling process was automatically stopped, and the filling connections were detached in reverse order to how they were connected.

The gas pressure was continuously monitored within the tank during the refuelling process to ensure that it did not exceed the safe maximum refuelling pressure, which was 125% of the Nominal Working Pressure (NWP) for gaseous hydrogen (438 bar). There were three hydrogen sensors fitted around the tank to ensure that the quantity of hydrogen in the surrounding environment was less than the Lower Explosion Limit (LEL). The data monitored by the HBT's sensors was fed back to the refueller via data connection and if any danger was identified, the hydrogen refuelling process was automatically stopped and the flow of hydrogen to the fuel tank shut off.

5.2.3.5 HBT Safety Features

The HBT was safety compliant to numerous different safety regulations and standards listed in Table 15. Conformity to EN IEC 62282-4-101 was important for this trial as it meant that this vehicle could be used in enclosed areas, which was the case when it operated in BRS's terminal undercroft (see Chapter 6 for sitemap).

Table 15: Hydrogen Baggage Tractor Safety Regulations and Standards

Regulation (Directive) or Standard	Description
2006/42/EC	Machinery Directive
2014/30/EU	Electromagnetic Compatibility Directive
2014/68/EU	Pressure Equipment Directive
2014/53/EU	Radio Equipment Directive
ATEX 2014/34/EU	ATEX Equipment Directive
Regulation (EC) No 1907/2006	Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)
ISO 21100	Safety of machinery - General Principles for Design – Risk Assessment and Risk Reduction
EN ISO 13849-1	Safety of machinery — Safety-related parts of control systems Part 1: General principles for design
BS EN 12312-7	Aircraft ground support equipment. Specific requirements - Air-craft movement equipment
BS EN 12312-15	Aircraft ground support equipment. Specific requirements - Baggage and equipment tractors
BS EN 12895	Industrial Trucks - Electromagnetic Compatibility
EN 1175:2020-10	Safety of Industrial Trucks - Electrical/Electronic Requirements
EN 50271:2019-03	Electrical Apparatus for the Detection and Measurement of Combustible Gases, Toxic Gases or Oxygen - Requirements and Tests for Apparatus Using Software and/or Digital Technologies
BS EN IEC 60079-29-1:2017-09	Explosive Atmospheres: Gas Detectors – Performance Requirements of Detectors for Flammable Gases
EN IEC 60204	Safety of Machinery - Electrical Equipment of Machines
EN IEC 62282- 4-101	Fuel Cell Technologies: Fuel Cell Power Systems for Propulsion Other Than Road Vehicles and Auxiliary Power Units (APU) - Safety of Electrically Powered Industrial Trucks
EN IEC 62282-4-102	Fuel Cell Technologies: Fuel Cell Power Systems for Industrial Electric Trucks – Performance Test Methods
EN IEC 62282-2-100	Fuel cell technologies - Part 2-100: Fuel cell modules - Safety
ISO/TR 22100-4	Safety of machinery - Relationship with ISO 12100 Part 4: Guidance to machinery manufacturers for consideration of related IT-security (cyber security) aspects

Additional HBT features to reduce the safety risks included:

- **Collision protection:** the fuel cell system was housed in the centre of the HBT, reducing the likelihood of impact damage. The hydrogen tank was also constructed from ISO 9809-1 certified stainless steel.
- **Temperature monitoring:** the fuel cell system was fitted with temperature sensors to detect any source of heat, such as a thermal runaway of the battery, which could lead to a fire or explosion.
- **Pressure control:** the hydrogen tank was designed to a pressure rating much higher than the NWP to provide a buffer, and the pressure inside the fuel cell system was continuously monitored by numerous pressure sensors.
- **Error detection:** if the HBT control system detected an error due to a collision, high temperatures or high pressures, the fuel cell system would immediately shut down; the tank valves will close to shut off the flow of hydrogen to the fuel cell and the safety valve on the hydrogen tank would automatically open to safely vent the hydrogen into the atmosphere and reduce risk of an ignition or explosion.
- **Hydrogen sensors:** the fuel cell system was fitted with three hydrogen sensors to detect the hydrogen concentration at various locations, as shown in Table 16. If any hydrogen leakage was detected, the hydrogen indicator light would activate on the control panel to alert the driver. Table 16 shows the response times of the system and the operation of internal fans according to the concentration level detected. There would be no fan operation at a hydrogen concentration of 3.75% to eliminate any potential ignition source, as this is the LEL of hydrogen. The concentration for fuel cell deactivation was based on 25% of the LEL, in accordance with EN 62282-4-101. In any case of leak detection, hydrogen would have escaped through the exhaust air openings at speeds of up to 20 mph and would have no longer been detectable within a few seconds.
- **Emergency stop buttons:** In the event of an emergency, such as smoke from the fuel cell system or a fire, the fuel cell system shuts down automatically. In addition, the fuel cell system could be shut down manually using the emergency stop button located on the fuel cell system, which was within reach when the fuel cell compartment was opened.

Figure 16: HBT Including Built-in Safety Features

Table 16: HBT Hydrogen Sensor Specifications.

Hydrogen concentration	Fuel cell deactivation response time	Internal fan operation
>1%	>10 seconds	100%
>3.75%	<1 second	No fan operation

6 Safety and Risk Assessment

The safety assessment for Project Acorn required a project-specific risk assessment to be submitted to the CAA prior to the airside trial taking place. Industry and academic engagement were key to understanding lessons learnt from others that have more experience in using hydrogen safely and helped to inform the safety risk assessment process.

6.1 Industry and academic engagement

The following Chapters 6.1.1 to 6.1.3 summarises engagement activities with three key stakeholder groups (Hamburg Airport and MULAG; Brighton & Hove Bus and Coach Company (Metrobus); and Cranfield University) to prepare for the development of the safety assessment for Project Acorn. In addition to these groups, project partners spoke with the relevant regulatory bodies and used UK safety regulatory guidance from the Health and Safety Executive (HSE) and Bristol City Council to ensure that local legislation was followed as shown in the Project Acorn Checklist developed in Chapter 11.

6.1.1 Hamburg Airport & MULAG

In 2004, Hamburg Airport phased out diesel-fuelled baggage tractors and switched to operating HBTs fuelled by natural gas. The safety mechanisms established to accommodate this transition required new refuelling and safety procedures for gaseous fuel in an airside environment. This natural gas risk assessment from Hamburg Airport was shared with Project Acorn to help develop the trial's own safety assessment.

Hamburg Airport also trialled and installed a hydrogen refuelling facility to power two MULAG gaseous hydrogen HBTs operating airside between 2007 and 2010. These MULAG HBTs each consisted of a 10kW fuel cell system that used 5.0 grade hydrogen supplied in gas cylinders. Each cylinder was stored at the refuelling facility at 420 bar and the hydrogen was used directly in the HBT's fuel cell.

6.1.2 Brighton & Hove Bus and Coach Company (Metrobus)

Brighton & Hove Bus and Coach Company (Metrobus) currently have a fleet of 20 hydrogen fuel cell buses that operate on routes from Crawley and Horley to Gatwick Airport, with the plan of expanding to 54 buses by the end of 2024. The single deck buses consist of eight hydrogen tanks in series located on the roof of the bus, storing a total of 35 kg of gaseous hydrogen, together with a 70-kW fuel cell stack and a battery located at the rear of the bus.

The gaseous hydrogen refuelling facility located in Crawley currently relies on gaseous hydrogen delivered via trucks, however *Air Products* has also installed liquid hydrogen refuelling infrastructure which once fully commissioned will serve as the largest hydrogen refuelling facility in Europe. This will enable Metrobus' entire Crawley fleet of over 140 buses to operate using hydrogen.

Metrobus successfully demonstrated that hydrogen can be used safely for passenger transit in a road environment, which has been a crucial factor in securing approval for their future expansion plans. This approval has been achieved by successfully implementing mitigation strategies to manage the risks associated with the use of hydrogen.

6.1.3 Cranfield University

As a key partner of Project Acorn, Cranfield University has been conducting vital research into the use of hydrogen as an aviation fuel. Associated research led by Dr Thomas Budd is looking to assess the impact of hydrogen use in ground operations vehicles.

Given their expertise in the field of hydrogen and its safety in aviation, Cranfield University was able to inform the safety assessment as well as conduct training for BRS's fire services. The key messages from the training are described in Chapter 7.1.

6.1.4 CAA

Collaborating on Project Acorn enabled the CAA (along with other stakeholders) to understand how hydrogen can be safely integrated into the existing aviation ecosystem and be used as a stepping-stone to scale the use of hydrogen as an alternative aviation fuel.

The CAA considered the following in their review of the safety assessment:

- The introduction of a fuel type not normally used in an airport airside location.
- Introducing a considered risk for travelling passengers from the current risk profile to the airside location.
- Different ways of working including transportation, storage and handling of hydrogen.

The CAA recognised Project Acorn's principal application of risk was through a Risk Assessment which could then be added to (BRS's) Aerodrome Safety Management System over the longer-term.

6.2 Project Acorn Risk Assessment

DSEAR assessments (see Table 4) were undertaken by both BRS and Fuel Cell Systems to supplement BRS's existing DSEAR assessment for its airside fuel storage (fuel farm). Additionally, Fuel Cell Systems provided a Risk Assessment Method Statement (RAMS) for BRS review.

These assessments included consideration of new potential risks (see Chapter 6) in standby and filling operations. The Assessors for both BRS and Fuel Cell Systems were qualified and experienced with expertise in storage, handling, and use of dangerous substances where relevant; while the BRS DSEAR Assessor had additional expertise with DSEAR in an airport environment.

The risks identified in the DSEAR Assessment have been summarised on the BRS Main Apron Map in Figure 17. Each risk event has been categorised into a general theme (seen in the key on the map) and then allocated to the location where the risks were likely to occur during the trial. Mitigations required to reduce these risks have been expanded in Table 17 and were part of the broader Project Acorn risk assessment.

Figure 17: Risk Assessment Map and Key

BRS, easyJet and DHL's risk assessment for this trial has been summarised and presented in Figure 17 and Table 17, while mitigations have been detailed in Chapter 6.3.

Table 17: Hydrogen Risk Matrix

Risk Map Reference Number ›	1	2	3	4	5	6	7	8	9	10	11
Risk Category ›	Fire & explosion	Incorrect emergency response	Handling & storage	HBT Tank pressure >438 bar	Hydrogen leaks	Airside operation	Confined space operation	Vehicle collision, tilting	Defective equipment	Lack of appropriate training	Lack of trial awareness
Risk Mitigation											
ATEX zoning – refueller parked remotely, 5m in-use ATEX Zone from HBT fuel filler	■				■						
Limiting the quantity of hydrogen stored to 60kg maximum	■		■								
Compulsory training and Safe System of Work (SSOW) to all operatives and safety briefing for Rescue and Fire Fighting Service (RFFS)	■	■	■	■	■	■	■	■	■	■	
HBT safety features	■			■	■			■	■		
RFFS firefighting risk card	■	■								■	■
MCP Swap-over completed by competent individual			■		■						
1m electrical device exclusion zone around the fuel dispenser	■				■						
Refueller safety features	■			■	■				■		
HBT parking location included in Temporary Airport Instruction (TAI)		■	■		■	■	■				■
Landside vehicle familiarisation	■	■	■							■	
Airside vehicle familiarisation	■	■	■			■	■			■	
DSEAR assessment fuel storage review	■		■		■	■					
HBT operational area mainly outdoors	■					■	■				
Portable (wearable) hydrogen detectors	■				■		■		■	■	
Airport Duty Manager communications		■				■					■

6.3 Risk Mitigations

Table 18 outlines risk mitigations for Project Acorn in accordance with the map of risks provided in Figure 17 and risk assessment summarised in Table 17. Additionally, the required ATEX zoning at BRS and the associated zoning classifications that formed part of the risk mitigations are shown in Figure 18.

Table 18: Hydrogen Risk Mitigations

Risk Mitigation	Description/Explanation	Risk Category Number (Figure 17)
ATEX Zoning - Refueller Parked Remotely, 5m in-use ATEX Zone from HBT fuel filler (Figure 18)	The ATEX zones from the refueller have been outlined in Chapter 5.2.2.3. The refueller was sited on a remote stand, as far from aircraft and buildings (including any smoking areas) as reasonably practicable, to reduce the likelihood of any damage in the event of fire-related incidents. When refuelling, an ATEX Zone 2 of five metres was required from the HBT fuel filler and a three metre ATEX Zone 2 was established from the MCPs. To mitigate the risk of hydrogen gas combustion, especially during refuelling, no electrical or other ignition-inducing devices were allowed within the zone unless flight mode (or equivalent) was activated. Given the refueller needed three-phase electric supply, this was located as far as reasonably practicable from the refueller, and the connection was enclosed.	1, 5
Limiting the Quantity of Hydrogen Stored to a Maximum of 60kg	The lower the quantity of hydrogen stored, the less risk of fire and explosion in case of ignition. Therefore, the quantity delivered to site was closer to 27 – 30 kg (well below the 60 kg maximum quantity limit).	1, 3
Compulsory Training and SSoW to all Operatives and Safety Briefing RFFS	Almost all risks were reduced with compulsory training and a Safe System of Work (SSoW) on the handling of hydrogen-powered vehicles and how they should be driven safely in an airside environment. Specific training was also crucial for an effective emergency response in case of a hydrogen fire, this was recommended to be delivered by Original Equipment Manufacturers (OEMs). Moreover, specialist HBT and refueller engineers were available throughout the trial and their contact details were included in TAI. An incorrect response resulting from a lack of training can have serious consequences such as an explosion, and potentially more damage to the surrounding infrastructure and equipment, as well as injury.	1-10
HBT Safety Features	The MULAG HBT was compliant to European safety regulations, various EN standards and 2014/34/EU ATEX. It contains several safety features which could reduce the overall risks, see Chapter 5.2.3.5.	1 ,4, 5, 8 & 9
RFFS Firefighting Refueller Risk Card	Firefighting refueller risk cards (refueller and HBT) were created to help emergency response services to correctly manage hydrogen fires and limit damage, by informing the services of the hydrogen-powered nature of the vehicle, and by making them aware of the different associated risks.	1, 2, 10, 11

Risk Mitigation	Description/Explanation	Risk Category Number (Figure 17)
MCP Swap-Over Completed by Competent Individual	To avoid any leaks or fire, qualified personnel from Fuel Cell Systems performed fuelling connections between the MCPs (to perform refuelling) and the refueller. Any leaks from the MCP valves were to be identified during commissioning.	3, 5
1m electrical device exclusion zone around the fuel dispenser	To reduce risks around ignition, all electrical items were not located within 1m of the fuel dispenser. This was because the electrical devices could have created a spark and in the event of a leak, there would be a higher risk of ignition. This aligned with ATEX zoning.	1, 5
Refueller Safety Features	The refueller was equipped with several safety components to reduce risks of leakage as well as fire and explosion as detailed in Chapter 5.2.2.3. The refueller was fitted with e-stop buttons in case of any emergency, as well as hydrogen and pressure sensors. Before the refueller was mobilised for the trial, a full inspection during commissioning was undertaken to reduce any risks identified - including any leaks on the MCP valves.	1, 4, 5, 9
HBT Parking Location included in Temporary Airport Instruction (TAI)	The HBT and refueller location on a dedicated remote stand (with no aircraft present at the stand) in an area away from the main terminal building is included in a TAI. This was a dedicated apron parking location to be allocated on the ramp, which was clearly marked and signed within a CCTV covered area. Having a specific parking location cordoned off on a remote stand without aircraft helped reduce the risk of damage to aircraft in case of leakage, or fire.	2, 3, 5, 6, 7, 11
Landside Vehicle Familiarisation	Before the trial and use of the MULAG HBT in the airport, Operatives as well as RFFS had to familiarise themselves with the vehicle, both outside the airport at Cranfield University, and inside the airport, before operation. Operatives and RFFS were made aware of how the vehicle was operated, where its safety features were located, and what procedures need to be followed in case of accident or fire.	1, 2, 3, 10
Airside Vehicle Familiarisation	The on-site vehicle familiarisation included the vehicle-site-specific safety procedures and emergency response that operatives and RFFS needed to be aware of, such as how to avoid damage to the airport building or aircraft in case of a hydrogen fire, where the HBTs should be parked, the routes they could drive, the specific hazards and zones to avoid in order to reduce damage in case of accident, hydrogen leakage or fire. This familiarisation reduced the risk of an incorrect emergency response.	1, 2, 3, 6, 7, 10
DSEAR Assessment Fuel Storage Review	DSEAR assessments were undertaken by both BRS and Fuel Cell Systems to supplement BRS's existing DSEAR assessment for its airside fuel storage (fuel farm). These assessed the suitability of the refueller location (including required ATEX zones) and storage requirements (e.g., hydrogen amount limits) were reviewed as part of the DSEAR assessment. The BRS hazardous area classification can be seen in Figure 18 and Appendix C.	1, 3, 5, 6

Risk Mitigation	Description/Explanation	Risk Category Number (Figure 17)
HBT Operational Area Mainly Outdoors	The initial scope for trial was to utilise the MULAG HBTs outdoors only. However, this was reviewed when more safety information on the HBT was received, and the risk assessment was updated to include use in the undercroft. This was because the HBT could be driven in EV mode so the vehicle would still be able to exit out of the confined space in the event of a fuel cell issue.	1, 6, 7
Portable (Wearable) Hydrogen Detectors	It was determined that if working in a confined space (such as the undercroft), portable oxygen/hydrogen detectors to be worn/utilised.	1, 5, 7, 9, 10
Airport Duty Manager Communications	Other airside partners were to be made aware of the trial, including specific safety mitigations that were in place. To do so, information regarding the trial was issued to the airport duty manager, specifically to advise of any airside operation restrictions that may be imposed when using the HBT, plus any specific measures should there been an incident. A TAI was produced advising BRS departments and DHL's team of the trial and any specific operating limitations to promulgate general awareness of the trial - detail included who to contact in the case of an emergency. In addition to a TAI, an Airport Information Notice was issued to all airside stakeholders advising of the trial.	2, 6, 11

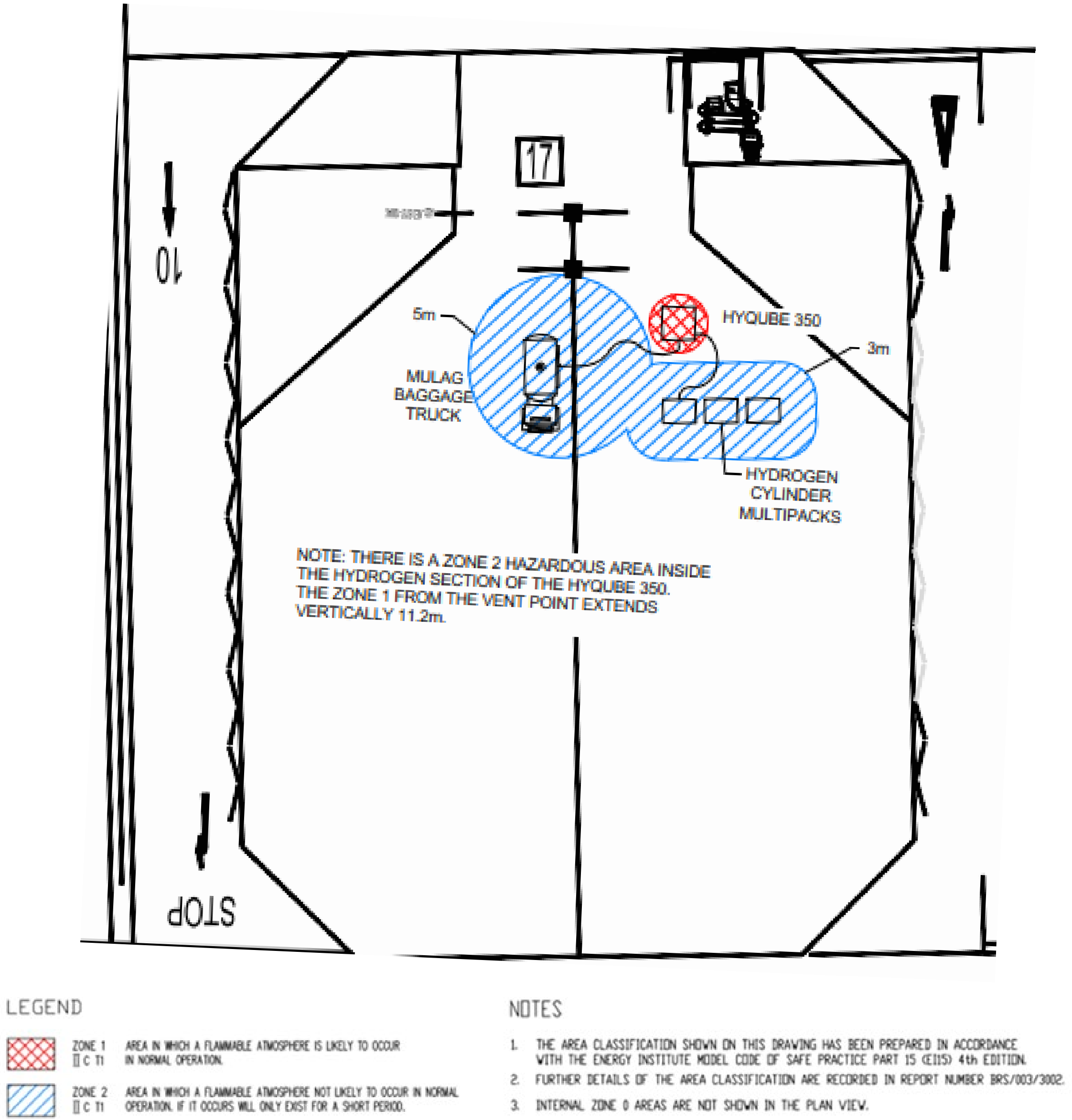


Figure 18: Bristol Airport Hydrogen Trial Hazardous Area Classification – Stand 17 (Not to scale)

7 Safety Briefing and Landside Training

Safety training was facilitated by Cranfield University and consisted of two main elements. First, a detailed safety briefing for BRS Fire & Rescue Service, operational staff and key project stakeholders. Second, a comprehensive landside training at Cranfield's University's *Centre for Propulsion and Thermal Power Engineering* (CPTPE) to teach safe refuelling and operation for both the refueller and HBT.

7.1 Safety Briefing

Staff from Cranfield University delivered the safety briefing to the BRS Fire & Rescue Service along with operational staff and project stakeholders. This training conveyed the importance of safety considerations, as discussed further in Chapters 3 and 6. Topics included hydrogen basics, hydrogen properties and associated risks, hydrogen infrastructure, hydrogen design considerations, as well as other considerations for aircraft and airside operations as summarised below:

- Storage-related safety hazards can be mitigated by reducing the quantity of hydrogen stored on site. The refueller should be stationed away from combustible materials and heavily travelled areas.
- Preventing contact with ignition sources, especially in enclosed environments, is crucial to reduce equipment damage and injuries. For instance, allowing only electric vehicles in the undercroft can reduce the risks of ignition of hydrogen, albeit not completely remove them.
- During the refuelling process, some heating effect can occur. This must be contained to avoid a hydrogen fire. To do so, the maximum refuelling pressure for gaseous hydrogen is set at 125% of the NWP, this is the pressure in the hydrogen tank of the HBT. The compressor discharged pressure should be monitored by a control system that would deactivate it once the discharge pressure reaches the target value.
- Future design changes to airside operations will need to adapt for hydrogen.
- Fuel safety zones for aircraft will need to alter if aircraft design changes and there will need to be changes to the ground handling operations such as aircraft turnaround locations and load control.

7.2 Landside Training

Landside safety training took place at Cranfield University with the aim to familiarise DHL baggage handlers (handlers) with operational and safety procedures for the HBT and refueller, before progressing to airside operations. The training was undertaken over several individual sessions by the equipment manufacturers themselves, focusing on hydrogen properties and safety implications, technological specifications (refueller and HBT), along with vehicle orientation, refuelling and driving lessons.

Importantly, refuelling and driving lesson components allowed the handlers to refuel and drive the HBT on Cranfield's University's private test track. This gave them an opportunity to operate the HBT itself and the refueller with limited external pressures or hazards. Driver training was also conducted by the technology and equipment manufacturers, alongside Cranfield University personnel, so any questions or concerns could be addressed quickly directly by experts. At the end of training, the handlers were signed off by the manufacturers as competent personnel to operate the refueller and HBT. A high-level overview of the training focus areas and key feedback and insights from the training from both participants and trainers is outlined in the Appendix D.

Figure 19: MULAG Training DHL Handlers

8 Airside Trial

In March 2024, the one-week airside hydrogen refuelling and operational trial of the HBT took place at BRS. The trial's operational delivery, data collected, and achievements are described in the Chapters 8.1-8.3.

8.1 Trial Operations

As per the mitigations outlined in the Safety and Risk Assessment (Chapter 6) the hydrogen refueller and MCP were situated on a remote stand in the east of BRS airfield (Stand 17) and subject to the ATEX zones. The HBT was driven and parked at this location to refuel, which was distant from the nearest parked aircraft, but did have spare equipment storage in the adjacent stands and vicinity, as shown in Figure 20.

Figure 20: HBT Parked at Stand 17 at Bristol Airport Alongside the Refueller and MCP

A summary of key milestones of the trial operations over five working days are outlined in Table 19 and Table 20 below, along with accompanying photos in Figure 21 and Figure 22:

Table 19: Summary of Key Milestones of Trial Operations (Day 1)

Trial Day 1	
Delivery	The HBT was delivered to BRS on a flatbed truck by TCR Group from IAAPS and driven through BRS security checkpoints by DHL Handlers with GLOBE Fuel Cell Systems providing driving supervision and support. Initially, the HBT was driven onto the airfield using its electric battery-only mode because the hydrogen tank needed to be completely empty during its delivery and transit on public roads (under UK regulation).
Location and refuelling	Upon entering the airfield, the HBT was driven on electric battery-only mode across the airfield to Stand 17 and parked alongside the refueller and MCP MULAG, GLOBE and Fuel Cell Systems were on hand to assist and supervise the initial refuelling process. They also conducted refresher training for the DHL handlers as outlined in Chapter 6. Following initial hydrogen refuelling, the HBT was restarted in its hydrogen-fuel cell mode.
Operation	The focus of this initial day of the trial was for the DHL handlers to become familiar with driving the HBT in the airside environment and refuelling – before integrating the HBT into normal airside operational activities. The HBT was driven continuously around the airfield during the routine shifts of each trained DHL handler and refuelled intermittently.

Figure 21: HBT at Bristol Airport During Initial Refuelling

Table 20: Summary of Key Milestones of Trial Operations (Days 2-5)

Trial Days 2-5	
Operation	The DHL handler team then used the HBT to service easyJet aircraft turnarounds, transporting passengers' bags to and from aircraft as part of routine operations. During this period, there were 10 refuelling events completed each time the HBT fuel tank was at 30% capacity or below. The HBT was refuelled at the end of the last shift on Trial Days 2-4. The HBT towed baggage trailers to easyJet aircraft for outbound flights and collected inbound bags throughout the day. During these movements, the HBT was towing 3-4 baggage trailers (an example of which is shown in Figure 22 below), weighing between 5 and 6 tonnes in total. The DHL handlers also used the HBT for ad hoc equipment movements to support turnarounds and many of these movements involved the HBT traversing the undercroft area numerous times in any given shift. At no point were there any health or safety incidents due to the trial activities.

Figure 22: HBT Towing Baggage Trailer at Bristol Airport During Aircraft Turnaround

8.2 Trial Data

During the trial, telematics data was collected from the HBT by both MULAG and GLOBE Fuel Cell Systems relating to its movements and performance across a range of metrics.

In terms of movements, the raw MULAG HBT GPS route tracking map shown in Figure 23 demonstrates the typical coverage of the HBT's operations across BRS – with limited data anomalies. It can be inferred from the data that the HBT became integrated with normal operations and had the range in movement to operate across all available aircraft stands, as necessary.

Figure 23: MULAG HBT GPS Route Tracking

The HBT's key performance metrics are summarised in Table 21 and shows it was driven for a total of 10 hours, operated for 26 hours - with the ignition on for 30.7 hours (the term "ignition on" refers to the activation and start-up of the GLOBE fuel cell whereas the "operating hours" is the activation and starting of the COMET 4FC HBT vehicle). During this period of operation, it was driven 140km around the airfield – the equivalent driving distance between BRS and Aberystwyth in Wales.

Table 21: Trial Summary from MULAG HBT Telematics

Driving hours	10 hours
Operating hours	26 hours
Odometer	140 km

Vehicle ignition on	30.7 hours
Hydrogen used (approx.)	8.5 kg
Hydrogen used per kWh (approx.)	0.047 kg
Energy consumption	92 kWh
Energy consumption per hour driven	9.18 kWh

Appendix E contains further tables and figures which show the operational performance of the HBT and its fuel cell on each day including:

- Gaseous hydrogen tank level
- EV battery charge
- Power
- Ambient temperatures
- Ambient humidity
- Ambient pressure

The data should build confidence in hydrogen-fuelled vehicles as a potential replacement of existing battery or diesel fuel operated HBTs in the future - as the technology continues to develop.

8.3 Trial Achievements

As outlined in Chapter 2.3, there were several drivers, aims and objectives for Project Acorn. Overall, the trial achieved these high-level results, as follows:

- **Demonstrated safe refuelling of hydrogen airside**: Project Acorn refuelled airside over a period of five days in a live operational environment.
- **Zero safety incidents**: There were no near misses or safety incidents reported for Project Acorn – the only user system warning was relating to the EV battery level as low.
- **Mitigations covered the activity risks sufficiently**: The Safety Assessment was submitted to the CAA for review who had oversight of the safety case to enable the demonstration to proceed.
- **Effective handling of the HBT for easyJet's, DHL's and BRS's operations**: The DHL handlers' feedback (see Chapter 9) was positive and indicated the use of the HBT had been effective by enabling them to carry out their shifts as normal.
- **Successful collaboration with partners across the supply chain:** As indicated in Chapter 2.5, Project Acorn involved 12 partners and many other industry stakeholders which provided advice and guidance integral to the success of the trial.
- **Dissemination of the trial results:** A large amount of coverage via news outlets, social media, industry and company websites was obtained following the trial and on the completion of the trial report.
- **Enabled partners and industry to support the future development of a regulatory framework:** Data and experience gathered during the trial has provided a solid base to support the development of a regulatory framework for the industry's wider use of hydrogen.

9 Project Feedback

DHL Handlers (handlers) and BRS Fire and Rescue Service provided feedback on both landside and airside phases of Project Acorn, including their attitudes towards hydrogen refuelling and the HBT operations by answering a series of open-ended survey questions. Their responses and recommendations are summarised in general terms in Table 22 below to maintain anonymity:

Table 22: Feedback on Landside and Airside Phases from Handlers and BRS Fire and Rescue Service

Feedback Giver	Description/Explanation	Project Phase
Handlers	Prior to the training handlers generally had little knowledge of hydrogen or hydrogen safety. While some handlers had heard about the impacts or safety incidents involving hydrogen, these were typically confined to major historical events. With limited knowledge, it is understandable that many operational staff shared reservations about hydrogen safety, especially in an airside environment. There was an exception, with one handler sharing they had no safety concerns about hydrogen refuelling. They shared they had done their own research into the fuel and its application before the training, so they understood the existing safety protocols.	Landside Pre-Training
Handlers	Generally, feedback following training was very positive. All handlers felt comfortable and safe with the refuelling process once the training had been conducted. The feedback from most handlers was that the training had provided them with confidence and influenced their views on hydrogen refuelling – namely that it could be undertaken safely. There were two handlers that commented refuelling equipment and HBT were very simple and easy to use. One commented on the granularity of the training as reassuring, and that it also gave them great confidence in knowing exactly what to do during the refuelling process. However, there was also feedback from handlers that if hydrogen is to be used as a permanent fuel in aviation, training on technical terminology and theory such as *pressure* and *bar* would need simplification. None of the DHL handlers said they felt unsafe or unsure how to refuel or operate the HBT during the airside trials.	Landside Post-Training
BRS Fire and Rescue Service	Prior to the training, BRS Fire and Rescue expressed understandable concerns relating to the risk of fire and explosion because of hydrogen refuelling. However, they were supportive of the trial with safety mitigations in place as described in the safety assessment. Following the training BRS Fire & Rescue Service expressed their confidence in the refuelling process and HBT technology. They confirmed they understood the protocol if the HBT should it catch fire or if there is a fire nearby to this equipment. They were also confident that adequate safety mitigations, as well as emergency response protocols were in place for the trial.	Landside Post-Training
Handlers	Most handlers felt that the refuelling process was straightforward, with one specifically commenting that the process felt safe. One handler also commented that although the refuelling of the HBT was slower than a fossil fuel HBT comparatively, it was still much	Refuelling During Airside Trial

Feedback Giver	Description/Explanation	Project Phase
	quicker than charging an EV HBT. However, it was also noted that an advantage of an EV was that it could be left to charge without supervision, whereas the Project Acorn HBT could not be left unattended during refuelling. The handlers also gave further feedback about the refuelling process, specifically the noises made by the refueller which required getting used to. While none required ear defenders, the noises could be loud – like the high-pitched whistle when GH_2 was discharged from the refueller, or the sounds associated with pumping action made by the refueller during the process of gas compression. However, it was also observed by some DHL handlers that as they gained more experience refuelling during the trial week, these noises were no longer concerning, and their impact dissipated over time. Feedback provided also indicated that it was at times difficult for handlers to know how much GH_2 was left in the MCPs. Specific feedback was that this type of data should be available via the user interface if this method of GH_2 storage would be used in the future. Finally, it was noted that during the trial, several handlers realised they would have appreciated further demonstrations of all the potential fault codes and alarms the refueller may sound. However, it is not always possible to replicate situation where these alarms may sound given safety considerations. It was suggested in future training that videos could be made during the testing of equipment and shown to the DHL Handlers to meet this need. As a stop-gap during the trial, there were GLOBE/Fuel Cell Systems and MULAG Engineer available for any queries on the refueller and to discuss and clarify different fault codes – despite no alarms being reported during the trial.	
Handlers	Overall, there was consensus that the HBT was able to perform the required functions for baggage turnarounds and had the capacity to tow the required tonnage. However, the following were the recommendations from handlers that should be considered before HBTs were rolled out for business-as-usual operations: ▪ Wider education on hydrogen is needed so that users are confident that health and safety incidents are unlikely to occur if handled and stored competently. ▪ Given the risk mitigations required (see Chapter 6), having sufficient space for hydrogen storage and refuelling would be challenging since BRS is spatially constrained. Airports of the future may be better placed integrating hydrogen infrastructure at the planning stage rather than as a retrofit. ▪ The hydrogen fuel was used quickly, when the hydrogen tank needed to be emptied for its removal from BRS, the hydrogen tank fell to 6% within 4 hours 30 mins. If used as a single team asset, rather than being driven by selectively trained DHL handlers in a trial, it is likely that the HBT would last an entire day of shifts. ▪ Like all major airports in the UK today, BRS is not yet ready for hydrogen-powered GSE and does not yet have any EBTs (electric baggage tractors). Any transition to either technology will require associated infrastructure and operational changes to accommodate new ways of working. ▪ More education on hydrogen is needed so that people are confident that issues are unlikely to occur if handled safely and competently	Operations During Airside Trial

Feedback Giver	Description/Explanation	Project Phase
BRS Fire and Rescue Service	As stated previously, the Fire & Rescue Service were confident with the trial's risk assessment and mitigations put in place. There were remaining concerns around using the HBT in enclosed spaces such as the undercroft that there would benefit from further mitigations if they became a permanent solution at BRS (e.g., installation of fans to ensure there was no accumulation of hydrogen in the event of a hydrogen leak). Additionally, BRS recommended further research into firefighting tactics and techniques if HBTs were to be rolled out more broadly at the airport.	Operations During Airside Trial

10 Project Learning

As the UK's first hydrogen airside refuelling trial at a major airport, Project Acorn partners learned a great deal during trial development and delivery. Additionally, the project required coordination of multiple partners located across Europe and the hydrogen supply chain which added to project complexity. This chapter discusses the high-level lessons learnt during Project Acorn by our partners – highlights, challenges and solutions in the specific context of the trial, as well as recommendations for the future.

By sharing project learning, Project Acorn's partners hope to inform and enable further airside hydrogen trials and demonstration projects at scale and reduce uncertainties surrounding potential projects that are associated with a lack of operational experience and regulatory framework for airside hydrogen refuelling specifically.

Table 23: Project Learning Phases, Description and Recommendations

Project Phase	Learning Description	Recommendations
Trial Development	Once the safety assessment was complete, the trial development was initiated. This required weekly project management meetings to coordinate all the partners and ensure the completion of critical path activities, including: ▪ Confirming availability of staff, arranging airside passes, logistics and delivery of equipment and arrangement for training of handlers and the BRS Fire & Rescue Service. ▪ Agreement of the location of the refueller and trial by easyJet's, BRS's and DHL's airside operations team to ensure that the trial activities were remote and did not interfere with existing business as usual activities. ▪ The nature and type of data that would be collected so that the relevant partner organisations would know what to expect at the end of the trial and how to measure success.	▪ Initiate regular meetings with all stakeholders and encourage an open and solution-oriented discussion. ▪ Identify all required permits and passes needed to gain airside access and initiate well in advance. ▪ Agree on a location for the trial which does not affect business as usual activities. ▪ Agree on the data collected to understand what the next steps should be. ▪ Airport senior leadership team to engage key stakeholders to facilitate operation.
Regulatory Framework	Given there is no current UK regulation relating to airside hydrogen refuelling – a blend of various standards and regulations across the hydrogen value chain were considered, interpreted and utilised to complete the trial. In terms of highlights: ▪ Numerous engagement activities with industry and academia to learn from best practice in the initial trial development phases, including Hamburg Airport and Brighton and Hove Bus and Coach Company. ▪ Successful collaboration to develop three Risk Assessments for easyJet, BRS and Fuel Cell Systems, which were combined into one final overarching Risk Assessment for submission to the CAA – which proved to be sufficiently robust to enable an airside trial. ▪ Appointment of an assessor with specific experience in the BRS airside environment to perform the DSEAR assessment, with the support of Project Acorn partners, given initial efforts to locate and employ	▪ Use the steps in the development of the Safety Assessment as a blueprint to ensure engagement is built into the programme and allow ample time for the review from key stakeholders. More specifically: ▪ Clearer role definition for airline, airport and ground handler, as well as agree standardised template for safety assessment across these three elements. ▪ Identify a competent DSEAR Assessor early and confirm availability.

Project Phase	Learning Description	Recommendations
	an assessor with specific airside hydrogen experience were unsuccessful due to the emergent nature of the fuel technologies involved. ▪ Active engagement with the CAA (with consistent delegates) to ensure the regulator had appropriate resources available to review the Risk Assessment during tight project turnarounds. Ensuring the CAA received ample notice so that they could resource, and workforce plan was essential – to be factored into the project programming and timelines. ▪ Advanced site visits were highly useful in assisting the development of the safety case and mitigations, particularly in terms of determining the best location for refuelling. ▪ Clear guidelines on gas separation distances from the British Compressed Gas Association in the case of the refueller to assist the Safety Assessment, in the absence of a specific regulatory framework for airside refuelling of hydrogen. Conversely in terms of challenges: ▪ One of the initial challenges was the significant period or time required for the Risk Assessment development process - prior to it being submitted to the CAA for review. ▪ The initial timeline for the Safety Assessment was too optimistic, particularly given the change in technology of refueller and storage for the trial.	▪ Notify CAA (or equivalent authority) well in advance of review timeframe and factor in a minimum review period. ▪
Trial Delivery	Once the trial was initiated and the HBT was completing operational activities there were a small number of additional, yet significant challenges faced by the operations team - mainly around logistics and transportation of equipment, as follows: ▪ The preferred source of hydrogen from the IAAPS' facility (see Appendix F) was unavailable at short notice, as the intended mobile refueller was awaiting certification to enable it to be transported on UK roads. These delays meant the originally intended integrated mobile refueller and storage solution became inappropriate for the trial. In summary, the project required a new hydrogen fuel source, storage and refuelling solution to that which was originally intended at concept stage. ▪ The intention of the project partners was to utilise green GH_2 from IAAPS for the trial. However, it became evident that the lead time for an empty MCP to be made available for IAAPs to fill with green GH_2 was too long a delay given the timelines of the project. The only supply readily available at short notice was grey GH_2 rather than green GH_2. After consideration, the decision was made to proceed with the project given the aim of this trial was airside safe handling and refuelling of hydrogen. ▪ Although the project was able to obtain an alternative storage and delivery technology using Fuel Cell Systems' HyQube 350 refueller and GH_2 MCP storage, being fixed rather than a mobile solution meant it	▪ Ensure that all technology is suitable for the weather conditions predicted for the trial and necessary storage is available. ▪ Ensure that all deliveries for equipment are scheduled with contingency and ideally that the fuel storage solution is delivered with associated refuelling equipment prior to a trial start date. ▪ The lack of experience of GH_2 suppliers accessing airside may be a potential barrier for future trials. Therefore, notify all delivery and logistics companies of the airside passes and permits which are needed for access. Ensure that they are aware of the airside risks. ▪ Communications leads to do site visits to enable clear direction to media about location restrictions

Project Phase	Learning Description	Recommendations
	required a three-phase electricity connection. Hence a revised Safety Assessment was required due to the change in proposed technology and location of the refueller at BRS – delaying the project by approximately three months. While the additional assessment would not have required three months end-to-end, the timing fell over the Christmas period (one of the busiest annual holiday and aviation operational periods). ▪ One of the consequences of the three-month delay was that the proposed landside training and airside trial would now occur during the UK winter and one of the coldest forecast times of the year. As the MULAG HBT was a prototype on loan (which did not yet have commercial levels of fuel cell insulation), it could not be exposed to temperatures below zero degrees for over three hours whilst stationary - without risking irreversible damage to the Globe Fuel Cell System membrane. ▪ Due to overnight below zero conditions and freezing conditions forecast over the two-week trial period, this meant the trial had to be delayed. Additionally, BRS would not permit the HBT to be stored indoors at any location airside. Hence the HBT was emptied of hydrogen fuel and stored at IAAPs DSEAR compliant storage facility at Emersons Green until the temperature reached overnight levels of above zero degrees. ▪ Further to this, there was a component failure in the HyQube system which meant that the pressure needle valve had to be replaced by Fuel Cell Systems. This failure was identified through internal monitoring and successfully caused a full system shutdown, eliminating the risk of an incident. However, due to the maintenance required, the trial was to be pushed back to the following week, using its allocated contingency week.	in terms of access and equipment for videographers and photographers.
Hydrogen Supply and Storage	Given Project Acorn's ambitions to demonstrate hydrogen refuelling, one of the major areas of learning related to the supply and storage of hydrogen. In terms of learning highlights: ▪ Selected systems worked well together with zero health or safety incidents. ▪ One automatic system shutdown before the trial began (after its delivery to BRS) proved the inbuilt safety systems operated as intended – when a fault (not a leak) was detected. The fault was a component failure (a needle monitoring a specific valve between the MCP and refueller was faulty – potentially from damage during transit) which was easily replaced on site at BRS prior to the trial. In terms of challenges: ▪ The original intention was to use a first-of-its-kind mobile refuelling and storage solution; however, this was not yet ADR certified to travel or be shipped on UK roads, and it became apparent this certification	▪ Absolute clarity on requirements and equipment availability for refuelling systems to 'get it right first time' to mitigate transportation and delivery certification (and other related) challenges. Minimise uncertainty by choosing supply and storage mechanisms with low risk. ▪ Conduct in depth evaluation of risks on a first principles level (hydrogen production, compression, transfer, storage, transport and refuelling). For example, understanding the certification process for ADR and transport of hydrogen.

Project Phase	Learning Description	Recommendations
	would not be achieved within project timeframes. The replacement solution required a power source and repositioning within BRS. ▪ Securing low carbon or green hydrogen from a UK provider following a rethink of the original refuelling and storage concept – this was not possible in the timeframes required by the project and instead grey hydrogen was procured. Still, due to supply shortages only half the ordered hydrogen was received. ▪ It was difficult to monitor the remaining hydrogen in the MCP given a lack of user interface for refuelling. Instead, mathematical calculations were performed by the support team to calculate remaining storage volumes following refuelling.	▪ Conduct a delivery risk assessment and obtain sign-off commitment from suppliers on volume of hydrogen. ▪ Approach green hydrogen suppliers with more than 12 weeks' (3 months') notice. ▪ Get precise specification on positioning requirements of storage (e.g., power source). ▪ Early planning could have secured higher pressure and faster hydrogen storage/refuelling solutions (e.g., HyQube 500).
Refueller	Refuelling was the core focus of Project Acorn and it being undertaken airside was one of the major successes of the trial. There were numerous key learning highlights as follows: ▪ The refueller was reported to be straightforward and easy to use by DHL Handlers during both training and operation. ▪ Systems worked as intended with zero health and safety incidents. ▪ The use of the remote stand (Stand 17) enabled safe distances from aircraft, equipment storage and other BRS operational areas. ▪ The refueller had an inbuilt ATEX zone, which meant DHL Handlers were not required to wear hydrogen-specific personal protective equipment (PPE). By contrast, challenges included: ▪ The pressure of the refuelling process was less than 500 bar increasing the time taken to refuel – because the refueller had to compress the hydrogen from180 bar in the MCP to 300 bar before it was able to refuel the HBT.	▪ Use a higher-pressure storage solution which enables hydrogen compression in advance of refuelling. Although larger equipment, technology and greater safety considerations the refuelling would have been significantly faster – particularly since the refuelling process could not be undertaken without supervision by DHL Handlers. ▪ If using higher pressure storage, a more sophisticated refuelling nozzle would provide additional safety features – such as infra-red and two-way communications connections to monitor pressure differential during a faster refuel. ▪ Provide a one-page summary on airside restrictions and pass application process/validity for third parties involved in the trial.
HBT Operations	The MULAG HBT performing airside turnarounds facilitated a great deal of operational learning and interest in hydrogen technology at BRS – both from DHL handlers involved in the trial and their operational colleagues and competitors. In terms of highlights: ▪ It was easy to use and intuitive to operate and drive, generating a great deal of interest across airport operational staff on a range of its features – from hydrogen fuel to heated seating.	▪ Early documentation of all risks and dependencies to ensure sufficient contingency and mitigation (e.g., if adverse weather is experienced during a trial period or the trial is shifted to another season which may impact hydrogen technologies employed –

Project Phase	Learning Description	Recommendations
	▪ Data collected by GLOBE Fuel Cell Systems and MULAG via telematics provided insights daily which will be important for any wider rollout of hydrogen-powered GSE in the future. Whereas, in terms of challenges: ▪ The HBT did not come with a static airport safety beacon installed (flashing orange light above cabin). While a temporary battery-operated solution was explored this was considered inconsistent with ATEX requirements whilst refuelling. As such, a special dispensation was obtained via the Safety Assessment to obtain permission to only use the HBT's existing hazard lights while it operated airside. ▪ Given the HBT's fuel cell could not be less than zero degrees Celsius, this meant that the trial had to be delayed for several weeks due to weather. (Notably, Globe Fuel Cell Systems have since designed a fuel cell which can withstand freezing temperatures which will be rolled out on future HBTs). ▪ While HBTs require less refuelling time, the current cost of hydrogen fuel would be difficult to integrate into mainstream ground handling because it would likely make some airlines uncompetitive as DHL operates with an open book on charges (all costs are passed through to the respective airlines).	ensure adverse weather kit, contingency or alternative solutions for the HBT). ▪ Airport to share motor transport requirements to GSE suppliers prior to trial (e.g., requirement to integrate airport safety beacon as standard on future MULAG HBTs and ensure the electrical components of this equipment are ATEX rated). ▪ Conduct a specific weather-related risks and dependencies study and related plan (e.g., storage of equipment in adverse weather and contingency plans as applicable).

11 Project Acorn Checklist

A summary of the critical steps taken during Project Acorn in terms of the safety and risk assessment are summarised in a generalised checklist format as shown in Table 24 below, listed in chronological order:

Table 24: Checklist of High-Level Steps and Tasks Undertaken for Project Acorn

Step	Task	Description
1	**CAA Innovation Team Engaged**	CAA Innovation Team engaged as collaborator on Project Acorn from kick-off to provide continuous guidance.
2	**Safety Consultant Engaged**	HSE Buxton engaged to review risk assessment.
3	**Local Council Engaged**	North Somerset Council engaged to ascertain permissions and any specific permits needed to carry out hydrogen trial at BRS.
4	**CAA Aerodrome Team Engaged**	The CAA Aerodrome Team responsible for aerodrome compliance and safety is engaged.
5	**Airport DSEAR Assessment (Updated)**	Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) assessment for BRS updated to include the storage of GH_2 airside.
6	**Refuelling Electrical Equipment ATEX Rating Confirmed**	All electrical equipment and fittings confirmed ATEX rated by suppliers (Fuel Cell Systems Ltd and MULAG).
7	**Insurance Confirmed**	Confirmed that airport and ground handler insurance agreements cover the planned activity, including that of third-parties contracted to assist with the work.
8	**Operational Process Review (OPR)**	Performed OPR, which is an industry standard procedure for risk assessment and mitigation.
9	**Training Plan for Operatives**	Formal training plan developed for DHL handlers, Airside Operations Team and BRS Fire and Rescue Department.
10	**Emergency Services Sign-off**	Airport, local emergency services and local authority informed and conducted site visit to sign-off trial activity.
11	**Safety Consultant Review**	Feedback from HSE followed by refinements to risk assessment.
12	**CAA Review**	Risk assessment review by CAA Aerodrome Team who had oversight of the safety case to enable the demonstration to proceed.
13	**Landside Trial**	Landside trial in controlled environment at Cranfield University to test and troubleshoot hydrogen equipment.

Step	Task	Description
14	**Landside Training**	Operator training and familiarisation for key stakeholders in controlled environment at Cranfield University and SSoW provided.
15	**Airside Trial Day 1**	Airside equipment checks and test operation at BRS. Communications/briefing document to all airside ops personnel.
16	**Airside Trial Days 2-5**	Full airside operation serving easyJet aircraft turnaround at BRS.
17	**Airside Lessons Learnt**	Feedback and lessons learnt from airside trial with partners/key stakeholders.
18	**Knowledge Sharing**	Sharing of key insights across the industry to feed into the creation of industry safety guidance and regulatory framework.

12 Next Steps

Project Acorn was the first airside hydrogen refuelling and operational trial in the UK. It was a small but critical step in the UK's journey towards zero carbon aviation, by integrating the handling of hydrogen and refuelling into ground operations at BRS.

In terms of safety, the next steps are to assist in the development of a standardised set of procedures and processes for conducting hydrogen trials in live environments. This includes but is not limited to issues around risk assessments, training and safety provisions for operators. The main contribution of Project Acorn in that regard, was the development of the Project Acorn Checklist alongside the safe working procedures and learning outlined in this report. It is hoped that these resources will help guide other airports in the UK and around the world as they prepare for their own operational hydrogen trials. In this sense, Project Acorn proved what was possible and became an important step in developing safe airside hydrogen working.

In terms of technology, the next step is to consider what additional safety cases, risks and processes need to be understood and developed to refuel an aircraft destined to carry passengers. This is the focus of the recently-announced activity that CAeS will be leading within the SATE (Sustainable Aviation Test Environment) in Orkney, building on learning from the Acorn project. Without these, aircraft powered by hydrogen propulsion systems, vehicles, storage and technologies such as those being developed by collaborators CAeS, MULAG, Fuel Cell Systems and Globe Fuel Cell Systems will not be able to enter service. There is no reason to wait until hydrogen aircraft arrive to lay the foundations for safe hydrogen operations.

Project Acorn's literature review demonstrated the complex and fragmented landscape of hydrogen safety regulations, codes and standards for hydrogen refuelling, both in the UK and internationally. To enable hydrogen-ready airports, there must be further streamlining and development of an airside hydrogen regulatory framework. The CAA trialled a new and collaborative way of working on Project Acorn in its review and oversight of the safety case to enable the trial to proceed. The CAA has already launched a challenge for the aviation industry to help leverage the potential of hydrogen as a zero-carbon emission aviation fuel. The learning from Project Acorn will inform the CAA as it establishes its regulatory sandbox approach to make sure regulation is fit for purpose and reduce challenges associated with its potential introduction as a fuel.

However, further work is also needed before hydrogen can become established as an airside GSE fuel. Data collected from Project Acorn will be analysed by Cranfield University to form a basis for modelling and forecasting around the use of hydrogen for GSE. Previously, little was known about the performance of hydrogen vehicles airside. Project Acorn data will now be utilised to develop more accurate models and forecasts about the use of hydrogen airside and for other GSE applications. It is hoped a more accurate model will assist in master planning decisions around future demonstration activities and scale up of hydrogen-powered GSE.

While widespread decarbonisation of aviation will require liquid hydrogen and storage in the air and on the ground, Project Acorn as a small-scale gaseous hydrogen trial was a vital step towards understanding the safety cases and risk management that will underpin future safe working procedures for new hydrogen-based technologies, safety regulations for hydrogen refuelling, in airport master planning and live operational environments.

Figure 24: Project Acorn Partner Representatives at BRS During Project Acorn Airside Trial Day 1

Appendix A. Project Acorn Partners and their Involvement

Table 25: About the Partners and their Involvement

Project Leadership		
Organisation	**About**	**Involvement**
Bristol Airport – Amazing journeys start here	Bristol Airport is England's third largest regional airport, acting as the international gateway for the Southwest of England and South Wales. The Airport has taken a leadership position on developing hydrogen-powered, zero-carbon emissions flight, forming regional and national partnerships with Rolls Royce, Airbus, GKN Aerospace, and easyJet to accelerate the development of the technology.	BRS was the host location for the airside trials. They worked in collaboration with multiple other parties to facilitate and coordinate Project Acorn to ensure a successful trial of hydrogen ground infrastructure in the most realistic and representative environment possible.
easyJet	easyJet is Europe's leading airline offering a unique and winning combination of the best route network connecting Europe's primary airports, with great value fares and friendly service. The airline has published its roadmap to net zero-carbon emissions by 2050, with a focus on new technology and the ultimate ambition to achieve zero-carbon emission flying across its entire fleet. In 2022, they worked in collaboration with Rolls Royce to run the first ever ground test with hydrogen on an aircraft combustion engine.	easyJet played a key role in galvanising major industry players from across the value chain to join the programme and collaborate in conducting the first ever airside hydrogen refuelling trial. They led the development of the safety case to facilitate operational trials at Bristol and led the communications of the trial results to the public and other important stakeholders (government officials, policymakers, media, industry peers and organisations).

Advisory Services Partner		
Organisation	**About**	**Involvement**
Jacobs – Challenging today. Reinventing tomorrow.	Jacobs provides a full spectrum of professional services including consulting, technical, scientific and project delivery for the public and private sector. Jacobs helps clients navigate an uncertain future around decarbonisation, electrification demand and decentralisation, by providing innovative and efficient solutions, including strategic advisory services.	Utilising their core consultancy skills and hydrogen expertise, Jacobs led the development of this report to disseminate the trial's outcomes. Jacobs has extensive experience working in both hydrogen and aviation related projects and was therefore well positioned to provide technical input into the analysis of the trial outcomes.

Delivery Partners		
Organisation	**About**	**Involvement**
Cranfield Aerospace Solutions	CAeS is a UK SME (Subject Matter Expert) with UK CAA regulatory approvals to design & certify complex modifications to aircraft as well as capabilities for whole aircraft concept design. Recognising the significant challenge of maturing nascent technology for the use in large aerospace applications, CAeS's systems are currently targeting small platforms, and by doing so, CAeS aim to drive the necessary regulation, supply chains and hydrogen infrastructure that will form the foundation upon which the rest of the industry can build.	Drawing from their experience in developing hydrogen propulsion technology to accelerate the world's transition to zero emissions flight, CAeS provided key input into the assessment of hydrogen refuelling risks and acted as a hydrogen advisor to the project.
Cranfield University	Cranfield University is a world-leading specialist postgraduate university. Cranfield works in partnership with business, academia, governments and other organisations to develop and deliver applied research and innovative education in science, technology, engineering and management. Cranfield University is synonymous with aerospace and their hydrogen research and development (R&D) cover all aspects of the generation and use of the fuel at airports and in aircraft.	Cranfield University hosted the landside training at their facility to troubleshoot and conduct necessary training to prepare for airside trials. They also conducted an online safety briefing to the BRS Fire and Rescue Service. Associated research led by Dr Thomas Budd will be assessing the impact of hydrogen use in ground operations vehicles. Further to this, the GH_2 fuelling technology for the hydrogen baggage HBT was provided via Cranfield's partner, Fuel Cell Systems, a hydrogen equipment specialist.
DHL	DHL Group is a world leading logistics company. Operating in more than 220 countries and territories worldwide, DHL connects people and markets enabling global trade. DHL are easyJet's ground handlers at BRS. DHL are committed to reducing all logistics-related emissions to net zero by 2050 and have been investing heavily into climate-neutral solutions by 2030. These investments are in equipment such as battery electric and alternative fuelled vehicles, cleaner aircraft and new buildings and facilities.	DHL invested significant time and expertise in collaboration with the Project Acorn partners, to ensure successful planning of the progressive opportunity. This includes full risk analysis, process mapping and workstream ownerships. DHL operated the hydrogen powered baggage tractor for the duration of the trial and were responsible for the refuelling activity.
IAAPS Advancing Propulsion	IAAPS is a world-leading centre of excellence for research and innovation of clean, efficient and affordable zero carbon propulsion technologies based at the Bristol & Bath Science Park.	As leaders in the field of hydrogen R&I, IAAPS played a crucial role in developing the safety case for Project Acorn. They were also initially identified as the green hydrogen suppliers for Project Acorn but due to

	Created as a secure environment for collaborative research and validation, IAAPS offers unrivalled expertise and innovation capabilities to safely develop new hydrogen fuel technologies from fundamental research to new product development to harness the potential hydrogen offers.	unforeseen issues, alternative solutions had to be made, as detailed in Appendix F.
MULAG	MULAG is one of the leading German manufacturers of high-tech products and special solutions for airport ground support and roadside maintenance vehicles. MULAG has over a decade's experience in developing and providing fuel cell vehicles. However, the technology is not yet established on airport platforms and still at the demonstration vehicle stage. Tests which have been conducted thus far have proven that fuel cell baggage HBTs can operate effectively and efficiently in airports.	MULAG's hydrogen fuel cell baggage HBT, COMET 4FC, was used to demonstrate the safe use of hydrogen fuelled equipment in an airside setting.
TCR	TCR provide services such as Full-Service Rental, Supply of Refurbished GSE, Telematics, Full Fleet Sales and Rent Back or Fleet Advisory. They have proven GSE expertise with longstanding experience in the GSE market.	TCR's logistics support was chosen for Project Acorn, allowing movement of equipment to and from trial locations.
Regulatory Advisor		
Organisation	**About**	**Involvement**
UK Civil Aviation Authority	The UK CAA are a public corporation, established by Parliament in 1972 as an independent specialist aviation regulator. The UK Government requires that their costs are met entirely from charges to those they provide a service to or regulate. Most aviation regulation and policy is harmonised across the world to ensure consistent levels of safety and consumer protection. Worldwide safety regulations are set by the ICAO.	The UK CAA acted as an aviation advisor and were the final reviewer of the trial's risk and safety assessment.

Appendix B. High-Level Literature Review on Hydrogen Regulations, Codes and Standards

✓	Area of application explicitly stated in text
x	Area of application not explicitly stated in text
-	Area of application not explicitly stated in text but applicable to project

Table 26: Summary of High-Level Literature Identified on Hydrogen Regulations, Codes and Standards

Area of application	Regulation, Codes and Standards	Compressed Gaseous Hydrogen	Liquid Hydrogen	Area Control	Description	Type of Vehicle	Safety Measures	Equipment Use
Hydrogen Fuel Quality	ISO 14687 Hydrogen fuel quality – Product specification* **(A new version of this standard is under development- ISO/DIS 14687)*	✓	✓	x	Hydrogen fuel for utilisation in vehicular and stationary applications (boilers/cookers, power generation, aircraft and space vehicle support systems and PEM fuel cells for road)	Road vehicles, aircraft, space vehicles	x	x
	BS EN 17124 Hydrogen fuel – Product specification and quality assurance for hydrogen refuelling points dispensing gaseous hydrogen – Proton exchange membrane (PEM) fuel cell applications for vehicles	✓	x	x	Hydrogen fuel is dispensed at hydrogen refuelling stations for use in PEM fuel cell vehicle systems.	Road vehicles, fuel cell power train	x	x
	SAE 2719 – Hydrogen Fuel Quality for Fuel Cell Vehicles	✓	x	x	Commercial PEM fuel cell vehicles (FCVs) at the point of interface between the vehicle and fuelling station.	FCVs	x	x
	ANSI/CSA CHMC 1 Test methods for evaluating material	✓	x	x	General – compatibility of a given metallic material with gaseous hydrogen.	–	x	x

Area of application	Regulation, Codes and Standards	Compressed Gaseous Hydrogen	Liquid Hydrogen	Area Control	Description	Type of Vehicle	Safety Measures	Equipment Use
Fuel Cell Vehicle	compatibility in compressed hydrogen applications — Metals.							
	ANSI/CSA CHMC 2 Test methods for evaluating material compatibility in compressed hydrogen applications — Polymers	✓	×	×	General – compatibility of a given polymer material with compressed hydrogen gas environments.	–	×	×
	BS EN 13445-1 – Unfired pressure vessels Part 1: General information on design and manufacturing of vessels	✓	✓	×	General – unfired pressure vessels with a maximum allowable pressure greater than 0,5 bar gauge.	–	×	×
	NFPA 2 – Hydrogen Technologies Code	✓	✓	✓	Hydrogen storage and utilisation in vehicles and stationary applications.	FCVs	✓	✓
	NFPA 55 – Compressed Gases and Cryogenic Fluids Code *(For compressed hydrogen gas or liquefied hydrogen gas in accordance with NFPA 2, this code does not apply when there are no specific or applicable requirements in NFPA 55).*	✓	✓	✓	General – storage, handling and utilisation of compressed gas systems	-	✓	✓
	CSA/ANSI HGV 2 Compressed hydrogen gas vehicle fuel containers	✓	×	×	Requirements for the material, design, manufacture, marking, and testing of Type HGV 2 containers for the storage of compressed hydrogen gas for on-road vehicle operation. These containers: are to be permanently attached to the vehicle;	Road vehicles	×	✓

Area of application	Regulation, Codes and Standards	Compressed Gaseous Hydrogen	Liquid Hydrogen	Area Control	Description	Type of Vehicle	Safety Measures	Equipment Use
					have a capacity of up to 1000 L (35.4 ft3) water capacity; and have a nominal working pressure that does not exceed 70 MPa.			
	ISO 19881 Gaseous hydrogen — Land vehicle fuel containers* **(A new version of this standard is under development - ISO/DIS 19881)*	✓	×	×	Requirements for the material, design, manufacture, marking and testing of containers for the storage of compressed hydrogen gas for land vehicle operation. These containers: are permanently attached to the vehicle, have a capacity of up to 1000 l water capacity, and have a nominal working pressure that does not exceed 70 MPa. The scope is limited to containers containing fuel cell grade hydrogen according to ISO 14687 for fuel cell land vehicles and Grade A or better hydrogen as per ISO 14687 for internal combustion engine land vehicles. This document also contains requirements for hydrogen fuel containers acceptable for use on-board light duty vehicles, heavy duty vehicles and industrial-powered trucks such as forklifts and other material handling vehicles.	Land vehicles	✓	×
	BS EN ISO 21009-2 Cryogenic vessels – Static vacuum insulated vessels Part 2: Operational requirements*	×	✓	✓	Stationary – operational requirements for static vacuum-insulated vessels designed for a maximum allowable pressure of more than 50 kPa (0.5 bar). This applies to vessels designed for cryogenic fluids in ISO 21009-1.	–	✓	✓

Area of application	Regulation, Codes and Standards	Compressed Gaseous Hydrogen	Liquid Hydrogen	Area Control	Description	Type of Vehicle	Safety Measures	Equipment Use
	**(A new version of this standard is under development - ISO/FDIS 21009-2)*							
	IEC 62282-2-100 : Fuel cell Technologies – Part 2-100: Fuel cell modules – Safety	✓	×	×	Fuel cell modules – safety-related requirements for construction, operation under normal and abnormal conditions and the testing of fuel cell modules.	-	✓	×
	EN IEC 62282-4-101	✓	×	×	Fuel Cell Technologies: Fuel Cell Power Systems for Propulsion Other Than Road Vehicles and APU - Safety of Electrically Powered Industrial Trucks	Electrically powered industrial trucks.	✓	✓
	EN IEC 62282-4-102	✓	×	×	Fuel Cell Technologies – Part 4-102: Fuel Cell Power Systems for Electrically Powered Industrial Trucks - Performance Test Methods	Electrically powered industrial trucks.	✓	✓
	SAE J2600 - Compressed Hydrogen Surface Vehicle Fuelling Connection Devices	✓	×	×	Design and testing of Compressed hydrogen Surface Vehicle (CHSV) fuelling connectors, nozzles, and receptacles. Applies to devices which have Pressure Classes of H11, H25, H35, H50 or H70.	Road – CHSV (also known as gaseous hydrogen land vehicle (GHLV))	✓	✓
Hydrogen Transport	NEN PGS 35 Hydrogen: Hydrogen: Installations for delivery of hydrogen to road vehicles *(This is intended to be used in conjunction with the subsequent PGS 35 reports detailing the*	✓	✓	✓	Applies to hydrogen delivery installations on land, including the associated and/or necessary auxiliary equipment, with a maximum delivery pressure of 350 bar or 700 bar of gaseous hydrogen for road vehicles with European type approval.	Road vehicles	✓	✓

Area of application	Regulation, Codes and Standards	Compressed Gaseous Hydrogen	Liquid Hydrogen	Area Control	Description	Type of Vehicle	Safety Measures	Equipment Use
	internal and external safety distances.)							
Hydrogen Storage	BS EN 17533 Gaseous hydrogen – Cylinders and tubes for stationary storage	✓	×	×	General – requirements for the design, manufacture and testing of standalone or manifolded cylinders, tubes and other pressure vessels intended for the stationary storage of gaseous hydrogen.	-	✓	✓
	ISO 11114 - Gas cylinders — Compatibility of cylinder and valve materials with gas contents — Part 1: Metallic materials	✓	×	×	General – safe selection and compatibility of metallic gas transport cylinders and valve materials with cylinder gas content.	–	×	×
	BSI BS EN ISO 10961 - Gas cylinders - Cylinder bundles - Design, manufacture, testing and inspection	✓	×	×	General – specifies the requirements for the design, construction, testing and initial inspection of a transportable cylinder bundle.	–	✓	✓
	ISO 9809-1:2019 Gas cylinders — Design, construction and testing of refillable seamless steel gas cylinders and tubes. Part 1: Quenched and Tempered Steel cylinders and tubes with tensile strength less than 1 100 MPa	✓	×	×	Specifies minimum requirements for the material, design, construction and workmanship, manufacturing processes, examination and testing at time of manufacture for refillable seamless steel gas cylinders and tubes with water capacities up to and including 450 l.	-	✓	✓
Refuelling	SAE J2601 (all chapters) Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles	✓	×	-	Protocol and process limits for hydrogen fuelling of vehicles with total volume capacities greater than or equal to 49.7L.	Medium and heavy-duty vehicles,	✓	✓

Area of application	Regulation, Codes and Standards	Compressed Gaseous Hydrogen	Liquid Hydrogen	Area Control	Description	Type of Vehicle	Safety Measures	Equipment Use
	(Standard is intended to be used in conjunction with SAE J2600)					industrial trucks		
	SAE J2799 Hydrogen Surface Vehicle to Station Communications Hardware and Software *(Standard is intended to be used in conjunction with SAE J2601 and SAE J2600)*	✓	×	×	Communications hardware and software requirements for fuelling hydrogen surface vehicles, such as fuel cell vehicles, HDVs (e.g., busses) and industrial trucks (e.g., forklifts) with compressed hydrogen storage.	FCVs, HDVs, industrial trucks	×	✓
	ISO 17268 Gaseous hydrogen land vehicle refuelling connection devices	✓	×	×	Defines the design, safety and operation characteristics of gaseous hydrogen land vehicle (GHLV) refuelling connectors.	Road – GHLV (also known as CHSV)	✓	×
	ISO 19880-1 Gaseous hydrogen – Fuelling stations – Part 1: General requirements *(The ISO 19880 family of documents specifies requirements for fuelling road and a broader range of vehicles.)*	✓	×	✓	Defines the minimum design, installation, commissioning, operation, inspection and maintenance requirements, for the safety, and, where appropriate, for the performance fuelling stations that dispense gaseous hydrogen to light duty road vehicles (e.g., fuel cell electric vehicles).	Fuelling stations for (but not limited to): motorcycles, forklifts, trams, trains and marine applications	✓	✓
	SAE J2719/1 - Application Guideline for Use of Hydrogen Quality Specification	✓	×	×	The purpose of this TIR is to provide guidance for minimising test requirements based on SAE J2719 while still ensuring fuel quality at hydrogen fuelling stations for PEM fuel cell vehicles (FCVs) and ICEVs (to the extent that has been determined).	PEM fuel cell vehicles (FCVs) and ICEVs	×	×

Area of application	Regulation, Codes and Standards	Compressed Gaseous Hydrogen	Liquid Hydrogen	Area Control	Description	Type of Vehicle	Safety Measures	Equipment Use
	ISO 19880-8 Gaseous hydrogen – Fuelling stations – Part 8: Fuel quality control* **(A new version of this standard is under development - ISO/DIS 19880-8)*	✓	×	×	Protocol for ensuring the quality of the gaseous hydrogen at hydrogen distribution facilities and hydrogen fuelling stations for proton exchange membrane (PEM) fuel cells for road vehicles. The ISO 19880 family of documents specifies requirements for fuelling road and a broader range of vehicles.	FCVs	×	✓
	ISO 19885-1 Gaseous hydrogen – Fuelling protocols for hydrogen-fuelled vehicles – Part 1: Design and development process for fuelling protocols. *(This is intended to coordinate with the ISO 19880 family of documents. ISO 19885-1 is currently under development with subsequent chapters - ISO 19885-2 and ISO 19885-3 - dealing with fuelling protocols)*	✓	×	×	Design and development of fuelling protocols for compressed hydrogen gas dispensing to vehicles with compressed hydrogen storage of fuel.	Transportation (not limited to) – LDVs, HDVs, industrial trucks, rail locomotives, airplanes, drones, maritime ships, boats	×	✓
	BSI BS EN 17127 Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols	✓	×	×	Minimum requirements to ensure interoperability of hydrogen refuelling points, including refuelling protocols that dispense gaseous hydrogen to road vehicles (e.g., Fuel Cell Electric Vehicles) that comply with legislation applicable to such devices. Safety and performance requirements for the refuelling station is not included.	FCV	×	✓

Area of application	Regulation, Codes and Standards	Compressed Gaseous Hydrogen	Liquid Hydrogen	Area Control	Description	Type of Vehicle	Safety Measures	Equipment Use
Fire Safety and Explosion Prevention	IEC 60079 (all parts) Explosive Atmospheres	✓	✓	✓	General requirements for construction, testing and marking of Ex Equipment and Ex Components intended for use in explosive atmospheres. Safety requirements are for explosion risk only. The subsequent chapter documents outline specific parts and associated technical specifications.	–	✓	✓
	ISO/IEC 80079 (all parts) Explosive atmospheres* *(A new version of this standard is under development - ISO/IEC AWI 80079)*	✓	✓	✓	General – explosion protection for electrical and other equipment.	–	✓	✓
	BS EN 1127-1 Explosive atmosphere – Explosion prevention and protection Part 1: Basic concepts and methodology	✓	✓	✓	Methods for the identification and assessment of hazardous situations leading to explosion and the design and construction measures appropriate for the required safety achieved through risk assessment and reduction.	–	✓	✓
	ISO/TR 15916 Basic considerations for the safety of hydrogen system	✓	✓	×	Guidelines for the use of hydrogen in its gaseous and liquid forms as well as its storage. It identifies the basic safety concerns, hazards and risks, and describes the properties of hydrogen that are relevant to safety.	-	✓	×
	NASA NSS1740.16 – Safety Standard for Hydrogen and Hydrogen Systems: Guidelines for Hydrogen System Design, Materials Selection, Operations, Storage and Transportation	✓	✓	✓	Minimum guidelines applicable to NASA Headquarters and NASA Field Centres for hydrogen system design, materials selection, operation, storage, and transportation.	-	✓	×

Area of application	Regulation, Codes and Standards	Compressed Gaseous Hydrogen	Liquid Hydrogen	Area Control	Description	Type of Vehicle	Safety Measures	Equipment Use
	ICC I-CODE IFC International Fire Code	x	x	✓	The model code and design document that regulates the minimum fire safety requirements for new and existing buildings, facilities, storage, and processes. It addresses fire prevention, protection, life safety, safe storage, and the use of hazardous materials..	-	✓	x
	ISO 11999-1 - PPE for firefighters — Test methods and requirements for PPE used by firefighters who are at risk of exposure to high levels of heat and/or flame while fighting fires occurring in structures — Part 1: General (A new version of this standard is under development -ISO/FDIS 11999-1)	x	x	x	ISO 11999 specifies minimum design and performance requirements for personal protective equipment (PPE) to be used by firefighters, primarily but not solely to protect against exposure to flame and high thermal loads.	-	✓	✓

Appendix C. BRS Hazardous Areas Classification – BRS

LEGEND

	ZONE 1 II C T1	AREA IN WHICH A FLAMMABLE ATMOSPHERE IS LIKELY TO OCCUR IN NORMAL OPERATION.
	ZONE 2 II C T1	AREA IN WHICH A FLAMMABLE ATMOSPHERE NOT LIKELY TO OCCUR IN NORMAL OPERATION. IF IT OCCURS WILL ONLY EXIST FOR A SHORT PERIOD.

NOTES

1. THE AREA CLASSIFICATION SHOWN ON THIS DRAWING HAS BEEN PREPARED IN ACCORDANCE WITH THE ENERGY INSTITUTE MODEL CODE OF SAFE PRACTICE PART 15 (EI15) 4th EDITION.
2. FURTHER DETAILS OF THE AREA CLASSIFICATION ARE RECORDED IN REPORT NUMBER BRS/003/3002.
3. INTERNAL ZONE 0 AREAS ARE NOT SHOWN IN THE PLAN VIEW.

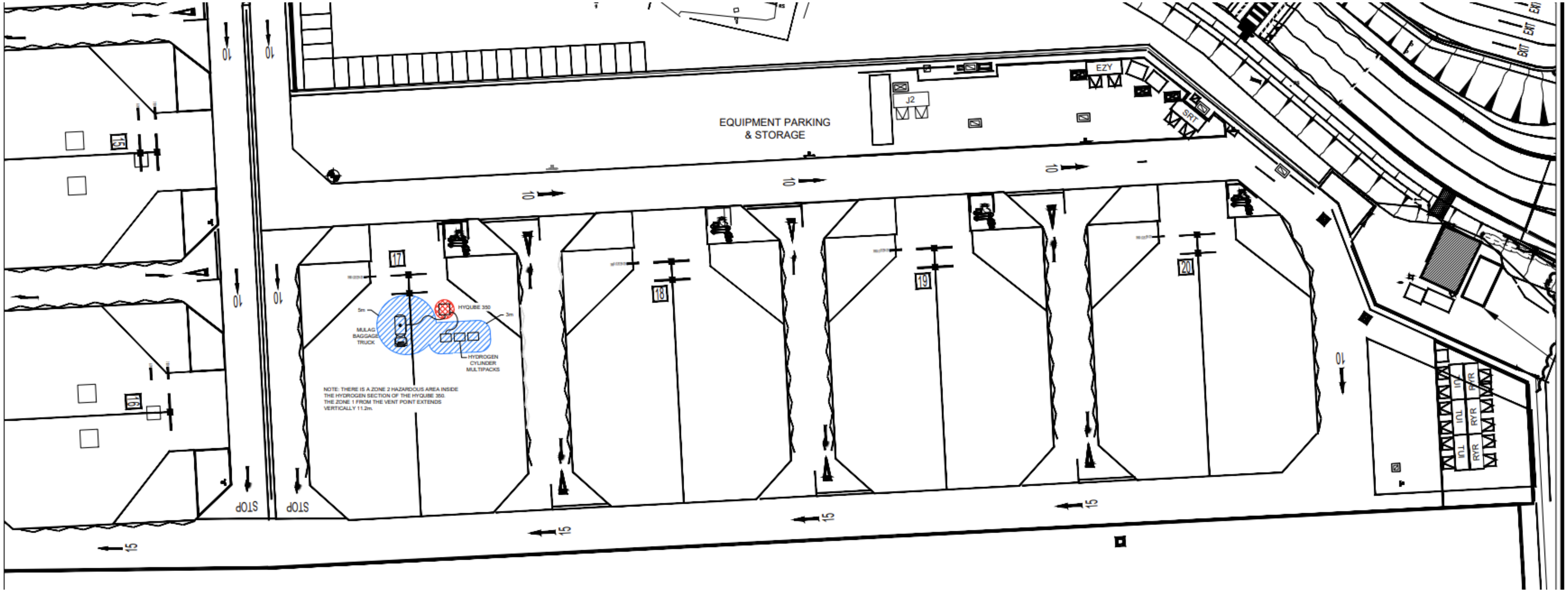


Figure 25: Bristol Airport Hydrogen Trial Hazardous Area Classification- Full Map

Appendix D. Further Detail on Landside Safety Training

Refueller (HyQube)

All the DHL handlers were given an overview of the refueller, its fuel and components, starting with the incoming hydrogen fuel quality necessary to help protect the fuel cell integrity in the HBT. Components discussed included its three-phase driven air compressor, hydrogen compression pump, hydrogen sensors, gaseous refuelling nozzle, safety shutdown features and mechanisms, as well as awareness of the chimney which performs hydrogen venting. The user interface panel (start, stop and emergency stop buttons) was also demonstrated and compressors were run to familiarise staff with the noise levels.

Cranfield University then provided a demonstration of the entire refuelling process, whilst the DHL handlers actively monitored the user interface panel to understand how much hydrogen was being dispensed until the safe pressure limit was reached (the HBT gaseous hydrogen tank is full) – which prompted the refueller to turn off automatically. The emergency stop button was also explained, which initiates a complete refueller shutdown and vents the hydrogen from the refueller into the atmosphere through the chimney.

It was also explained that hydrogen was vented to pressure release at the end of each refuelling session, to leave the refueller without any compressed hydrogen or air in it. The DHL handlers were forewarned that venting would occur at the end of each refuelling event, if the emergency stop button was pushed, or automatically in the event of a fault being detected by the refueller. This venting would also result in a very high-pitched sound – which was demonstrated first whilst all attendees covered their ears, and then repeated to ensure the DHL handlers were prepared for the sound and not startled during operation.

DHL handlers were also shown inside of the refueller, so they had a basic understanding of the components of the HyQube and its inner workings and connection to the MCP. The communication links between the MCP and the refueller were outlined, including an overview of how pressure sensing between each of the two pieces of technology and equipment occurred via pressure monitoring in the connecting pipe. It was explained that the pressure in the tank was dependent on temperature, not just the amount of gas being pumped in – reinforcing the importance of the user interfaces to understand the amount of hydrogen delivered to the HBT during each refuelling session, as well as in-built and automated safety mechanisms in different conditions.

DHL handlers practiced inserting, removing and storing the gaseous hydrogen refuelling nozzle in the HBT and refueller, as well as monitoring the user interfaces in both the refueller and HBT. However, while the refuelling time could be as low as three minutes in some cases, not every handler was able to test the whole refuelling process end-to-end, and not all operators were able to observe all possible operator information messages that might display on the HyQube user interface during refuelling (e.g., when the HBT was full or the MCP was signalling that it was empty or low on pressure).

Therefore, further training and briefings were given before the commencement of the airside trial at BRS to ensure all operatives were competent and comfortable with the potential user interface messages and the safe operation of the refuelling process. This process involved learning safe operation and implementing risk mitigation associated with the following steps:

1. Taking the nozzle from the refueller
2. Inserting into the HBT
3. Starting refuelling
4. Stopping refuelling
5. Removing the nozzle from the HBT
6. Returning the nozzle to the refueller.

Additionally, DHL handlers were familiarised with the sound hydrogen would likely make in the unlikely event of a leak, procedures to vent hydrogen and other fail safes.

MULAG Comet 4FC (HBT)

The DHL handlers' orientation of the HBT was provided by MULAG who gave an overview of the main components of the vehicle to perform their baggage handling duties. Components discussed included the main switches, automatic reversing system and rear-view camera, dashboard and cabin, fuel cell display system, hydraulic brake and steering system, as well as parking brakes and emergency systems.

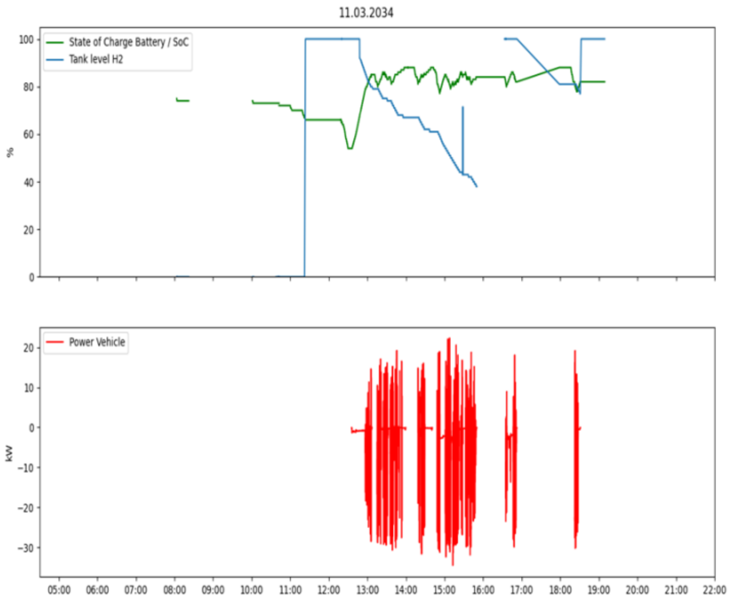
An overview of the fuel cell system was also given by GLOBE Fuel Cell Systems as part of the DHL handlers' vehicle orientation which included; an overview of the fuel cell, hydrogen pump and tap, steel tank (filled with approximately 1.63kg of H_2), the battery system and driver control panel. DHL handlers were able to view these systems located in the rear of the HBT and ask questions about the equipment and its specifications.

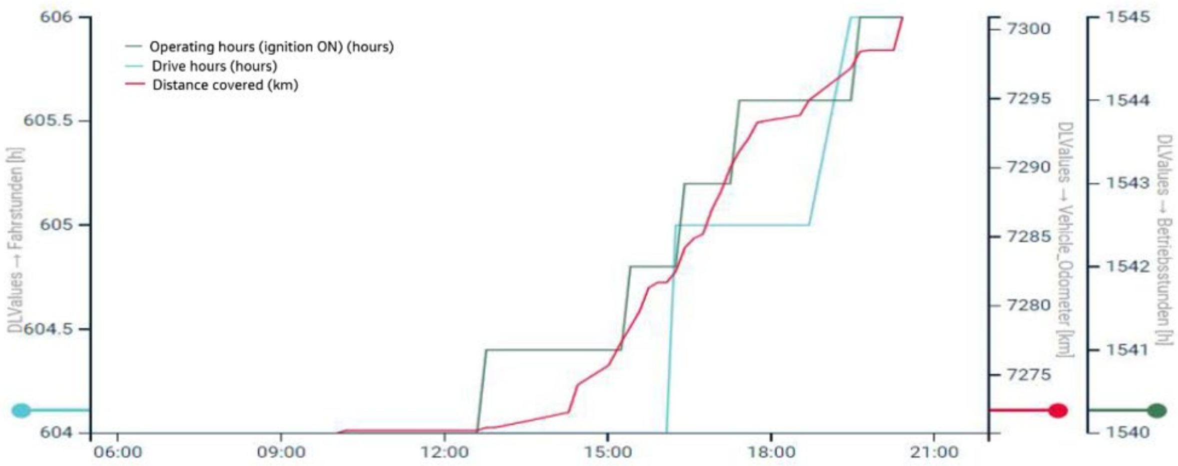
All the DHL handlers were also trained to drive the HBT during one-on-one lessons, as well as practice manoeuvring the HBT at Cranfield University's campus. However, not every handler was able to test the 'driver-out' (driverless) reversing feature due to poor weather for some of the scheduled training period. As such, further training and briefings were given before the commencement of the airside trial at BRS to ensure full understanding of the HBT's systems and safety features prior to operation.

Appendix E. BRS HBT Daily Telematics

Day 1:

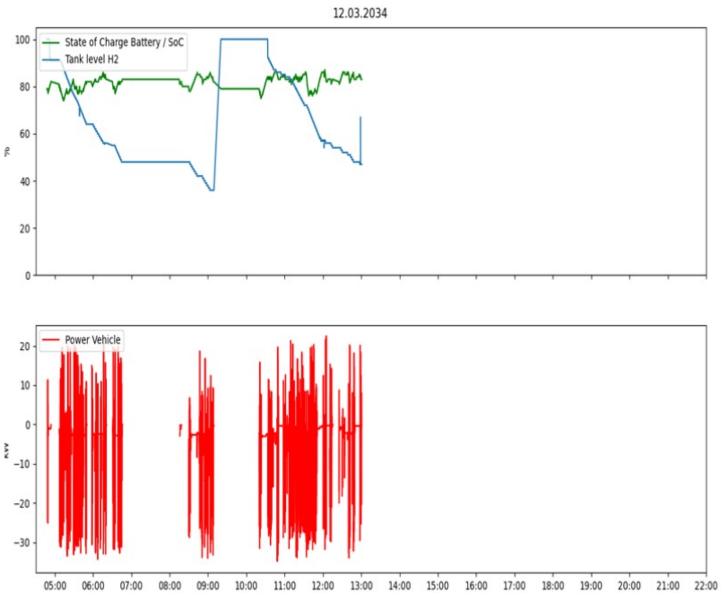
Ambient Temp Max [°C]	13.3
Ambient Temp Min [°C]	8.1
Ambient Humidity Max [RH%]	78.8
Ambient Humidity Min [RH%]	53.6
Ambient Pressure Max [mbar]	1,003
Ambient Pressure Min [mbar]	990

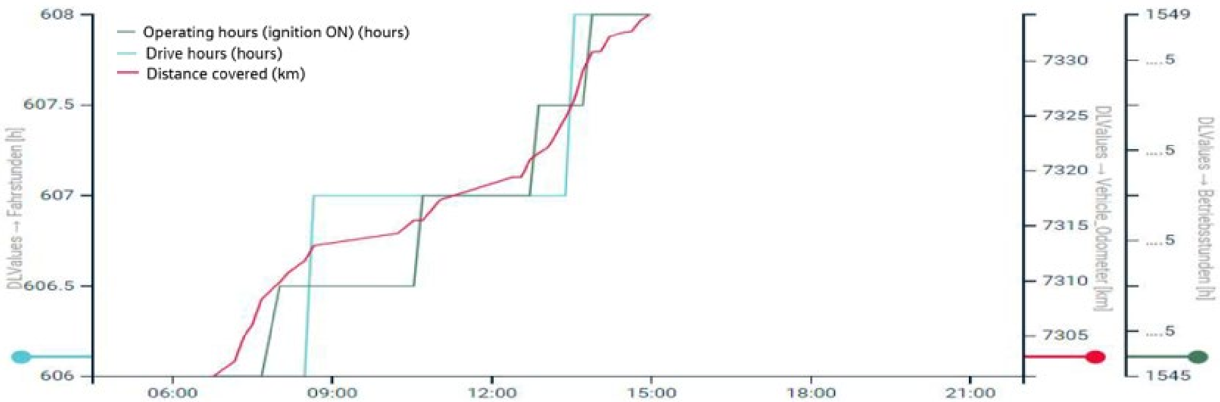




Day 2:

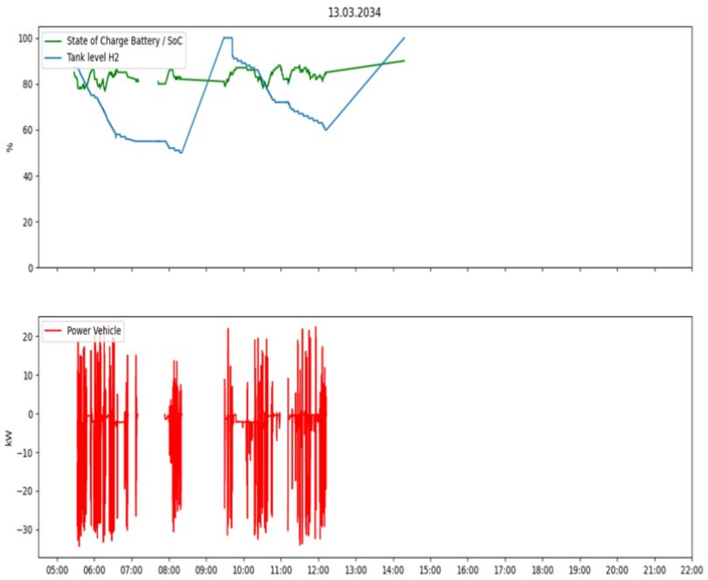
Ambient Temp Max [°C]	21.4
Ambient Temp Min [°C]	9.5
Ambient Humidity Max [RH%]	90.3
Ambient Humidity Min [RH%]	51.4
Ambient Pressure Max [mbar]	993
Ambient Pressure Min [mbar]	989

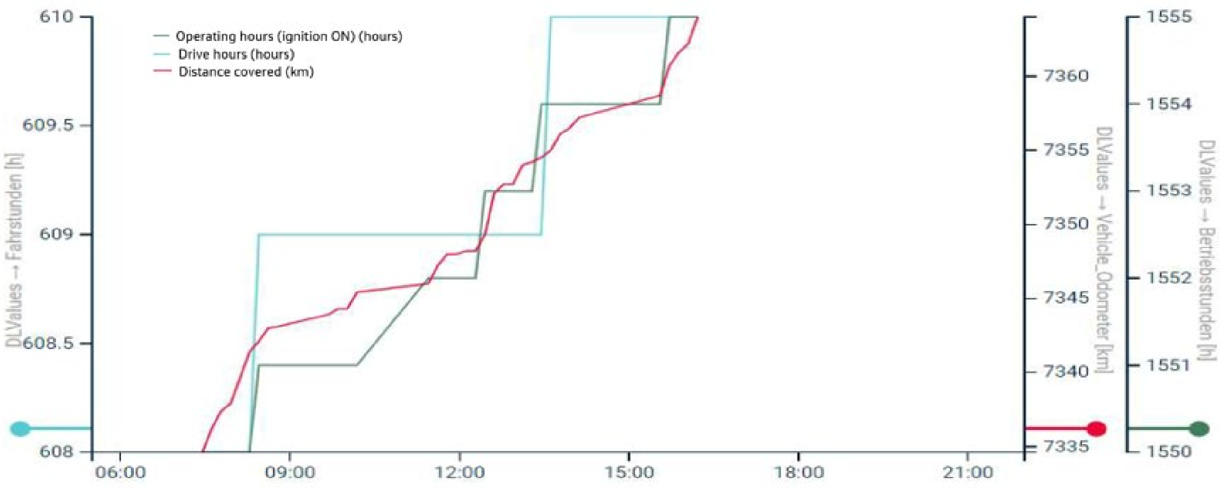




Day 3:

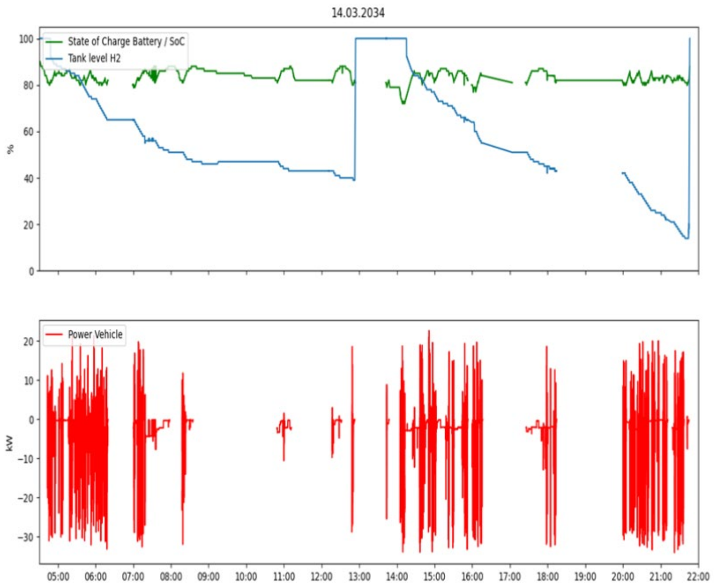
Ambient Temp Max [°C]	23.4
Ambient Temp Min [°C]	9.9
Ambient Humidity Max [RH%]	86.4
Ambient Humidity Min [RH%]	46.0
Ambient Pressure Max [mbar]	993
Ambient Pressure Min [mbar]	988

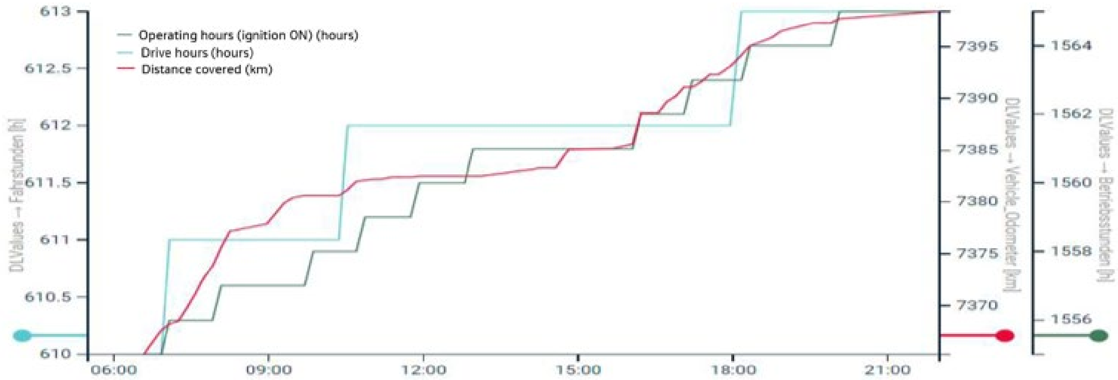




Day 4:

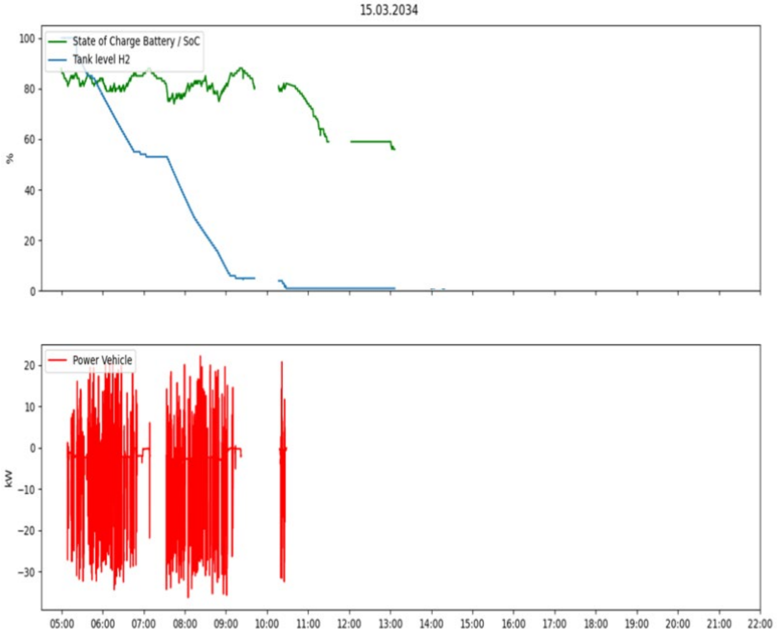
Ambient Temp Max [°C]	21.1
Ambient Temp Min [°C]	10.0
Ambient Humidity Max [RH%]	88.0
Ambient Humidity Min [RH%]	52.6
Ambient Pressure Max [mbar]	989
Ambient Pressure Min [mbar]	983

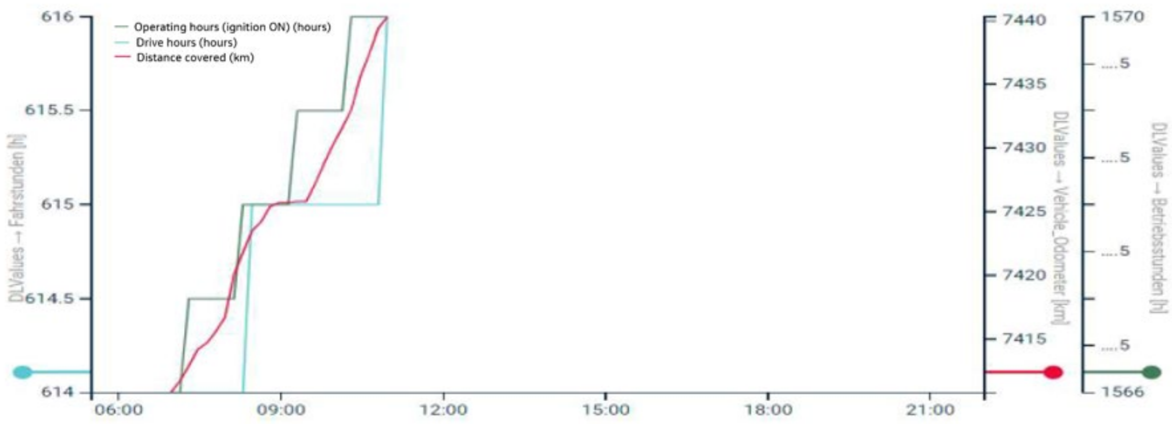




Day 5:

Ambient Temp Max [°C]	21.1
Ambient Temp Min [°C]	10.0
Ambient Humidity Max [RH%]	88.0
Ambient Humidity Min [RH%]	53.0
Ambient Pressure Max [mbar]	989
Ambient Pressure Min [mbar]	983





Appendix F. Further Detail on Hydrogen Supply and Storage Challenges

Project Acorn planned to use IAAPS' green hydrogen production facility at the Bristol and Bath Science Park, which became operational in August 2023. The specification for the IAAPS green hydrogen production facility is shown in Table 27 below. This facility includes a storage tank and a 500kW electrolyser, which is powered by a 400kW array of solar PV panels located on the roof of the IAAPS building. The green hydrogen would have been stored and distributed using a mobile refueller, but this option was not possible due to delays relating to manufacture.

Furthermore, due to a lack of available infrastructure for storing and distributing the green gaseous hydrogen from IAAPS to BRS, an alternative hydrogen source had to be procured. Alternative green gaseous hydrogen suppliers were identified which had the capability to deliver the required 30kg for the trial at BRS. However, there was an evident shortfall in commercially available green hydrogen at the time of the trial. The only supply Project Acorn could obtain was high purity grey hydrogen produced via steam methane reforming from an alternative industrial gas company. While not the green hydrogen that Project Acorn had intended, this shortfall highlighted the need for more logistics capability to store and move hydrogen from production sites to test-sites. This may also prove to be a challenge that the aviation industry will face in obtaining sufficient low carbon hydrogen supply in the future.

Table 27: IAAPS Green Hydrogen Intended for Project Acorn

Specification	Value
Electrolyser Max Power Rating	500 kW
Solar Array Capacity	400 kW
Hydrogen Generation Capability	9 kg/hour
Hydrogen Pressure	30 bar
Storage Tank Capacity	270 kg
Hydrogen Purity	ISO14687 Standard (>99.97 %)

Appendix G. Glossary

ADR Certified	Certification required by the European Agreement concerning the International Carriage of Dangerous Goods by Road which confirms that a vehicle is safe to transport dangerous goods on the road.
Apron Parking Location	A designated area of an airport where aircraft are parked, unloaded, loaded, refuelled, and boarded by passengers. This is typically located adjacent to the terminal building. It is also where ground support equipment, such as baggage carts, fuel trucks, and catering trucks, operate near the aircraft.
Breakaway Connector	Connector between the HyQube refuelling nozzle and the HBT receptacle that is designed so that if the hydrogen baggage tractor (HBT) moves during refuelling, the connector will seal immediately so minimal gaseous hydrogen is released.
Cryogenic	The science that addresses the production and effects of very low temperatures. In terms of liquid hydrogen, this is a cryogenic by nature because to liquefy hydrogen, it must be cooled to cryogenic temperatures through a liquefaction process.
Electrolyser	Electrolysers use electricity to split water into hydrogen and oxygen. They are the critical technology required for producing low-emission hydrogen from renewable (green hydrogen) or nuclear electricity (pink/purple/red hydrogen).
Earthed	When equipment is fitted with a low resistance wire that will transmit the electrical energy to the earth in the event of a lightning strike, protecting the equipment and reducing the likelihood of ignition.

Main Apron	The area of an airport where aircraft are parked, unloaded, loaded, refuelled, and boarded by passengers.
Manifold Cylinder Pallet (MCP)	A MCP is a series of industrial gas cylinders that are all joined together. MCPs are often called Industrial Cylinder Banks. These gas banks are filled and discharged together and are used where high volumes of industrial gas are required, in this case hydrogen.
Minimum Ignition Energy (MIE)	Defined as the minimum amount of energy required to ignite a fuel-air mixture without the presence of an external flame or spark. For hydrogen, this is exceptionally low, meaning it can ignite easily.
Mobile refuelling	When the fuel is delivered directly to the application requiring the fuel, at the desired location. This is as opposed to stationary refuelling from a fixed unit, like a refuelling station.
Multiple-Element Gas Containers (MEGCs)	A unit used to store and transport high pressure gases, such as gaseous hydrogen. They contain elements which are linked to each other by a manifold and mounted on a frame, and which can then be applied to a trailer, ship container or fixed location. The following elements are parts of a multiple-element gas container: cylinders, tubes, pressure drums or bundles of cylinders.
Proton-Exchange Membranes (PEMs)	This is the type of fuel cell employed. The electrolyte layer between the anode and cathode is contained within a membrane. This electrolyte membrane is responsible for the transport of protons (H+) from the anode to the cathode, where it reacts with air. Damage to the membrane is irreversible and reduces ionic conductivity until the cell is unable to perform its function.

Flight mode	A setting on a smartphone or tablet for use on board an aircraft, in which the device does not receive or transmit wireless signals and so does not interfere with the aircraft's communication systems.
Fuel farm	A hazardous storage facility where products are stored in large quantities in fixed bulk tanks above or below ground.
Green hydrogen	Hydrogen produced without any CO_2 emissions and using renewable electricity to power the electrolysis process used to split water molecules into hydrogen and oxygen.
Grey hydrogen	In the UK currently, hydrogen is commonly produced through industrial processes from fossil-fuel feedstock (via steam-methane reforming or SMR), classified as grey hydrogen.[xlviii]
Ground handler	Personnel involved in the servicing of an aircraft while it is on the ground and parked at a terminal gate of an airport
Ground Support Equipment (GSE)	The support equipment found at an airport, usually on the servicing area by the terminal, used to service the aircraft between flights.
Hydrogen Baggage Tractor (HBT)	MULAG Comet 4 Hydrogen Baggage Tractor used in this trial to load, transport, and unload passenger baggage.
Hydrogen fuel cell	A device that produces electricity by using a chemical reaction to convert hydrogen and oxygen into electricity, heat and water.
Radiant heat	Also known as thermal radiation, it describes the exchange of heat energy. Hydrogen is said to have a lower radiant heat than conventional gasoline because a hydrogen molecule is much smaller. During combustion, fewer bonds in the molecule must be broken, releasing less heat. Therefore, at a constant volumetric flowrate, hydrogen will have a lower radiant heat per mole.
Receptacle	An object that holds something, such as a device in a wall that you put a plug into. Here, the hydrogen refuelling between the HyQube and HBT. The connection is made from the HyQube nozzle to the HBT vehicle receptacle using the supply hose.
Residual Current Device (RCD)	A safety device that switches off electricity automatically if there is a fault.
Safe System of Work (SSoW)	A method of work which puts in place control measures arising from a risk assessment, in order to eliminate identified hazards (where possible) and complete the work with minimum risk.
Sustainable Aviation Fuels (SAF)	Typically, these are biofuels derived from biomass or waste materials like cooking oils and fats. Advanced biofuels, synthesized from sources such as solid feedstock and biomass crops, provide a secondary option. Synfuels, also known as power-to-liquid fuels and e-kerosene or e-fuels, can be manufactured using hydrogen and CO_2 from industrial processes, or direct-air capture.[xlix]
Temporary Airport Instruction (TAI)	A notification of a temporary change to an airside operating procedure of instruction (according to Bristol Airport’s Aerodrome Manual).
Thermal radiation	Also known as radiant heat. In the context of hydrogen having low radiant heat/thermal radiation, this makes it difficult for humans and traditional heat or thermal/flame sensors to detect.
Transportable Pressure Equipment	This sets out detailed rules on transportable pressure equipment, to improve safety and to ensure free movement of such equipment within the EU. It updates previous legislation,

HyQube refueller	A modular, scalable and re-deployable hydrogen refuelling system, which provides high energy efficiency and a compact design for space optimisation at required refuelling locations.
JET A-1 kerosene fuel	A conventional fuel grade that is suitable for most turbine engine aircraft.
Low carbon hydrogen	The UK Government's Low Carbon Hydrogen Standard was introduced in 2022 to support the UK's move towards net-zero emissions. To be compliant, any hydrogen produced should have a final GHG emission intensity less than or equal to 20 gCO_2e/MJ_{lhv}.

Directive (TPED)	particularly regarding conformity requirements, conformity assessments, periodic inspections and checks in relation to transportable pressure equipment.
Turnaround	The time elapsed between an aircraft arriving on its parking stand and departing for the next flight.
Undercroft	The enclosed back-of-house baggage sortation and drop-off area at Bristol Airport. A relatively confined and busy space with numerous activities taking place, including the loading and unloading of passenger baggage.
Zoning	In short, zoning is a method to segment a system/area into zones with different risk levels. In the UK, airports have responsibilities under the Health and Safety at Work Act 1974 to secure the safety of persons at work and public from hazards arising out of activities on their premises. Therefore, they have a duty to be complaint with the Dangerous Substances and Explosive Atmosphere Regulations 2002 (DSEAR) as they handle aviation fuel and other dangerous substances. Specific rules relating to zones are mandated by the Civil Aviation Authority (CAA) and European Directive relating to explosive atmospheres (ATEX) (Garrison, 2018).[l]

Endnotes

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[1] Mixed fleet scheduling method for airport ground service vehicles under the trend of electrification: https://www.sciencedirect.com/science/article/abs/pii/S0969699723000224
[2]What Share of Global CO_2 Emissions Come from Aviation?: https://ourworldindata.org/global-aviation-emissions
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