Jet Zero Taskforce Hydrogen Task and Finish Group Report

Abstract

This report presents the findings and recommendations of the Jet Zero Taskforce's Hydrogen Task and Finish Group, outlining a strategic roadmap for hydrogen-powered aviation in the United Kingdom. It confirms the technical viability of hydrogen propulsion, identifies key enablers such as infrastructure, regulation, and certification, and highlights the UK's opportunity to lead globally in zero-emission flight. The report details phased deployment through six Evolution Points, from initial gaseous hydrogen operations to full-scale liquid hydrogen networks. It emphasises the need for coordinated investment, policy support, and regulatory development to unlock economic, environmental, and industrial benefits by 2050 and beyond.

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Foreword

Hydrogen in aerospace remains a promising avenue to drive the decarbonisation of the aviation sector. Whilst SAF, greenhouse gas removal and contrail avoidance are key to addressing aviation's contribution to climate change, hydrogen propulsion offers the prospect of genuinely new, clean propulsion for the future. It has been a real privilege to work with British companies delivering the sort of innovation that has not happened in this sector since Frank Whittle pioneered the jet engine. Whittle may have shrunk the world, but it's now our responsibility to keep economies, people and cultures connected for generations to come while addressing carbon emissions.

Making a hydrogen aircraft is a hard enough challenge, but it also requires a whole ecosystem of infrastructure and operational processes to work practically and safely in an industry as regulated as aviation. The task and finish group has brought together academics, aerospace companies, innovators, airlines that will fly hydrogen aircraft, airports where they will land and refuel, and the national regulator to provide expertise across the entire breadth of the problem. This report is the first time I have seen these different perspectives brought together in a single document, and the commitment, passion and knowledge of the group has been invaluable.

The market will start with smaller aircraft and scale up from there. The UK's geography, particularly in areas like the highlands and islands of Scotland, means that hydrogen aviation can generate value in regions even at its birth. The UK is uniquely placed not only to develop the technology for hydrogen flight, but also to demonstrate its viability.

The significant benefits from hydrogen propulsion will come with scaling up to larger, liquid-hydrogen powered aircraft that can fly more passengers on more routes. That will require consistent effort across the aerospace community, with innovation not just in propulsion, but in support for airport infrastructure, and for fuel production. These are challenges that cross into energy supply and industrial policy more generally.

It's an exciting time to be involved in aviation, and as we anticipate some significant milestones in the coming years, I'd like to thank all of the members of the task group for their continuing efforts in this critical field.

David Debney

Group Members

Adrian Bates, GKN Aerospace
Abrar Bajwa, Airbus
Rebecca Borresen, Loganair
Graham Bolton, Mott Macdonald
James Cox, Bristol Airport
David Debney (Chair), ATI
Helen Leadbetter, CAA
Hervé Morvan, Rolls-Royce
Jenny Kavanagh, Independent
Gia Kroeff, Easyjet
Mutinda Musuva (Secretariat), ATI
Fiona Smith, AGS Airports
Dominic Weeks, ZeroAvia
Mark Westwood, Cranfield University
Officials from the Departments for: Business and Trade, Transport, and Energy, Security and Net Zero.

Executive Summary

Hydrogen presents a fundamental opportunity for UK aviation to progress toward net-zero emissions and achieve global leadership in sustainable aviation. This report presents a strategic roadmap outlining the deployment of hydrogen-powered aircraft and possible route networks, infrastructure requirements and operational changes. It details the evolution from initial gaseous hydrogen aircraft operations to full-scale liquid hydrogen networks, identifying key milestones, challenges, and actions. The analysis shows that the majority of hydrogen impact before 2050 will be delivered through sustainable fuels in combination with direct fuel use for regional airline operations, with larger hydrogen aircraft directly using hydrogen having a significant impact after 2050.

The target of initial UK commercial operations by 2030 is feasible with the right support. UK-led demonstrations show that hydrogen propulsion systems are maturing to support sub-regional aircraft (with fewer than 19 seats) in this timeframe. These aircraft are expected to be technically capable of supporting the UK's existing route network, particularly in rural and island regions. Public Service Obligation (PSO) routes offer an adaptable mechanism to provide subsidy for initial operations while the system is still being cost-optimised.

Infrastructure development is a critical enabler that needs specific focus. Airports are currently struggling to make investment cases for infrastructure due to the lack of clarity over aircraft project timelines. New airport infrastructure will need to be developed, tested and installed. Operational procedures for refuelling, storage and fuel supply will need to be developed and integrated to ensure safe hydrogen operations. Gaseous operations can build on automotive technology. For liquid hydrogen operations, early investment in two to three regional hubs with European connectivity presents a scalable model; however, planning timelines, technical and investment challenges must be addressed.

The Civil Aviation Authority (CAA) is globally respected for the progress it has made in hydrogen aviation regulation through programmes such as the Hydrogen Challenge; however, increasing its capability and capacity to develop hydrogen regulations is a critical enabler. Defining the overall regulatory framework is complex and will require multiple regulators to come together and share expertise in a short timescale to achieve the initial operations target, as well as the future introduction of larger aircraft using liquid hydrogen fuel.

Hydrogen is an essential feedstock for decarbonising the sector. Whilst direct use as a fuel will scale up after 2050 as larger platforms come into service, hydrogen as a direct fuel for regional hydrogen operations and as a feedstock for SAF is critical to support the UK Net Zero 2050 target. Enabling access to hydrogen for use in aviation is, therefore, a limited risk strategy that complements SAF and Electrification in the Net-Zero Transition. With coordinated investment, policy support, and regulatory development, the UK can lead in zero-emission flight and secure long-term environmental, economic, and industrial benefits.

Hydrogen Task and Finish Group Key Findings

1. Delivering the first commercial gaseous hydrogen flights by 2030 from a UK airport is a feasible target

The summary roadmap for achieving initial gaseous hydrogen operations (Figure 1) shows the different timelines across the key elements of the ecosystem that need to be delivered. Several UK-based R&D projects, some of which have received ATI funding, have been developing hydrogen-electric powertrains for sub-regional aircraft. The Task and Finish group concluded that sub-regional aircraft technology readiness is on track for the 2030 timeline. However, the regulations for hydrogen aircraft are not yet defined. The CAA will need to work closely with industry to develop the knowledge and skills necessary to create appropriate regulations.

Several specific challenges have been identified that need to be solved to enable the 2030 operational target. Importantly, the solutions developed for these challenges also serve as enablers for introducing liquid hydrogen operations.

- **Fuel quality assurance:** The use of fuel for aviation is governed by a stringent assurance process to ensure that the fuel the aircraft receives is free of harmful contaminants. The current method of ensuring hydrogen fuel purity requires sampling and lab testing. This may be sufficient for initial operations, but it will limit how quickly and effectively they can be scaled. The target is to enable production-line or in-line purity testing. The National Physical Laboratory is working on this technology, but the timelines are uncertain.
- **Hydrogen operational procedures:** Pilot hydrogen activities already initiated at airports identified a fragmented legislative landscape and a lack of consolidated operational guidance for airside hydrogen storage and refuelling, including safety zones. Clarity is required to mitigate safety and business risks associated with commercial operations.
- **Airport business case:** Investment support would enable investment in hydrogen refuelling and storage infrastructure at a small number of selected airports. This support could be delivered through capital grants or green infrastructure funds.
- **Fleet planning and route selection:** Airlines typically plan their fleet requirements five years ahead or more. Operators and the UK Government will need to work closely together to identify routes for initial hydrogen operations, as a level of subsidy is expected to be required. Public Service Obligation (PSO) routes appear to be likely candidates, as these routes are already subsidised. Operational incentives, such as emission credits, or reductions in air navigation or landing charges for zero-emission flights, should also be considered.

2. The UK is well positioned for early hydrogen operations, which would support regional jobs and growth

The analysis completed by the task and finish group shows a possible route network for aircraft with 9-19 seats in the UK and Europe. This sub-regional segment provides local and feeder networks, often via public service obligation (PSO) routes, particularly in rural and island regions. These networks include routes in the Scottish Highlands and Islands, as well as mainland connections to Northern Ireland. Other currently unserved opportunities may emerge, for example, in South West England and Wales, where limited surface transport connectivity has historically justified the provision of air services.

3. **To realise significant commercial and sustainability benefits from hydrogen aircraft, the sector must scale to large commercial aircraft using liquid hydrogen**

Today, regional aircraft account for around 3% of UK aviation CO2 emissions, single-aisle aircraft around 29% and widebody aircraft around 68%. This is skewed by the large number of long-haul routes that operate from the UK. Globally, the share for single-aisle aircraft is around 37% with a corresponding reduction in widebody emissions. Therefore, to have any significant sustainability or economic impact, hydrogen aviation must break into the single-aisle market segment, and ideally the widebody segment.

The task and finish group has compiled a market scenario which estimates when large commercial hydrogen aircraft may enter service following early operations with aircraft that have 50 seats or fewer. It shows a regional aircraft with 100 seats in 2042, a single-aisle aircraft (160-180 seats) in 2050 and a widebody in 2063. This means that the most significant sustainability benefits of hydrogen aviation will only be delivered after 2050.

However, recognising the long lead-time of technology development in aerospace, investment is needed now to develop some of the critical technologies that will underpin the development of these aircraft platforms.

4. **Hydrogen infrastructure development is not progressing at the required rate**

For both gaseous and liquid hydrogen operations, the airport and refuelling infrastructure are close to the critical path. Figure 1 and Figure 2 both show that infrastructure development needs to accelerate. Airbus has stated that a key reason for delaying the ZEROe aircraft programme was the lack of progress on the low-carbon liquid hydrogen production supply chain and economic development.

Consultation with airports around the UK as part of the task and finish group research identified a difficulty in making the investment case without the launch of an aircraft programme providing a demand signal. Fixed infrastructure at airport sites and the supply network will be pivotal to enabling the ecosystem to scale at pace. Not all airports need to move to hydrogen to create a successful network, although these early adopter sites are key to enabling the scaling up of hydrogen operations. This could mean that some early adopters do not evolve beyond that stage, and therefore, the case for investment would be unlikely to be met without support.

Airport planning timescales for large-scale electrical infrastructure or major land acquisition can exceed 10 years, and this is critical for scaling up hydrogen operations. These lead times will necessitate investment earlier than the financial case closes for the asset owners and operators. Bridge funding in some form will therefore be required, potentially in the form of capital grants or green infrastructure funds.

Refuelling technology development is another key area to allow liquid hydrogen operations to scale.

5. **Significant benefits from hydrogen can be achieved at scale with only a few hydrogen-enabled airports supporting large commercial hydrogen aircraft**

The ATI-funded LH2GT project's conclusions emphasise the UK’s opportunity to lead in hydrogen aviation by investing early in a few large airports capable of handling liquid hydrogen. The study suggests 80% of the overall sustainability benefit achieved by fully deploying hydrogen can be realised with only 20 key European airports having liquid hydrogen capability. As a result, the UK can promote a collaborative and phased transition to hydrogen aviation, meeting future fuel mandates. Focusing on just three strategic hubs in the UK could enable scalable, low-carbon air travel across Europe, delivering up to a 7% improvement in airline profitability and a 14% reduction in UK electricity consumption, which provides tangible economic incentives. These hubs would complement UK regional airports that have developed hydrogen capability as part of the evolution of hydrogen in aviation.

6. **The majority of aviation hydrogen demand before 2050 will come from sustainable fuel production rather than direct usage. Hard to decarbonise sectors, like aviation, should be prioritised when considering future hydrogen demand.**

The market scenario developed by the task and finish group indicates that direct hydrogen demand in aviation is expected to be relatively low until after 2050. However, many types of SAF, including biofuels and e-fuels, require hydrogen as part of the production process. The UK SAF Mandate includes a minimum quantity of e-fuels, due to scalability concerns with some bio-feedstocks. The result of this is that around 90% of aviation's hydrogen demand before 2050 will be to support SAF production.

The Department for Energy Security and Net-Zero (DESNZ) estimated aviation will receive approximately 16% of total UK hydrogen production in a 2023 report. Analysis by the Task and Finish group projects that this will be sufficient to meet UK aviation demand until 2050, but demand ramps up significantly by 2070. The modelled scenario shows that aviation will consume the majority of the hydrogen produced in the UK by 2070. This means that the UK's hydrogen production capacity will need to increase by 2070 if the UK is to ensure its sovereignty of hydrogen supply. Infrastructure decisions will need to be made sufficiently early to allow for long lead times.

7. **A nationally coordinated demonstration programme is needed to bring together aircraft OEMs, airports, infrastructure and equipment providers, hydrogen suppliers, operators, training organisations and the regulators.**

Currently, different disciplines are demonstrating technologies and developing processes independently, which introduces a risk of a coordination failure. A national programme, or centralised facilitation, would focus efforts, set goals, and ensure consistency across all disciplines needed to accelerate/ensure success. The UK risks falling behind Europe unless it moves from isolated demonstrations to an integrated network of physical, digital and regulatory test environments. This is vital for testing and validating technology, operations, and safety at a system-wide level. Demonstrations strengthen knowledge and skills related to the use of hydrogen and other zero-emissions technologies across the sector, supporting growth, job creation and upskilling. Initiatives such as the Hydrogen Airports Community of Practice could be utilised as a platform for sharing best practices and learning.

8. **Hydrogen aviation strengthens the UK's global leadership and innovation edge**

The UK hosts pioneering firms (e.g. ZeroAvia and Intelligent Energy) as well as established incumbents with proven capability to take solutions through certification and into global markets. It is therefore well positioned to lead in certification, operations, and export markets for hydrogen aviation. First-mover advantage in hydrogen aviation supports energy security and global competitiveness in green technologies. This also reinforces the UK's Science Superpower ambition, Global Britain strategy, and Clean Growth Strategy.

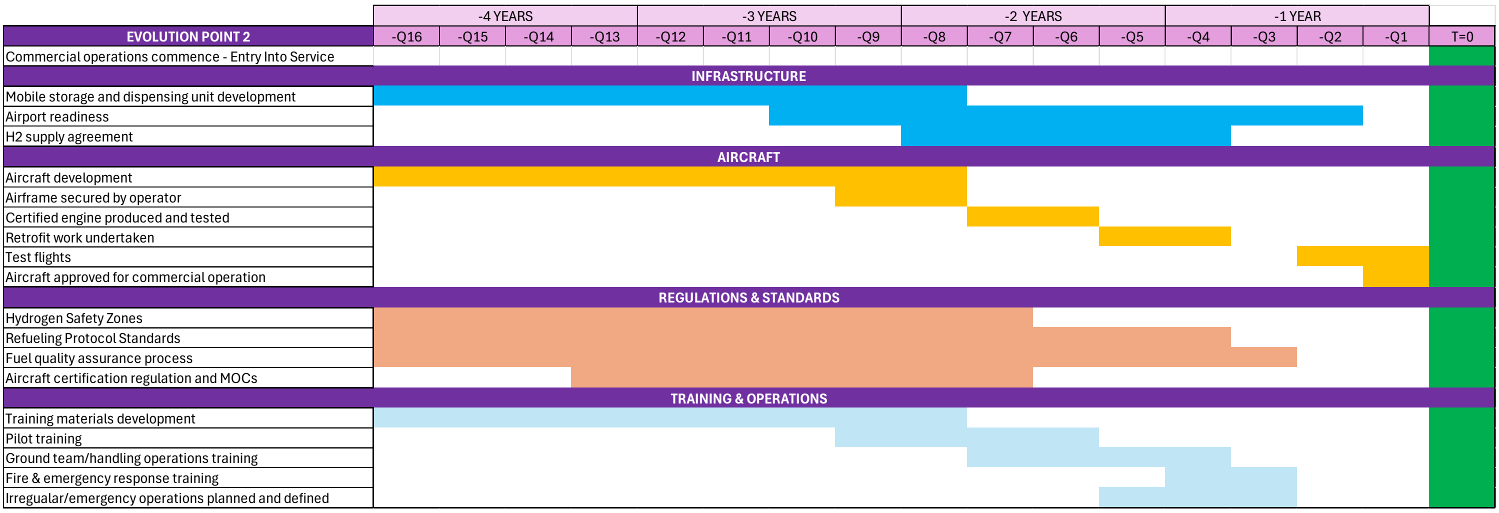


Figure 1: Building commercial hydrogen operations through an integrated ecosystem of trials, regulation and early deployment. Entry into service (EIS) is assumed at T-0. Gaps to this point are intended as capabilities need to be delivered in advance of EIS.

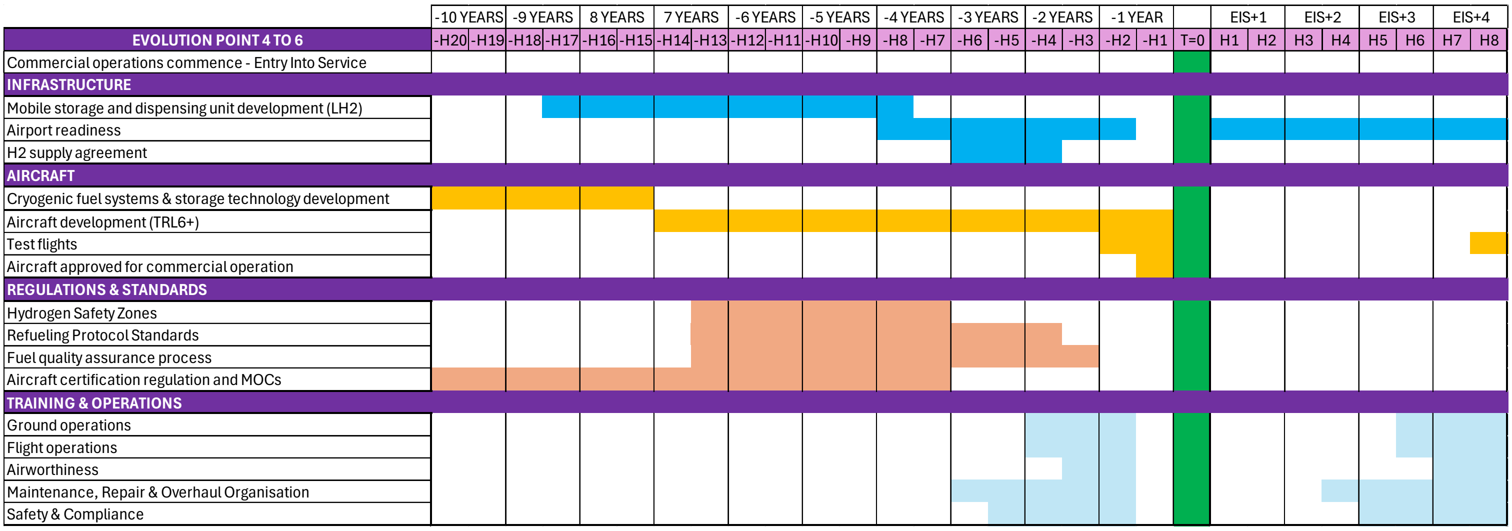


Figure 2: Transitioning to liquid hydrogen operations requires a longer lead time, sustained ecosystem collaboration and coordinated airport readiness. The transition to EP6 continues after aircraft EIS to enable scaling up of operations.

Recommendations

1. Create a national zero-emission flight programme to accelerate the development of hydrogen aircraft, infrastructure and operational procedures. This should centrally coordinate, facilitate and support physical, digital and regulatory workstreams and provide access to test platforms. A key objective of this programme should be to establish a route for scaling up hydrogen aviation with liquid hydrogen fuel.
2. Establish a support mechanism for the development of airport infrastructure ahead of a market demand signal. This is important to ensure the scaling up of hydrogen operations is not restricted by infrastructure limitations.
3. Provide additional funding for the CAA, and if needed, the Health and Safety Executive (HSE) to support the development of certification regulations and means of compliance for hydrogen and other zero-emission technologies, in collaboration with international regulators and agencies.

4. Empower the CAA to lead the development of a scalable fuel assurance process for hydrogen, involving other stakeholders as required, including international peers. A cross-sector approach is worthy of consideration.
5. Construct a coordinated policy framework to accelerate the commercial introduction of hydrogen-powered flight in the UK. This should include the assessment and deployment of financial and regulatory incentives, such as innovation grants, tax and charge credits, and targeted Public Service Obligation (PSO) mechanisms, to de-risk early operations and stimulate investment across the supply chain.
6. Clarify the grant-funded support mechanisms available for refuelling technologies (gaseous and liquid).
7. Develop a national training programme for Emergency Rescue & Response personnel for hydrogen-related incidents (gaseous & liquid).

Further Work

Delivery mechanisms could include further task and finish groups as part of the Jet Zero Taskforce, or standalone projects.

- Design of the zero-emission flight programme – what it would encompass, how it would be structured, how it would be facilitated across the aerospace and aviation sector, how it would be governed, funded and supported by the Government.
- Definition of the regulatory minimum conditions and associated means of compliance for an airport and airline provision of a hydrogen-powered air transport service.
- Gap analysis of key airport technology development and compilation of a hydrogen airport infrastructure body of knowledge to be shared with relevant UK organisations.
- Benchmarking of hydrogen airport and infrastructure preparedness activities in other countries compared to the UK. This should include any lessons that can be learned from the funding environment/approach. Other transport sectors should also be included where relevant, e.g. marine.
- Full economic analysis of the benefit to the UK of hydrogen aviation to assist with a strategic investment case. This should include economic growth and regional development, high-value job creation, supply chain opportunities and connection to relevant government strategies for hydrogen and sustainable development plans.

Workstream 1 – Market Analysis

UK and European Domestic Route Aviation Network

Introduction

Hydrogen has been identified as a front-runner alternative fuel in the aviation industry due to its high energy density and zero-carbon-emission exhaust. Global industrial and academic organisations have been researching on-aircraft hydrogen technologies, particularly hydrogen fuel cell technologies, for small, shorter-distance aircraft. However, adopting hydrogen aircraft presents a range of complex challenges across technological, economic, regulatory and infrastructural domains. It requires entirely new aircraft designs, cryogenic fuel storage systems, robust safety protocols, refuelling infrastructure and new airport and airline operational procedures.

First generation hydrogen aircraft have been identified as a critical stepping stone and offer an opportunity to create controlled, low-risk environments to deploy and refine hydrogen technologies, build operational experience and develop infrastructure while scaling towards zero-emission aviation across broader domestic and international networks. However, it is important to investigate whether these initial hydrogen aircraft will provide a sustainable business case for all stakeholders, from aircraft and engine manufacturers to airports and airlines.

To support the submissions in this report, the financial implications and likelihood of airlines adopting hydrogen technology were analysed to assess the impact on profitability and the UK and European aviation route network. The UK and European domestic aviation route network assessment is based on a collaborative study between the Aerospace Technology Institute (ATI) and Air Transportation Systems Lab at University College London (UCL). The study, initially based on Public Service Obligation (PSO) routes across the UK and Europe, investigates the feasibility of hydrogen aircraft operations and demonstrates how knowledge gained from smaller hydrogen-propelled aircraft can be effectively applied to larger aircraft and broader aviation operations. The PSO routes, typically short-haul and regionally focused, are often subsidised by governments to ensure connectivity to remote and underserved areas. These routes align well with the early operational capabilities of hydrogen aircraft, which are usually limited in range and passenger capacity. Furthermore, this study extends beyond PSO routes to cover the overall UK and Europe aviation route network.

The ATS Lab's Airline Behaviour Model (ABM) is a computational framework that simulates how airlines operate and compete in a dynamic market environment. The model captures airline decision-making processes as they respond to changes in fuel types, operating costs, aircraft technologies, policy interventions, and market conditions. Its core objective is maximising airline profit while accounting for passenger choices, infrastructure constraints, and broader economic factors.

Within the model, airlines iteratively adjust key operational variables such as airfares, flight frequencies, and aircraft types across their networks. Passengers, in turn, make itinerary choices based on utility maximisation, considering factors like fare, service frequency, travel time, and carrier preference. The model runs through successive iterations until reaching a pseudo-equilibrium, where airline profits stabilise even as other variables may continue to fluctuate.

The ABM integrates socio-economic data, airport infrastructure characteristics, and detailed aircraft performance and cost profiles—including emerging technologies such as hydrogen propulsion. It has been validated against real-world market data and applied in strategic projects like NAPKIN and LH2GT to assess the commercial viability of hydrogen aircraft in UK and European aviation networks.

The ATI's Fleet and Sustainability models have also been employed to complement the ABM analysis. Based on entry into service (EIS) and new aircraft technologies adoption assumptions, the ATI fleet model forecasts annual fleet and flight demand, feeding into the sustainability model which evaluates the impact on environment that aircraft technologies and fleets are likely to have in the future.

Key Assumptions and Inputs

Aircraft Performance Characteristics and Operating Costs

The analysis only considers hydrogen-propelled aircraft as zero-carbon emission aircraft in line with this Task and Finish Group's scope and Terms of Reference. Both retrofit and clean sheet design aircraft are considered in this analysis, given the timeline of the analysis and consensus within the group on entry into service dates. The baseline data is as of 2019, prior to the impact of COVID-19. However, the effects and subsequent recovery post-2019, are accounted for in the analysis. The performance and cost data of aircraft models employed in analysis have been provided by member organisations within the Hydrogen Task and Finish group, i.e., ZeroAvia, ATI, GKN Aerospace, Airbus and Rolls-Royce.

The hydrogen aircraft feeding into the study include:

1. 9-seat retrofit gaseous H2 fuel cell aircraft – Based on the C208B Grand Caravan with a ZeroAvia ZA600 propulsion system, with an estimated EIS of 2029.
2. 14-seat retrofit gaseous H2 fuel cell aircraft – Based on DHC-6-400 Twin Otter with a ZeroAvia ZA600EP propulsion system, with an estimated EIS of 2029.
3. 48-seat retrofit liquid H2 fuel cell aircraft – Based on ATR72-600 with a ZeroAvia ZA2000 propulsion system, with an estimated EIS of 2033.
4. 75-seat clean sheet liquid H2 fuel cell aircraft – Based on the Flyzero regional concept targeting to replace the popular ATR-72-600 with an estimated EIS of 2037.
5. 100-seat clean sheet liquid H2 fuel cell aircraft – a scaled Flyzero regional concept similar to the Airbus ZEROe aircraft with pioneering initiatives from GKN Aerospace, UK's FlyZero, ZeroAvia and Rolls-Royce with an estimated EIS of 2040.

The UK and Europe domestic route network analysis is carried out for 2035 and 2050. These aircraft have been adopted into the ABM for analysis, and their performance and costing data are summarised in Table 1 below. Although the analysis primarily focuses on the immediate and longer-term operations of hydrogen fuel cell sub-regional and regional aircraft, it is critical to understand that the majority of benefits from hydrogen aviation emerge when operations scale up to narrowbody or single-aisle aircraft across a wider route network. This is discussed later in this section.

Aircraft	**9 – Seater**	**13 - Seater**	**48- Seater**	**75 - Seater**	**100 - Seater**
Target EIS	2029	2029	2033	2037	2042
Manufacturer	Zero Avia	Zero Avia	Zero Avia	FlyZero Regional	Scaled FlyZero Regional
Airframe Type	Retro-Fit	Retro-Fit	Retro-Fit	Clean sheet	Clean sheet
Propulsion System	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
Fuel System	Gaseous H2	Gaseous H2	Liquid H2	Liquid H2	Liquid H2
Range (nm)	250 (108)	220 (130)	640 (486)	800	1000
Total Payload (kg)	960	1,318	5,225	7,125	14,000
MTOW (tonne)	4.11	5.67	23	28.8	61
TOFL at MGW (m)	427	366	1,367	1,331	1600-2000
Aircraft Wholesale Value (Mill USD $)	2.0	5.6	15.8	21	55
Ground Time (hours/flight)	3	3	3	3	3.6
Cabin Crew	0	0	1	2	2
Airframe Maintenance Cost (USD $/FH)	117	140	510	570	600
Engine Maintenance Cost (USD $/FH)	208	208	260	280	500
Flight Crew Cost (USD $/FH)	459	459	918	918	1100

Table 1: Hydrogen aircraft performance and cost summary

The bracketed range in Table 1 above is the maximum range at maximum payload applied in the model based on the operational historical trends of the conventional equivalents and the design range and performance of the hydrogen aircraft. This provides the network model with some reasonable limitations when selecting an aircraft for a route. An estimated aircraft wholesale value (selling price/lease value) is used in the analysis instead of the aircraft list price provided by airframe manufacturers.

Global Market Scenario

The assumptions on the EIS dates and ramp up of production for the hydrogen-based aircraft are primarily aligned with the roadmaps for the different Evolution Points (EP) and the timelines for the relevant swim-lanes as discussed in the section covering Workstream 2 – Roadmap to Domestic Hydrogen Commercial Operations. Furthermore, the targeted EIS dates by various manufacturers developing these aircraft technologies are also considered. Although the UK and Europe domestic route network analysis via the ABM is carried out for the years 2035 and 2050, the ATI sustainability model analysis is carried out to 2070, considering larger aircraft technologies, to illustrate the environmental impact on aviation once the adoption of hydrogen has matured in aviation via the discussed Evolution Points. The diagram below summarises the first-of-its-kind aircraft for various market classes.

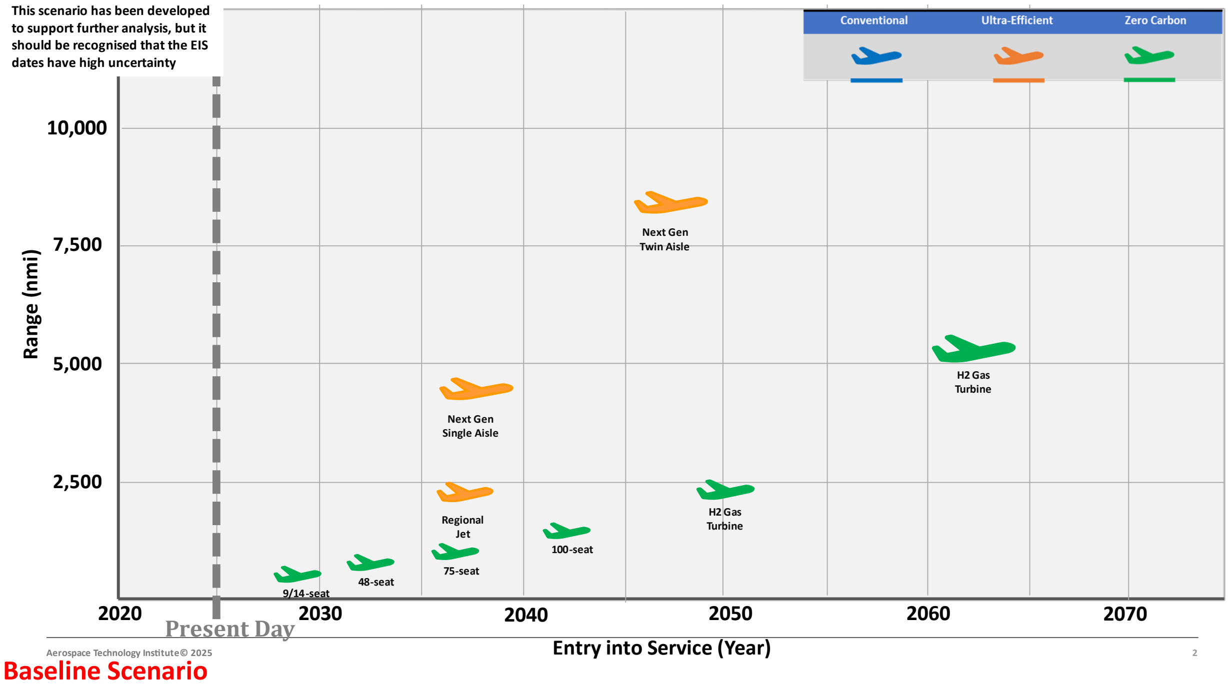


Figure 3: Entry into service timeline for hydrogen and the next-generation aircraft

Fuel Assumptions and Pricing

There is uncertainty about the future pricing of aviation fuels for conventional (Jet A, AVGas) and future (SAF, Hydrogen). However, the overall expectation is that the costs to produce variations of Hydrogen and SAF are expected to decrease over time, while the cost of using conventional kerosene fuels is expected to rise due to supply constraints, geopolitical instability, carbon pricing, and policy-driven alternative integration.

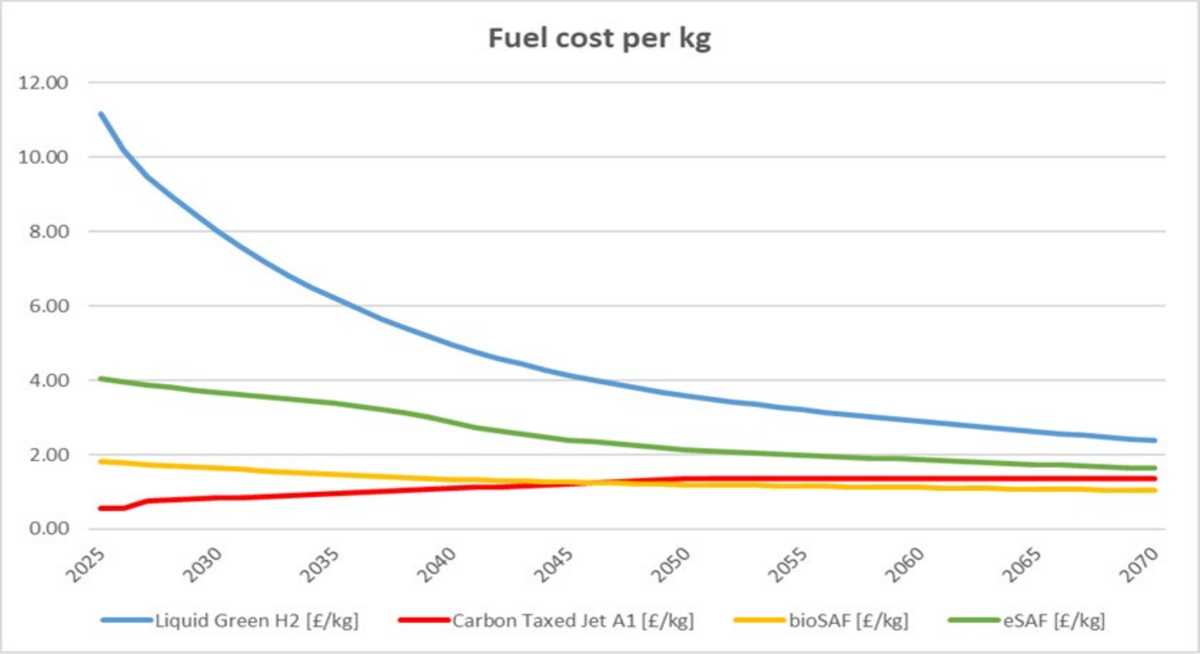


Figure 4: Price variation of aviation fuels to 2070

For this study, fuel pricing is based on GKN's Direct Operating Cost Model (DoC), a model that has previously been referenced and contributed to the FlyZero project, is employed. Only green hydrogen is considered in the analysis given that the ideal ultimate goal for aviation is to have a carbon-free fuel option, despite the current barriers for its adoption, such as higher production costs, limited availability of renewable energy and infrastructure. The pathway for green hydrogen is heavily dependent on electricity supply, electrolysis, transportation, liquefaction and storage, which ultimately contribute to the overall hydrogen price.

Jet A1 Fuel and AvGas baseline price is based on existing market benchmarks. As of 2027, it is assumed that they are subject to a carbon tax to reflect elements such as UK and EU Emissions Trading System. The price of carbon allowances is determined using present-day European averages and forecasted value for 2050 (at £250/tonne) according to IEA).

The proportions of BioSAF and eSAF in the analysis are based on both the UK (DfT) and European (ReFuelEU) SAF mandates. The 2035 analysis adopts an assumed 15% target, based on the UK projections between 2030 and 2040, with eSAF and bioSAF being 1.5% and 13.5% of the jet fuel respectively. The UK has not officially provided a set target for 2050, and therefore, the EU SAF mandate of 70% (35% eSAF and 35% bioSAF) is applied in the 2050 analysis.

A summary of the fuel pricing assumptions used in the analysis is presented in Table 2.

Fuel	**Price (USD $/tonne)**		
	2019	**2035**	**2050**
Jet A1 Fuel	720	1,250	1,760
AvGas	3,000	5,770	8,520
eSAF	-	4,400 (10% of SAF)	2,780 (50% of SAF)
bioSAF	-	1,920 (90% of SAF)	1,550 (50% of SAF)
SAF	-	2,160 (15%)	2,170 (70%)
Blended Fuel	-	1,380	2,040
Gaseous Green Hydrogen	-	5,610	3,140
Liquid Green Hydrogen	-	8,070	4,660

Table 2: Model inputs - fuel prices

The fuel prices for green hydrogen highlighted in the table are the "baseline" values used in the analysis. Note that Figure 2 provides the prices in GBP £/kg while Table 2 summarises the data in USD $/tonne in line with the ABM inputs format (2019 exchange rate of 1.3). Further analysis to investigate the impact of green hydrogen fuel price variations was also conducted with a low-price scenario and high-price scenario being 30% lower and higher than the baseline 2050 values respectively.

Analysis of UK and European Domestic Aviation Route Networks

Setting the scene – Baseline 2019 UK and European Domestic Aviation Route Networks

The UK and European aviation route networks are the basis of the analysis for both PSO and non-PSO routes. For the analysis, 16 airlines / alliances that operate in the UK and Europe were employed in the model. These include: Onewold, Star, Skyteam, Ryanair, Easyjet, Wizz, Flybe, Widereo, Loganair, Binter, Ethiad/Serbian, SATA, SkyExpress, DAT, TradeAir and Aurigny.

Generally, the model simulates the behaviour of competing airlines and passengers in the UK domestic aviation market, where each airline aims to maximise its profit. Passenger demand is influenced by factors such as origin-destination pairs, mode choice, and itinerary characteristics. Airlines can adjust fares, flight frequency, and aircraft type within operational constraints, and respond to competitors and passenger choices. The model runs iteratively until equilibrium is reached, and it can assess the uptake of new aircraft designs based on profitability. This is the case with PSO routes, though the only constraint is the minimum flight frequency obligations on airlines operating these routes. The model assumes these values to be as defined in the 2019 baseline data. Some PSO routes were omitted from the analysis as there was limited/no available flight schedule data to support the analysis.

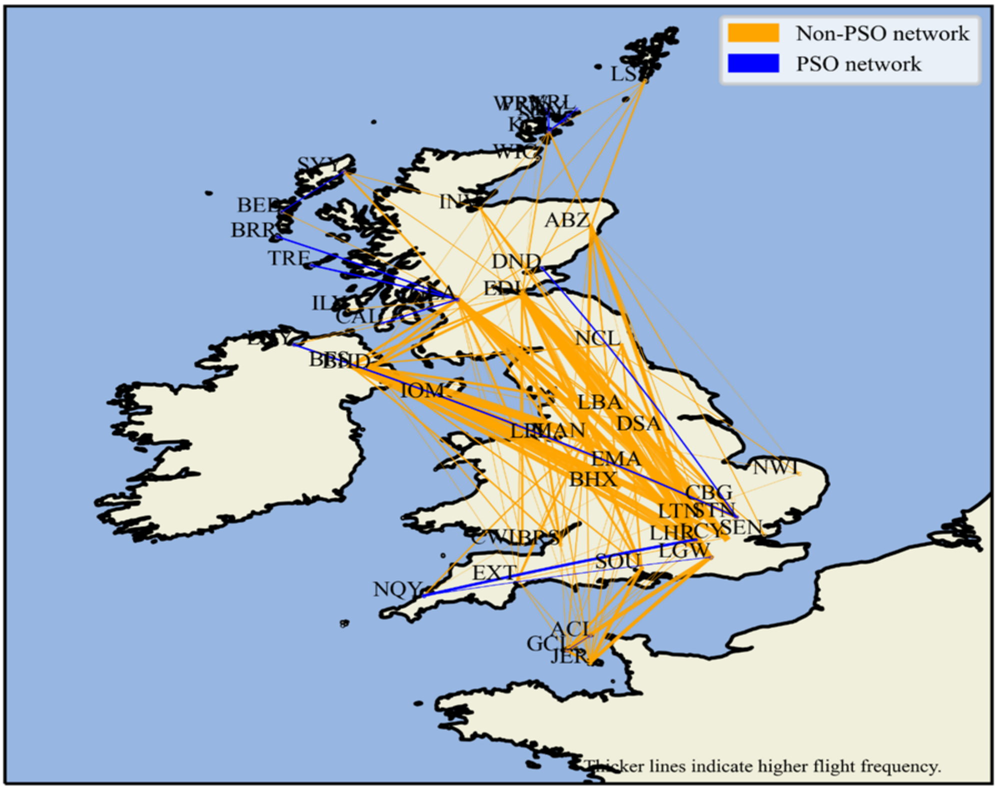


Figure 5: 2019 UK domestic aviation route network

Origin -Destination	Origin Airport	Destination Airport	Distance (nm)
LGW–NQY	London Gatwick Airport	Cornwall Airport Newquay	188
LHR–NQY	London Heathrow Airport	Cornwall Airport Newquay	183
BEB–SYY	Benbecula Airport	Stornoway Airport	63
BRR–GLA	Barra Airport	Glasgow International Airport	122
CAL–GLA	Campbeltown Airport	Glasgow International Airport	64
DND–STN	Dundee Airport	London Stansted Airport	292
KOI–NDY	Kirkwall Airport	Sanday Airport	9
KOI–NRL	Kirkwall Airport	North Ronaldsay Airport	18
KOI–PPW	Kirkwall Airport	Papa Westray Airport	2
KOI–SOY	Kirkwall Airport	Stronsay Airport	15
KOI–WRY	Kirkwall Airport	Westray Airport	10
LDY–STN	City of Derry Airport	London Stansted Airport	290
TRE–GLA	Tiree Airport	Glasgow International Airport	94
ACI–GCI	Alderney Airport	Guernsey Airport	19

Table 3: Model inputs - list of baseline UK PSO routes

The baseline UK PSO routes applied in the model are as of 2019 and are summarised in Table 3 above. A total of 196 PSO routes were employed in the analysis from the baseline dataset, of which 15 are within the UK. 140 aircraft served these PSO routes in Europe, with a total of over 300,000 flights as of 2019. Furthermore, 3,323 non-PSO routes, served by 2,585 aircraft, translating to over 4.35 million flights are included in the baseline dataset.

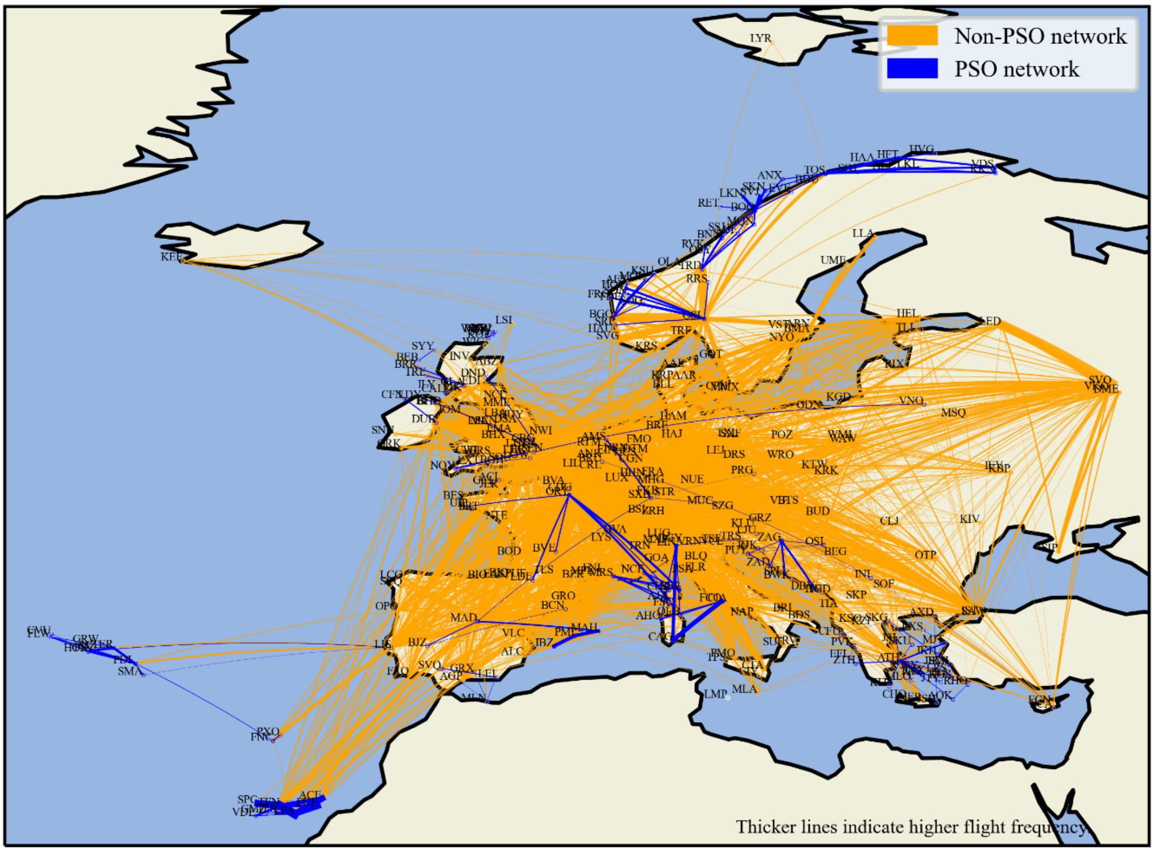


Figure 6: 2019 European domestic aviation route network

2035 UK and European Domestic Aviation Route Networks

Based on the entry into service dates used in the analysis, only the 9-seat, 13-seat, and 48-seat hydrogen fuel cell aircraft were introduced in 2035. To identify potential strategic airports that can be initially deployed for hydrogen operations, it is assumed that all airports would have no hydrogen supply constraints.

The results show that approximately 94% of the European ≤ 19-seat conventional aircraft utilised in PSO routes and 94% of flights are replaced by the small subregional hydrogen aircraft.

Overall, the small sub-regional hydrogen aircraft have the potential to replace 87% (65 aircraft) of the conventional aircraft ≤ 19-seat aircraft in the European fleet (UK included), catering for 93% of the total flights for all the routes analysed. While for the UK, over 70% of the ≤ 19-seat conventional aircraft and 56% flight operations are replaced by the small sub-regional gaseous hydrogen aircraft. There is limited uptake of the 48-seat retrofit liquid hydrogen aircraft due to the entry into service date (2033).

Airport Code	Airport Name	H2 Demand (tonne)	H2 Departures	H2 Average Segment (km)
IOM	Isle of Man Airport	20,690	1,177	156
BHD	George Best Belfast City Airport	16,526	888	167
GLA	Glasgow Airport	16,526	888	167
KOI	Kirkwall Airport	12,353	1,453	62
LPL	Liverpool John Lennon Airport	11,336	694	142
MAN	Manchester Airport	9,354	483	175
GCI	Guernsey Airport	7,979	1,250	38
JER	Jersey Airport	7,476	1,176	38
ABZ	Aberdeen Airport	3,643	168	199
NRL	North Ronaldsay Airport	2,918	386	53

Table 4: Top 10 UK airports for gaseous hydrogen demand in 2035

Table 4 provides a summary of the top 10 UK airports based on gaseous hydrogen used for domestic flight operations in 2035, based on the analysis.

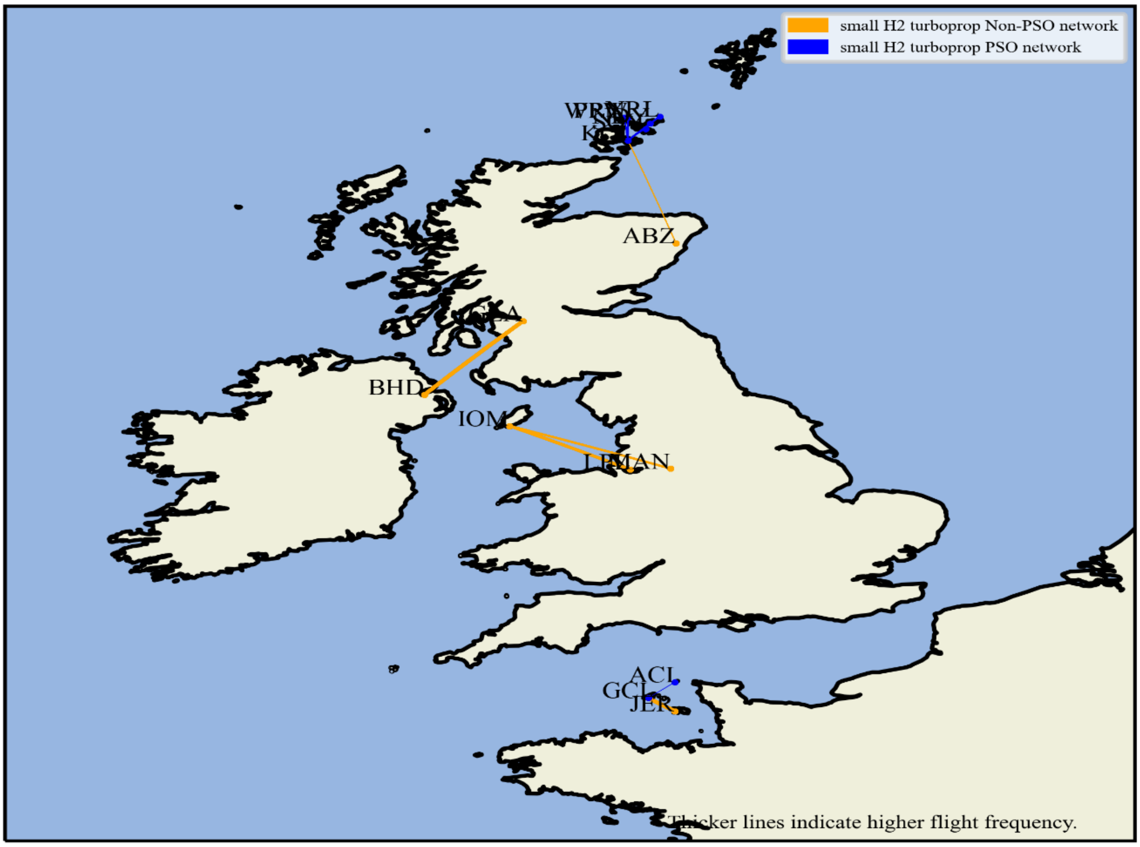


Figure 7: 2035 UK domestic hydrogen aircraft aviation route network

Strategic planning and decisions can be taken concerning initial gaseous hydrogen adoption in UK airports in line with EP2, where for instance, if Isle of Man, Liverpool (England), Belfast (Northern Ireland), Glasgow (Scotland) and Kirkwall (Orkney Islands, Scotland) airports were selected for hydrogen flight operations, with strategic operations such as tankering and hopper services that are common to these segments, a significant proportion of the hydrogen sub-regional commuter flights could be serviced by these airports.

Figure 7 and Figure 8 provide a graphical representation of the 2035 small sub-regional hydrogen aviation route network for the UK and Europe, respectively.

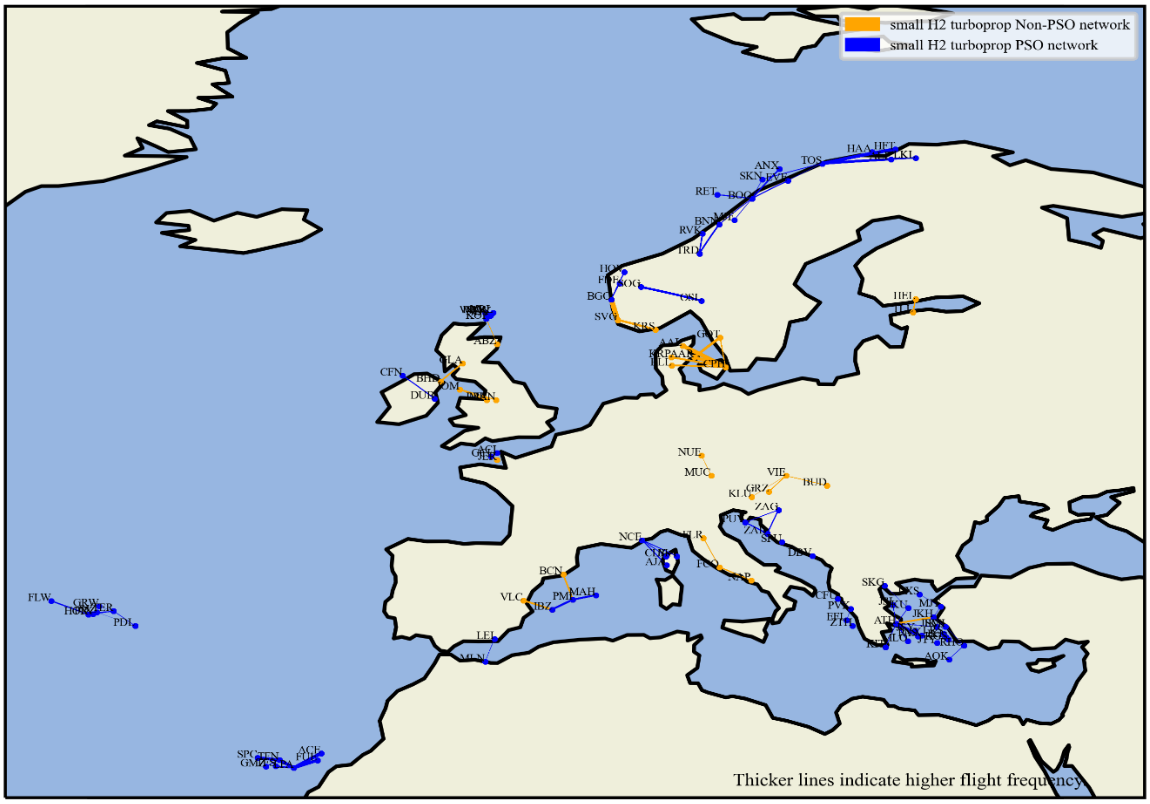


Figure 8: 2035 European domestic hydrogen aircraft aviation route network

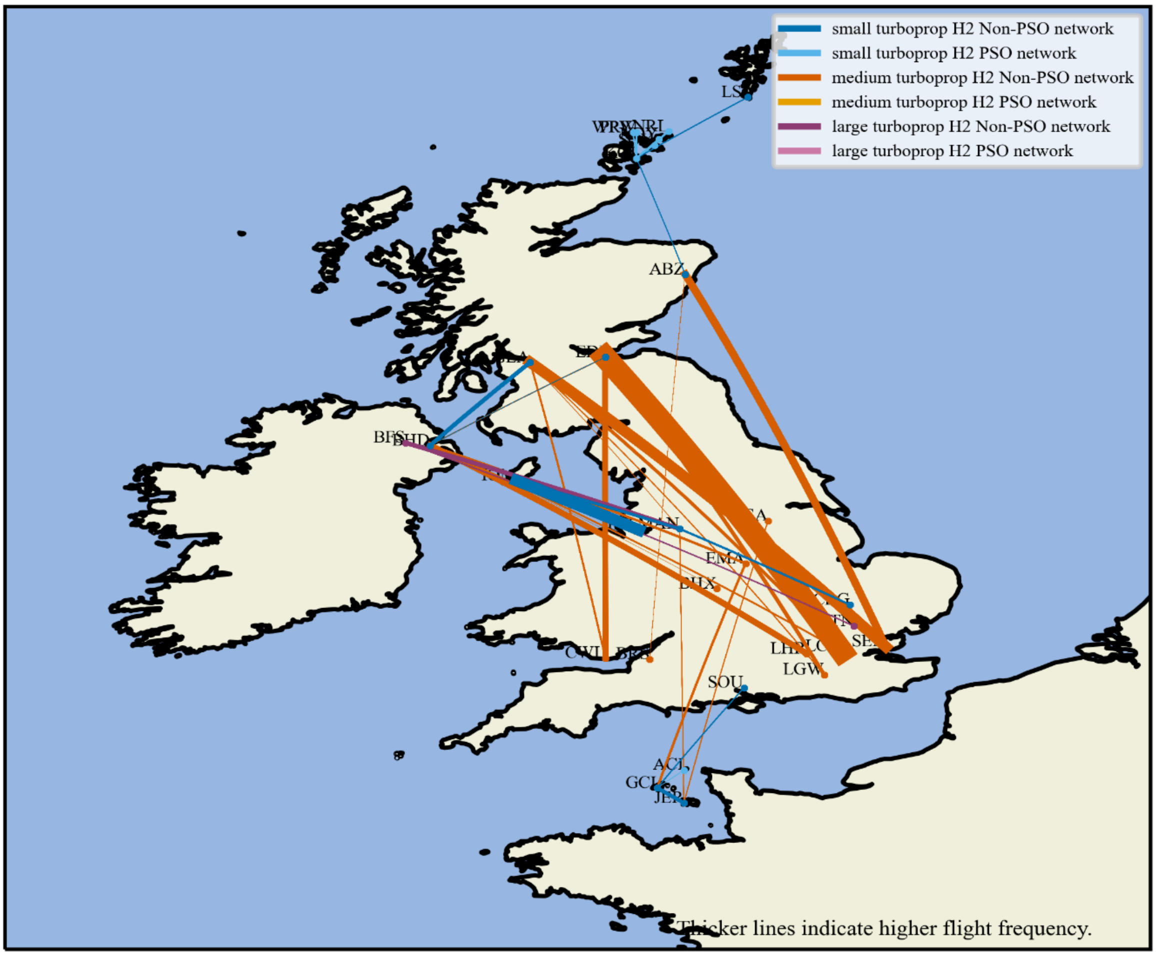
2050 UK and European Aviation Route Networks

In 2050, the gaseous hydrogen small sub-regional aircraft continue with a similar trend in Europe, with an increase in fleet size due to overall passenger demand growth, with a total 77 hydrogen aircraft servicing over 94% of the total flights for ≤19-seat commuter category. In the UK, the flight operations by this category of hydrogen aircraft have increased to over 65%, from 2035 (56%).

In contrast to 2035 analysis, the medium sized 48-seat liquid hydrogen aircraft make up 88% (640 aircraft) of the fleet, servicing 87% of all domestic European flights for this size category of aircraft. From the analysis, this aircraft is adopted primarily for non-PSO routes (618 aircraft - 97% of 48-seat H2 aircraft), implying profitability for the airlines. In the UK, 60% of the medium size turboprop domestic segment are replaced by the 48-seat hydrogen aircraft, servicing over 61% of domestic flights.

For the larger turboprop category (75-seat and 100 seat H2 aircraft), the hydrogen variant makes up approximately a quarter of the fleet of this size in Europe, servicing approximately 20% of all flights.

Overall, 820 hydrogen fuel cell aircraft make up the turboprop market's total fleet, accounting for over 65% of the total flights in this market segment in 2050.



Thicker lines indicate higher flight frequency.

Figure 9: 2050 UK domestic hydrogen aviation route network

Airport Code	Airport Name	H2 Demand (tonne)	H2 Departures	H2 Average Segment (km)
LCY	London City Airport	11,745,560	38,048	596
MAN	Manchester Airport	8,084,742	25,028	613
BHX	Birmingham Airport	4,534,595	16,818	558
EDI	Edinburgh Airport	4,374,795	14,791	687
LHR	London Heathrow Airport	3,325,757	9,965	684
LGW	London Gatwick Airport	2,207,107	4,635	875
STN	London Stansted Airport	1,605,476	4,796	547
ABZ	Aberdeen Airport	1,367,840	4,930	635
GLA	Glasgow Airport	1,113,814	4,000	598
SEN	London Southend Airport	1,076,410	3,958	613

Table 5: Top 10 UK airports for liquid hydrogen demand in 2050

Figure 9 and Table 5 provide a graphical representation of the UK domestic hydrogen aviation route network and the top 10 UK airports based on liquid hydrogen demand for domestic flight operations in 2050 respectively.

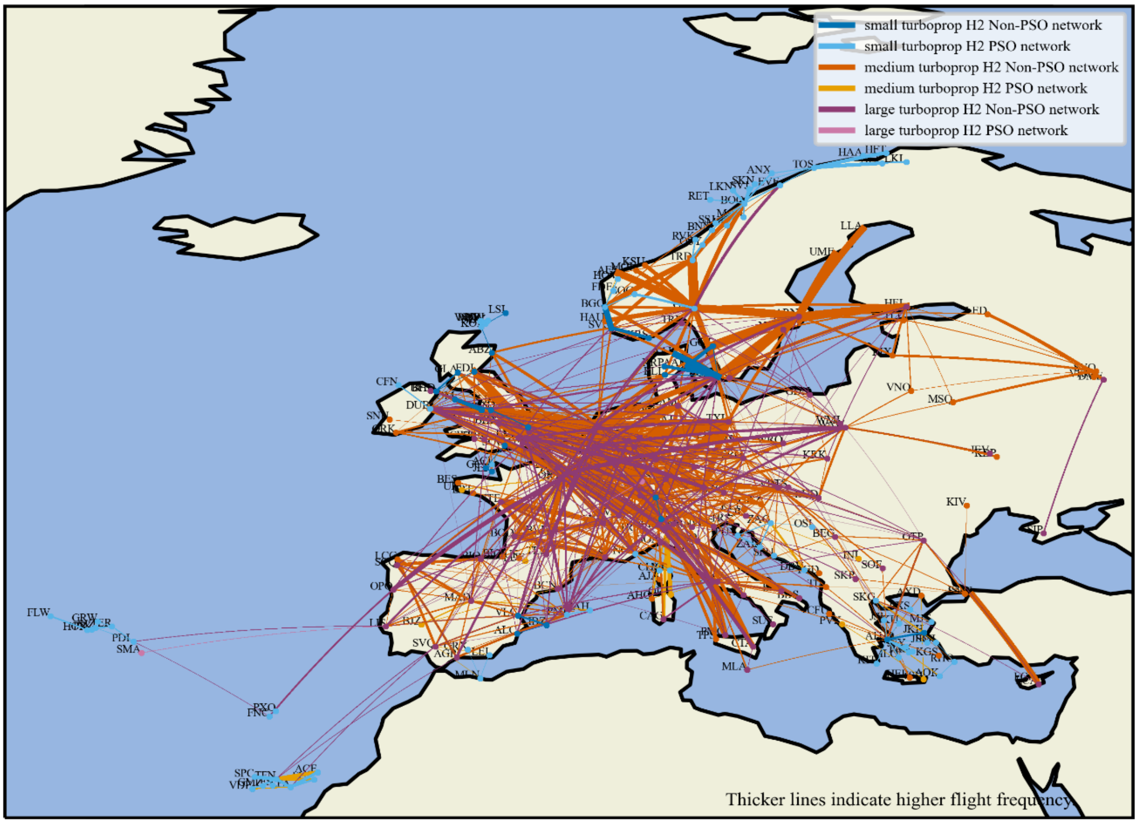


Figure 10: 2050 European hydrogen aviation route network

Airport Code	Airport Name	H2 Demand (tonne)	H2 Departures	H2 Average Segment (km)
CDG	Paris Charles de Gaulle Airport	30,607,216	91,660	713
AMS	Amsterdam Schiphol Airport	25,314,309	88,201	613
BRU	Brussels Airport	18,954,664	54,381	721
ORY	Paris Orly Airport	14,925,366	33,309	838
MXP	Milan Malpensa Airport	14,862,672	39,537	755
ARN	Stockholm Arlanda Airport	13,673,731	53,451	524
TXL	Berlin Tegel Airport	13,473,585	45,410	619
CPH	Copenhagen Airport	13,234,263	36,491	716
FCO	Rome Fiumicino Airport	12,208,877	37,739	619
OSL	Oslo Gardermoen Airport	12,049,966	46,769	502

Table 6: Top 10 European airports for liquid hydrogen demand in 2050

Figure 9 and Table 5 provide a graphical representation of the UK domestic hydrogen aviation route network and the top 10 UK airports based on liquid hydrogen demand for domestic flight operations in 2050 respectively.

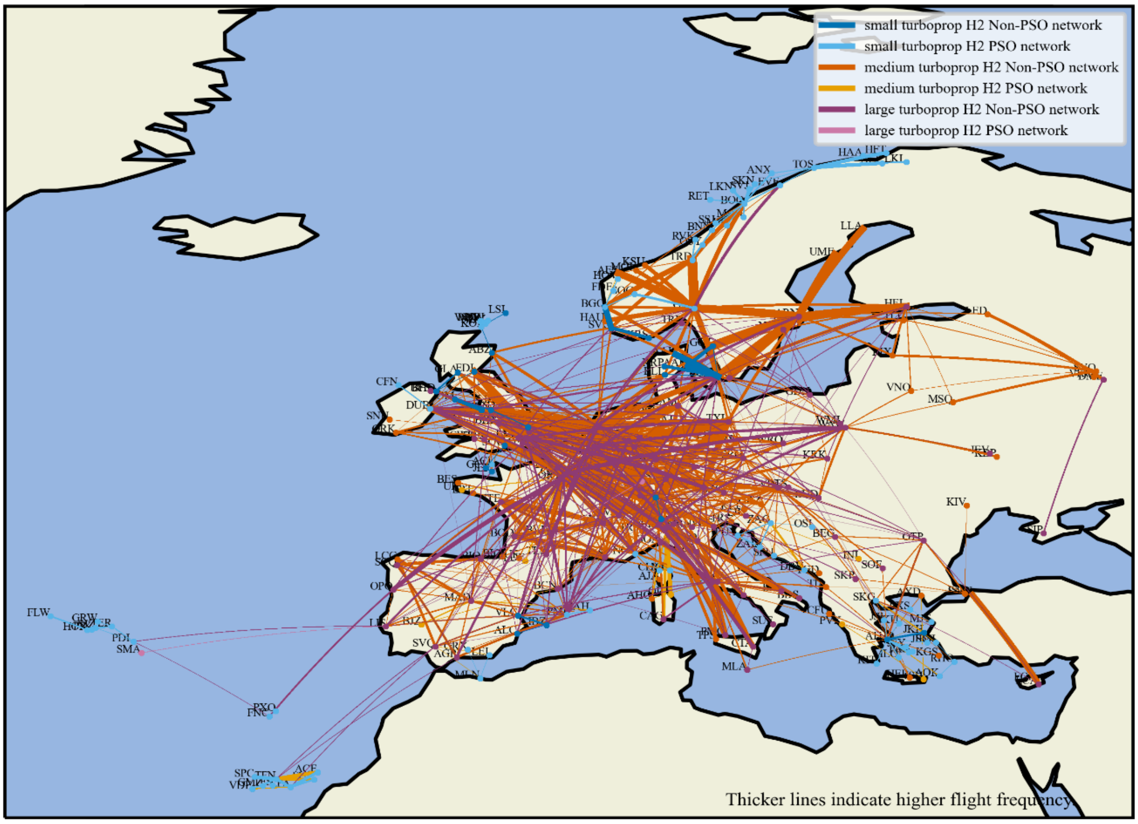


Figure 10 and Table 6 provide a graphical representation of Europe's domestic hydrogen aviation route network and the top 10 European airports based on liquid hydrogen demand for domestic flight operations in 2050 respectively. Many of the listed airports in the UK and Europe currently experience high passenger demand concentration, domestic and international connectivity with strategic positioning and multiple airlines operating from them. Furthermore, they can support a wide range of aircraft sizes and route lengths, and these factors create the economies of scale that would encourage early adoption for hydrogen operations, positioning them as leaders in sustainable aviation attracting airlines committed to decarbonisation, and benefitting from regulatory incentives.

Fuel Price Scenarios Analysis

Low and high fuel price scenarios were additionally incorporated in the analysis, with a 30% decrease and increase to the baseline fuel prices for green hydrogen in 2050 respectively. Table 7 provides a summary of the fuel price scenarios.

	2050 Price (USD $/tonne)		
	Baseline	**Low Scenario**	**High Scenario**
Gaseous Green Hydrogen	3,140	2,198	4,082
Liquid Green Hydrogen	4,660	3,262	6,058

Table 7: Fuel price scenarios for green hydrogen

The impact of the fuel price on the uptake of hydrogen aircraft is analysed and a summary of the number of hydrogen aircraft and flights in the UK and Europe are presented in Table 8 and Table 9 respectively.

Aircraft Category	Baseline		High Scenario		Low Scenario	
	Aircraft	Flights	Aircraft	Flights	Aircraft	Flights
H2 Small Sub-regional	9	13,980	8	14,378	7	12,009
H2 Medium Turboprop	17	28,896	8	13,907	19	35,437
H2 Large Turboprop	3	3,385	-	-	24	36,151

Table 8: Aircraft and flights in the UK for the different green hydrogen fuel price scenarios in 2050

Aircraft Category	Baseline		High Scenario		Low Scenario	
	Aircraft	Flights	Aircraft	Flights	Aircraft	Flights
H2 Small Sub-regional	77	158,638	89	188,385	79	160,778
H2 Medium Turboprop	640	1,272,357	484	962,713	796	1,582,088
H2 Large Turboprop	103	165,770	5	2,171	542	917,292

Table 9: Aircraft and flights in Europe for the different green hydrogen fuel price scenarios in 2050

The analysis indicates that the small sub-regional sized aircraft category is not significantly sensitive to the different fuel price scenarios. These commuter aircraft are characterised by lower fuel consumption per flight compared to longer regional operations. As a result, even when fuel prices change, the absolute decrease/increase in operating costs remains relatively modest. Additionally, smaller aircraft tend to have lower acquisition, maintenance, and crew costs, and their ability to serve a broader range of routes and adjust frequencies more flexibly allows operators to maintain profitability despite cost pressures. Furthermore, PSO operators are obligated to keep minimum frequencies for PSO routes, where usually small aircraft are used.

In the low scenario, the decreased hydrogen fuel costs make the hydrogen aircraft more competitive with the airlines' existing conventional medium/large single aisle sized fleet from a cost-per-seat basis (maintenance and crew costs per passenger would also decrease with larger aircraft), and they could opt to select the larger hydrogen fuel cell aircraft instead and increase flight frequency. The airlines may opt to further reduce the airfare, thus increasing passenger demand, or as was consistent in the analysis, increase it to maximise on profit. For the medium and large turboprop hydrogen aircraft, the impact of lower H2 fuel prices increases the number of aircraft and flight frequencies in the UK and Europe. Conversely, the high fuel price scenario observes a significant decline in hydrogen aircraft and total number of flights.

Environmental Impact until 2070

The overall environmental impact of the next generation of aircraft was analysed using the ATI Sustainability Model. The EIS dates of the larger hydrogen aircraft, assumed to be gas turbine, and ultra-efficient narrowbody and widebody aircraft are illustrated in **Figure 1.** The analysis is carried out until 2070, and hydrogen operations are responsible for CO2 abatement of 0.07 Gt in the UK, as illustrated in Figure 11, and 4 Gt globally. From the analysis, the smaller regional hydrogen fuel cell aircraft do not significantly reduce overall CO_2 emissions due to their limited passenger capacity and short-range operations. However, they play a critical role in enabling hydrogen adoption in aviation. They serve as early testbeds for hydrogen propulsion technologies, allowing manufacturers and operators to validate safety, performance, and infrastructure requirements at a manageable scale. These aircraft help build the supply chain for hydrogen production, storage, and refuelling, which is essential before scaling to larger, long-haul aircraft. Additionally, early deployment in regional markets demonstrates commercial viability, fosters regulatory frameworks, and accelerates technological learning curves, paving the way for broader hydrogen integration across the industry.

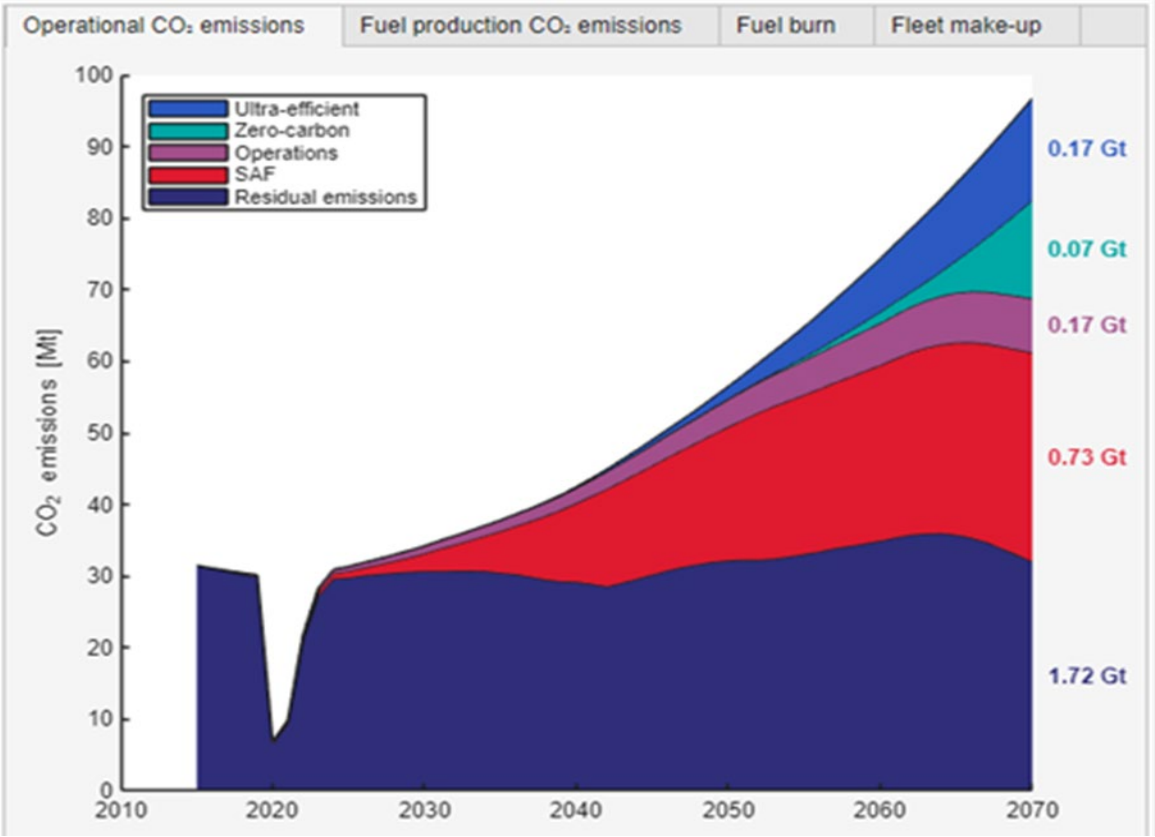


Figure 11: UK environmental impact of future aircraft technologies and fuels

For airlines, smaller hydrogen aircraft are important because they provide a lower-risk entry point into hydrogen operations. Deploying hydrogen on regional routes allows carriers to gain hands-on experience with new fuelling infrastructure, maintenance procedures, and safety protocols without the complexity and cost of larger aircraft operations. This early adoption helps airlines build internal expertise, train crews, and establish partnerships with airports and fuel suppliers. It also positions them as leaders in sustainability, which can enhance brand reputation and meet regulatory or corporate emissions targets.

Raising & Enabling Ambition: Delivering Impact at Scale following New Aircraft Entry into Service

As the Rolls-Royce-led LH2GT Project funded by ATI has recently highlighted, the prospect of a small-scale Europe-wide network of liquid-hydrogen-capable airports could deliver the benefits of hydrogen at scale, leading to a significant environmental impact as well as a financial incentive (over recourse to SAF) to airlines in the context of the new fuel mandates. A clear 'carrot' exists for airlines (7% improved profitability) and the UK (14% lower electricity energy use) to be attracted to this option, once the technology is available and comes into service.

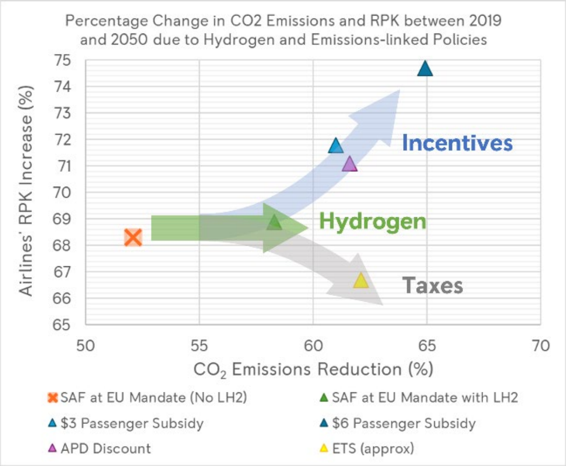


Figure 12: Percentage change in CO2 emissions and TRPK between 2019 and 2050

The option therefore exists for the UK to concentrate some of its hydrogen infrastructure investments at a few, well-chosen airports to enable early success at scale for mass air transportation (LH2GT considered the narrowbody segment within Europe, which offers both significant impact while remaining regionally focused; ideal conditions for the early deployment of such a hydrogen aircraft). These airports could initially serve as learning labs; however, the early learning phase could also be achieved at other partner locations until proven successful and deployable in service and at scale.

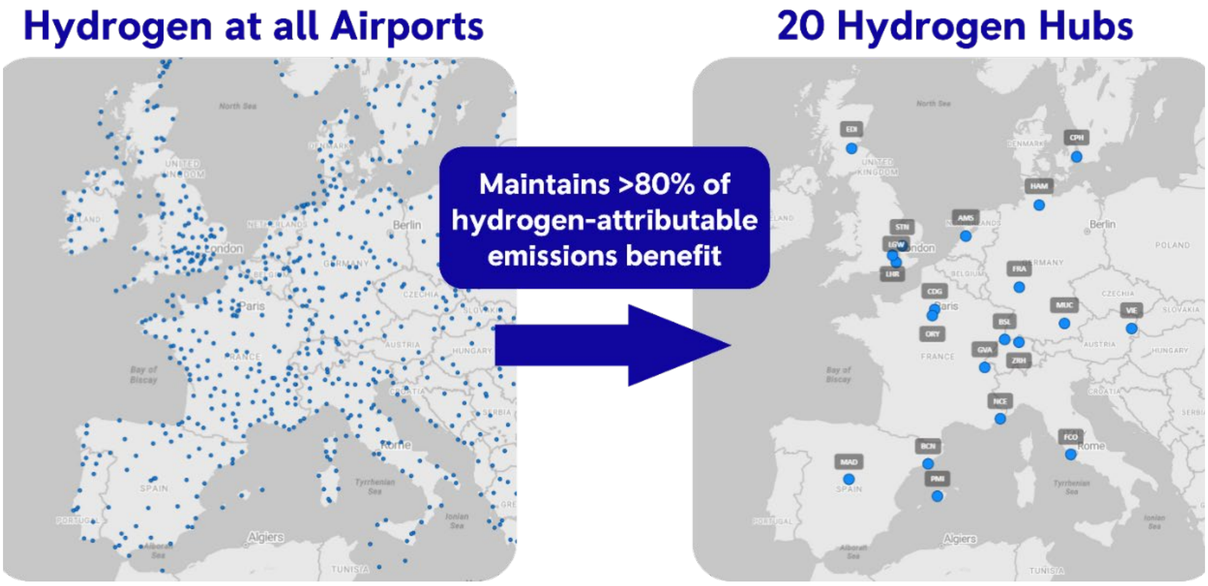


Figure 13: Locations of the 20 hydrogen hubs which deliver 80% of the total benefit

This is an important consideration, as it highlights how a prudent, early investment in enabling infrastructure would work effectively. It also challenges the notion that infrastructure should be addressed and resolved first across a relatively dense network, before a route to deployment, impact, and profitability can be established. The evidence shows that the UK could start with three operational airports, for example, the selection process for which would be based around the initial learning challenge, followed by the ability to scale and be deployed airside in a manner aligned to early airline leaders' ambitions. This could be planned and would remove the limiting anxiety around infrastructure. Of course, this would also assume that hydrogen was available for aviation use.

This would require the UK to work closely with its European neighbours and use its hydrogen leadership to spearhead a Europe-wide low-carbon aviation initiative. By building the system around a network of suitable hubs and routes, Europe could achieve early success and then scale progressively following aircraft entry into service. Analysis shows that hydrogen infrastructure at just 20 European airports would unlock around 80% of the potential impact, enabling hydrogen aircraft to operate across almost the entire continent.

The LH2GT results were obtained based on the ATS Lab's Airline Behaviour Model (ABM), as developed by UCL, Rolls-Royce and partners over the past 6 years and previously deployed in NAPKIN (a Future Flight Phase 2 project). A key outcome of the NAPKIN project was the need for scale, which LH2GT subsequently explored.

Operational Costs and Airline Business Case for Hydrogen Aircraft Adoption

Introduction and Context

This chapter examines the financial and operational implications of introducing hydrogen-powered aircraft into UK domestic aviation, including sub-regional and routes where Public Service Obligation (PSO) support is provided, as well as narrowbody operations. It evaluates whether hydrogen technology can deliver a viable business case for airlines and explores the critical role of operational cost analysis in supporting the adoption of hydrogen, as well as potential support mechanisms from governments, local authorities, and regulatory bodies.

Overview of Hydrogen Aircraft Cost Drivers

Hydrogen-powered aircraft present a promising route towards zero-emission domestic aviation, offering advantages over other low-emission technologies currently available. Both gaseous and liquid hydrogen solutions are under consideration to ensure the roadmap remains technology-agnostic. Hydrogen aircraft are expected to be available for sub-regional, regional, and narrow-body operations, with gaseous hydrogen aircraft forecasted to enter the market by 2029 and liquid hydrogen aircraft by 2042.

The principal operational cost considerations for hydrogen aircraft adoption include capital expenditure, fuel costs, maintenance and reliability, crew-related expenses, ground infrastructure, and overall operational efficiency.

- **Capital Expenditure:** Transitioning from conventional kerosene-powered aircraft to hydrogen-powered models will require significant investment in aircraft purchase, leasing, or retrofitting. Understanding the initial investment, aircraft lifespan, and the evolution of costs as production scales up is essential.
- **Maintenance Costs:** Maintenance expenses may be more substantial due to the increased complexity and novel technologies involved in hydrogen aircraft. Reliability is crucial to minimise costs and maximise operational availability. Some hydrogen aircraft may feature fewer moving parts, potentially reducing maintenance costs.

- **Crew Costs:** Crew-related costs are a significant operational factor. Operating hydrogen aircraft may entail higher insurance premiums due to different safety risks, as well as additional training costs arising from differences in aircraft type rating systems compared to conventional aircraft. The lack of economies of scale in the early stages, with smaller sub-fleets and dedicated crews, may further increase costs.

- **Ground Infrastructure:** The viability of hydrogen operations is heavily influenced by ground infrastructure costs, including airport taxes, benefits, and turnaround times. Infrastructure readiness and the availability of hydrogen supply are key considerations.

- **Operational Efficiency:** Efficiency must be evaluated at every stage, considering potential range limitations, payload penalties, utilisation rates, and aircraft turnaround times.

- **Hydrogen Fuel Costs:** The cost of hydrogen fuel—both gaseous and liquid—along with refuelling logistics, is a critical operational consideration. Government intervention can help establish a functioning market at scale, enabling economies of scale and driving down costs over time.

Operational costs must be assessed throughout the development of aircraft, infrastructure, and regulatory frameworks, aiming to align as closely as possible with current operating economics. Comparative analysis with existing aircraft is essential, as hydrogen aircraft must ultimately deliver a superior total operating cost per available seat kilometre (ASK) to be commercially viable.

Airline Business Case

The airline business case for hydrogen aircraft encompasses market analysis (passenger demand, itineraries, competition), operational factors (pilot and aircraft availability), revenue generation (flight frequency, aircraft selection, airport utilisation, profitability, network design), cost-benefit analysis (total cost of ownership and per-seat-kilometre cost), implementation challenges, risk assessment (including additional safety requirements), and opportunities for environmental impact reduction and growth.

For hydrogen aircraft, airlines must consider revenue and network risks at every stage of aircraft, infrastructure, operational, safety, and regulatory development. Key considerations include:

- **Aircraft Solution:** Evolving aircraft designs must address operational requirements. The adoption of new technology will present planning challenges and incur cost premiums for airlines and airports. Financial support from government and private sources will facilitate fleet investment and risk sharing.

- **Route Viability and Payload-Range Trade-offs:** Hydrogen aircraft require large, insulated tanks due to hydrogen's low volumetric energy density, which may restrict initial operations to regional and short-haul routes. Reduced payload and range can lower load factors and revenue per flight, impacting flight frequency. Government support for early route adoption, including operational exemptions and revised charging structures, is essential. Modelling by University College London (UCL) provides further analysis in this area.

- **Passenger Acceptance and Green Premium:** Passenger willingness to pay a premium for green flights depends on awareness of safety, infrastructure costs, trust in operators, and the price differential with conventional jet fuel. Support from the Civil Aviation Authority (CAA) and the government is crucial to addressing safety concerns and promoting initial routes. Currently, there is no evidence of a green premium, so cost competitiveness is vital. Government evaluation of hydrogen pricing and its impact on cost parity and revenue is also necessary.

- **Pilot Engagement, Training, and Insurance:** Hydrogen operations will affect airline procedures, requiring pilot input in aircraft, airport, safety, and operational design. Once solutions are defined, pilots will need additional training, incurring extra costs. The government could consider providing funding support for pilot conversion training.
- **Operational Economics:** Maintaining turnaround times comparable to current operations, establishing agreed safety and operational procedures, ensuring operational readiness among stakeholders, and providing suitable ground handling equipment and refuelling systems are all challenges. Early collaboration between airports, aircraft developers, airlines, and the CAA is crucial. The development of liquid hydrogen refuelling systems is a critical path, potentially requiring government-backed initiatives to accelerate technology development. If hydrogen-powered aircraft have a higher mass per passenger than kerosene-powered aircraft, this would drive increases in operational costs, such as landing, en route, and Terminal Navigation Services (TNS) charges.
- **Airport Infrastructure Roadmap:** Hydrogen flight operations necessitate the availability of gaseous and/or liquid hydrogen at airports, with appropriate storage, transport, and on-site refuelling. Planning, design approvals, and efficiency improvements will require time and investment. Early development of a comprehensive infrastructure roadmap is essential to avoid operational bottlenecks. The layout of hydrogen infrastructure can significantly affect turnaround times, so airline consultation is necessary at every stage. Government funding and expedited infrastructure development approvals are key.
- **Airports as Hydrogen Hubs:** Initial operations should focus on a limited number of hydrogen-equipped airports. For gaseous hydrogen, this enables early adoption; for liquid hydrogen, targeted infrastructure at select hub airports can enable significant emissions reductions. Government financial incentives should support infrastructure at 2–3 GH2 and 2–4 LH2-capable airports and routes, facilitating learning and supporting research, technology, and demonstration activities to benefit the whole UK Aviation sector.
- **Scalability:** Scaling hydrogen aircraft operations requires advances in propulsion, storage, and infrastructure. While the JZTF focuses on UK deployment, connectivity with Europe is vital for economic and environmental alignment, sustainability, and innovation. Tankering strategies to maximise range and minimise costs and emissions are also important, as highlighted in the LH2GT report.

The primary operational opportunities of hydrogen flight lie in decarbonising aviation and reducing fuel costs per revenue passenger kilometre (RPK), helping to decouple growth from emissions. Unlocking these opportunities will require strong government engagement and visible commitment. Potential policy levers include:

- Continued support for the development of both GH2 and LH2 flights to maintain a technology-agnostic roadmap.

- Support for initial operations of gaseous hydrogen aircraft, enabling learning and encouraging further investment.
- ATI-type programmes to accelerate key technology development, particularly for liquid hydrogen aircraft, propulsion and refuelling technologies.
- Infrastructure support with public co-investment in hydrogen refuelling and storage infrastructure through capital grants or green infrastructure funds to at least 2-3 GH2 and 2-4 LH2 airports at key locations in the UK. This facilitates learning around the handling of hydrogen and supports existing R&T and demo activities near-term. This will support the introduction of a small number of additional routes in the UK, linked to demonstration airports, covering different airline operating models.
- There is a fundamental transition risk still not addressed related to fleet renewal timing and the environmental impact of fleet renewal. Airlines typically commit to purchasing aircraft 5-10 years prior to the start of operations. This could easily delay the introduction of hydrogen flights further and reduce environmental benefits. Government support is needed to help industry progress hydrogen aircraft along their technology roadmaps and to provide targeted incentives, such as subsidies or lease guarantees, to make early hydrogen aircraft affordable for operators, who will otherwise face higher upfront costs.
- Operational incentives, such as emission credits or reductions in air navigation and landing charges for zero-emission flights.
- Regulatory alignment, with early certification and safety approval processes to facilitate timely entry into service.
- Emissions pricing, subsidies, and zero-emission aircraft credits. The UK SAF mandate includes credit for low-carbon hydrogen (produced from renewable or nuclear energy). This is helpful, but additional mechanisms may be required.
- This roadmap represents an initial step towards synchronising hydrogen aircraft, infrastructure, and supply, supporting the transition to a functioning market ultimately underpinned by government support.

PSO Routes and Regional Connectivity Business Case

Public Service Obligation (PSO) air services are a part of the UK’s domestic aviation network, ensuring essential connectivity for remote and peripheral regions where surface transport alternatives are limited or economically unviable. PSO routes are supported by public funding to maintain minimum service levels that would otherwise be uncommercially sustainable, thereby fulfilling social and regional development objectives.

These routes typically involve short sectors (under 500 km), lower utilisation, and strong public interest objectives, making them well suited to smaller hydrogen aircraft, and present a unique opportunity for early hydrogen deployment.

As of 2025, the UK’s PSO network includes services linking peripheral and island communities primarily in Scotland, Northern Ireland, and southwest England. Transport Scotland oversees the largest share, contracting operators such as Loganair to provide lifeline air services connecting the Highlands and Islands to the Scottish mainland. Examples include routes from Glasgow to Barra, Tiree, Campbeltown, and Benbecula, as well as intra-island services based from Kirkwall and Stornoway. These routes serve communities for which surface transport alternatives would involve multi-hour or multi-day journeys, and where air links underpin access to healthcare, education, tourism, and economic resilience.

The ATS Lab's analysis undertaken as part of this programme provides a detailed spatial and socio-economic mapping of these routes, demonstrating their significance in sustaining regional equality and supporting the UK Government's drive to 'power up regions'.

The relatively small scale of PSO route networks offers logistical advantages for introducing hydrogen operations. Aircraft tend to be based at a limited number of airports, simplifying infrastructure deployment and enabling controlled testing of fuelling, maintenance, and certification systems. The social visibility of PSO services also supports public engagement and acceptance of hydrogen technology, reinforcing government commitments to the transition of transport decarbonisation.

PSO contracts, which are tendered and monitored by the government, also provide a mechanism through which technology trials can be formally supported and incentivised. This reduces commercial risk for operators by guaranteeing minimum revenue or cost recovery. These routes offer high visibility and public interest, which makes them ideal for government-backed demonstration of zero-emission flight.

The introduction of hydrogen propulsion into PSO operations could also help insulate remote regions from fuel price volatility. Traditional jet fuel costs have historically accounted for a significant portion of PSO operating budgets, and the transition to domestically produced green hydrogen could, over time, enhance energy security and reduce exposure to global fuel market fluctuations. Logistically, this is further supported by the ability to produce hydrogen in situ, with the appropriate infrastructure, reducing costs but also the environmental impact of transporting fuel, and bringing broader socioeconomic benefits to the communities served by these routes, for example, through the creation of new economic output, jobs and skills development. The socio-economic rationale for PSOs – ensuring connectivity and reducing peripherality – could thus be extended to include decarbonisation and energy resilience as core policy objectives.

While early hydrogen operations are expected to face higher upfront and per-flight costs, several mechanisms could narrow the gap with conventional turboprops. Cost parity will depend on the relative prices of hydrogen and Jet A-1, infrastructure amortisation, and carbon cost trajectories. In the near term, government support will likely remain necessary; however, PSO contracts already operate within a subsidised framework, allowing for the integration of zero-emission incentives without fundamentally altering market structures.

To unlock this opportunity, Government engagement will be essential, as well as a visible Government commitment. PSO contracts could explicitly prioritise or mandate zero-emission technologies within their tender criteria, similar to low-emission bus or rail procurement frameworks. Policy levers might include:

- Infrastructure support with public co-investment in hydrogen refuelling and storage infrastructure at key regional airports, either through capital grants or green infrastructure funds.
- Fleet support through targeted subsidies or lease guarantees for hydrogen aircraft entering PSO service, helping operators manage the higher capital cost of early models.
- Operational incentives through emission credits, or reductions in air navigation or landing charges for zero-emission flights.

- Regulatory alignment with early certification and safety approval processes tailored to PSO-scale operations, facilitating timely entry into service.

Early buy-in from government, through both Transport Scotland and the UK Department for Transport, would send a strong signal to manufacturers, financiers, and regional authorities that PSO networks are a national priority for early hydrogen demonstration.

Initial candidate routes for hydrogen-powered PSO operations could include those in the Scottish Highlands and Islands, where distances, aircraft size, and community reliance align closely with hydrogen technology capabilities, as well as having existing government subsidy frameworks. Northern Ireland–mainland connections, such as Belfast–Aberdeen, also provide potential test cases due to suitable range and operational patterns. Other opportunities could emerge in South West England and Wales, where limited surface transport connectivity has historically justified air service provision. Over time, data from such operations would inform safety certification, cost modelling, and scalability assessments, supporting the UK's broader hydrogen aviation roadmap.

Sub-Regional Aircraft Operations

The sub-regional segment, typically encompassing 9–19 seat aircraft operating sectors under 216 nmi (400 km), represents the most promising early application for hydrogen-powered aviation. Aircraft in this class form the backbone of local and feeder networks, particularly in rural and island regions. They are well suited to the performance characteristics of first-generation hydrogen systems, which prioritise lower emissions and shorter range over payload and speed.

Sub-regional aircraft generally fly between 2,000 and 3,000 hours per year, often on multi-sector daily schedules linking smaller airports. They are designed for short runways, quick turnaround, and low infrastructure dependence—attributes that align well with the capabilities of hydrogen fuel cell aircraft.

Operational constraints will centre on fuel storage volume, refuelling logistics, and airport readiness. For small airports, on-site generation or local delivery using trailers may be more viable than centralised pipeline supply. Turnaround times will initially be longer than for conventional refuelling, but as procedures standardise and ground support equipment matures, these differences should diminish, which will be essential for operational and commercial viability.

The modular nature of sub-regional infrastructure also allows for incremental scaling. Once an airport supports one or two hydrogen aircraft, capacity can expand as fleet size grows, providing a flexible model for national rollout.

Early collaboration between airports, aircraft developers and the CAA is critical to defining practical operating standards.

Hydrogen aircraft will require new training programmes for pilots, engineers, and ground staff. Flight crews must be familiar with hydrogen system management and emergency procedures, while maintenance teams will need certification to handle high-pressure and cryogenic systems. Regional maintenance bases, such as those used by existing PSO and sub-regional fleets could serve as early hydrogen maintenance hubs.

Reliability and spare parts availability will be key concerns. Early aircraft are likely to operate under restricted duty cycles or within demonstration frameworks until performance data accumulates. Regional maintenance bases—such as those serving existing PSO and sub-regional fleets—will be ideal hubs for early hydrogen operations, combining existing expertise with targeted retraining programmes. Partnerships between manufacturers, operators, and maintenance providers will help address early reliability issues through data-sharing and predictive maintenance systems.

Sub-regional operations provide the foundation for scaling hydrogen technology to larger aircraft classes. Lessons learned in this segment—on refuelling procedures, safety regulation, cost performance, and public perception—will directly inform the next generation of 30–90 seat regional and single-aisle aircraft expected to enter service in the mid-2030s onwards. By starting with smaller, lower-risk aircraft and airports, the aviation sector can establish operational experience and regulatory frameworks that will de-risk subsequent adoption at scale.

Narrowbody class operations

Narrowbody operations account for approximately one-third of all aviation CO2 emissions. The routes served by narrowbody aircraft play a crucial role in connecting various regions within the UK, as well as facilitating business and tourism links between the UK and Europe. This segment also represents the largest share of revenue.

The development of hydrogen-powered narrowbody flight operations on these routes necessitates careful consideration of factors such as scale, regional diversity, and risk-sharing.

To ensure the viability of hydrogen-powered flight, it is essential to achieve economies of scale across several domains, including technological development, infrastructure adaptation, operational costs, and fleet transition. According to the LH2GT project, the narrowbody segment presents an opportunity to minimise initial investment by focusing on hydrogen infrastructure development at a select number of strategically chosen airports. This approach would enable early large-scale success in mass air transportation. Initial operations could be launched at two or three airports, which would serve as learning laboratories to address infrastructure challenges and demonstrate scalability.

Collaboration between the UK and European regions is vital for the successful rollout of hydrogen-powered flights. Such cooperation would help optimise and standardise infrastructure, reduce emissions, and position the UK as a leader in the transition to low-carbon aviation across Europe, particularly on suitable routes and at key hubs.

Several risks must be addressed to make regional narrowbody hydrogen flight a reality. Early-stage sharing of financial burdens, integration of supply chains, alignment of policy and regulation, and mitigation of market risks present significant opportunities for the UK. By taking a proactive approach, the UK could lead Europe in scaling up hydrogen aviation, potentially achieving 80% of the hydrogen environmental benefits by focusing on just 20 airports following aircraft entry into service (EIS).

Summary

Hydrogen-powered aircraft offer a credible pathway toward zero-emission domestic aviation, but near-term operations will likely entail higher operating costs and infrastructure investment. The economic case for airlines will depend on the pace of cost reduction in green hydrogen production and distribution, the rate of aircraft technology maturation, and the strength of policy incentives and carbon pricing mechanisms.

PSO and sub-regional operations together form the logical starting point for hydrogen-powered commercial aviation in the UK. They combine manageable scale, public visibility, and alignment with government priorities on connectivity and net-zero. With appropriate policy support, infrastructure investment, and continued operator engagement, these routes can pioneer the technologies, business models, and operational practices that will underpin a national transition to zero-emission flight. As technology and supply chains scale, these operations can form the foundation for a broader transition to hydrogen-fuelled narrowbody services. Key enablers will include stable hydrogen pricing, investment in airport infrastructure, certification readiness, and coordinated action between industry and government.

Liquid hydrogen operations continue to face technological and aircraft availability challenges. ATI-type programmes can accelerate the development of liquid hydrogen flight technology, such as refuelling systems. Public co-investment in hydrogen infrastructure at selected airports will support learning and demonstration activities, enabling the introduction of additional routes linked to demonstration airports and covering diverse airline operating models.

In summary, while hydrogen aviation will initially rely on targeted public support, it represents a strategically important step toward achieving the UK’s net-zero aviation targets and maintaining national leadership in clean aerospace innovation.

Workstream 2 – Roadmap to Domestic Hydrogen Commercial Operations

Introduction

Many roadmaps have been developed by industry and governments outlining the overall path to net-zero aviation by 2050 or focusing on specific aspects of hydrogen adoption. This roadmap is the first comprehensive analysis of how hydrogen-powered aviation can be introduced in the UK. It highlights the key dependencies between various activities, the expected timelines, potential challenges that could cause delays, and opportunities to accelerate progress.

The roadmap was created by the Hydrogen Task & Finish group, which includes executives from leading OEMs, airlines, airports, construction, academia, and aerospace/aviation consultants, with input and oversight from the Aerospace Technology Institute (ATI) and representatives from government departments including DBT, DfT, and DESNZ. The task and finish group believes that understanding how to achieve zero-emission commercial aviation is vital, with hydrogen being the most promising zero-carbon option in the foreseeable future.

The process involved a detailed bottom-up assessment to identify the critical actions needed to deliver hydrogen flight across various areas, including propulsion technology development, airframe programmes, regulation, skills and training, airport and hydrogen supply infrastructure, planning and construction, and commercial drivers. For each area, the group examined the current status, timelines for completion, urgency, importance, and key dependencies of the activities identified. This was followed by a top-down assessment of major hydrogen aviation rollout stages, referred to as six Evolution Points (EP 1-6). It is important to note that not all airports or route pairs will progress through each point in sequence. The Evolution Points represent the macro-level progression of hydrogen aviation in the UK.

The items in the detailed roadmap were assessed against the Evolution Points to build the final roadmaps and to identify the priority items for discussion in this report. The work was conducted via multiple group workshops and assigned tasks over the course of 2025.

The Task and Finish group would like to thank the Zero-Emission Flight Infrastructure Group (ZEFIG) for providing key information in support of the airport analysis.

Evolution Point	**Short description**	**Description**	**Type of network/operations**	**Service type**
EP1	GH2 - Ground Ops	Gaseous hydrogen airport ground operations	Ground vehicles only to support conventionally fuelled operations	Integration of small-scale hydrogen handling into standard airport operations.
EP2	**GH2 - First Ops - Retrofit**	**First GH2 flight operations. Geographically limited**	**Limited point-to-point network or single hub with 1-5 spokes, plus designated diversion airfields as needed. Refuelling locations may be restricted to a few sites or just the hub.**	**Scheduled or on-demand: passenger and/or freight.**
EP3	GH2 - Full scale - Retrofit	Expanded GH2 network - geographically limited but expanded from EP2. Probably end state for GH2	1-3 hubs; 3-10 spokes each or a wider point-to-point network. Refuelling at most airports in the network as H2 demand grows and sector length extends.	Scheduled or on-demand: passenger and/or freight.
EP4	**LH2 - First Ops – Retrofit or Clean sheet**	**First LH2 operations**	**Point-to-point or single hub with 1-5 spokes plus designated diversion airfields. Refuelling at most locations due to sector lengths enabled by clean sheet designs.**	**Scheduled passenger and/or freight.**
EP5	LH2 - Basic network	Expanded LH2 network	1-3 hubs; 3-10 spokes each. Refuelling at the majority of larger airports in the network due to increasing LH2 demand and sector length.	Scheduled passenger and/or freight.
EP6	LH2 - Full scale	Fully scaled LH2 aircraft operations	Scaled operations similar to existing networks. Refuelling at all airports in the network. Hub airports have fixed LH2 infrastructure.	Scheduled passenger and/or freight.

Table 10: Six primary evolution points for hydrogen aviation in the UK

Evolution Point 1 – Non-aircraft hydrogen use cases at UK airports

Airports can use gaseous hydrogen equipment in their ground operations to decarbonise Scope 1 and 2 emissions. This would involve hydrogen-powered vehicles supporting the turnaround of conventionally fuelled aircraft, utilising hydrogen for Ground Power Units (GPUs), and other forms of non-aviation mobility. In practical terms, this would integrate gaseous hydrogen-powered equipment into existing, standard airport operations, operating alongside well-established diesel and battery-powered equipment. Trials of using and refuelling hydrogen fuel cell-powered Ground Support Equipment (GSE) have been carried out in the UK. These have provided insight into the use of gaseous hydrogen in the airside environment, including forming the basis of a safety case that will be used in the future when airports host early hydrogen-powered aircraft.

While these trials have provided essential safety data for regulators and airports, the regular use of hydrogen-powered GSEs is not a necessary precursor for an airport to host hydrogen flight. Learnings can be adopted – outcomes from the UK trials are openly available to all airports. There are benefits to socialising the use of hydrogen in an airside environment, such as training employees and creating safety procedures, but these can be provided by external providers.

Hydrogen trials

Despite hydrogen being regulated and used safely across different industries for decades, a critical challenge to the delivery of hydrogen-ready airports was 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.

Trials on integrating hydrogen into airport operations have focused on ‘preparing the ground’ for airports to host hydrogen-powered flight. The landmark Project Acorn trial (held in 2023) focused on safe handling, storage and refuelling of hydrogen in an airside environment. Led by easyJet with support from Bristol Airport and a coalition including Cranfield Aerospace, Mulag, and Fuel Cell Systems, the trial included live refuelling and use of hydrogen for ground equipment during aircraft turnarounds. Project Acorn was delivered with the involvement of the Civil Aviation Authority (CAA) and support from the Health and Safety Executive (HSE), resulting in the establishment of a safety case that can be used at all airports. In addition, the project highlighted practical lessons for infrastructure siting, safe venting, and airside operations.

Building on Project Acorn’s momentum, Exeter Airport hosted a demonstration in 2025 in which hydrogen-powered GSE was used to service a TUI aircraft as part of a ‘hydrogen-powered turnaround’ exercise — described as the UK’s first hydrogen-fuelled live aircraft turnaround. That demonstration showed hydrogen can be deployed in live operational contexts with appropriate procedures and supervision.

Skills development

Hydrogen GSE trials provided three key areas of skills development: 1) for ground handlers operating and refuelling hydrogen-powered equipment, 2) the Airport’s Fire and Rescue Service regarding safety, and 3) for the Airport’s operations team integrating the new equipment into existing operations.

For Project Acorn, Cranfield University provided training at their own facility prior to the trial and briefings to the Airport’s Fire and Rescue Service. Cranfield University were able to train baggage handlers on the safety and operations of the hydrogen baggage tug and its refuelling. The trial laid the groundwork for future safe working procedures necessary for hydrogen-ready airports.

Deployment of hydrogen technology

There are three areas where hydrogen could be used at airports:

- Ground Support Equipment (GSE): hydrogen fuel cells can power baggage tractors, tugs, belt loaders, de-icers and other high-duty vehicles that today burn diesel.
- Ground Power & Heating: hydrogen can feed mobile or fixed Ground Power Units (GPUs) and auxiliary power for aircraft at stands. Hydrogen-powered GPUs promise high on-demand capacity where batteries struggle.
- Airport plant and vehicles: snow-clearing, airfield maintenance machines, buses and coaches.

Of these, hydrogen GSEs, such as used in trials mentioned above, and buses are commercially available now. Gatwick Airport is served by some hydrogen buses, which operate in Surrey.

Airports in the UK have set targets to decarbonise their own operations, with Gatwick Airport and Bristol Airport having the early target of achieving this by 2030. Given the short timeframes, airports are choosing to replace traditional diesel-powered equipment with either EVs or battery power. EV/battery ground service equipment is more readily available and likely to be a better long-term choice.

The deployment of hydrogen ground equipment and/or refuelling is not a prerequisite for airports to host early hydrogen-powered flights. Although it would be helpful for the familiarisation of safety management and operations, this experience can be gained elsewhere. The expertise and facilities at Cranfield University, and practical knowledge gained from hydrogen trials, can be shared with airports, allowing them to immediately move to Evolution Point 2, the first operation of gaseous hydrogen aircraft.

Evolution Point 2 – First Operations of Gaseous Hydrogen Aircraft

Introduction

Delivering the first gaseous hydrogen commercial flights before the end of this decade from a UK airport is a feasible target, catalysing significant action on both Research and Development and scaling of the hydrogen network in the 2030s.

The roadmap exercise identified many technology bricks required for this stage. Advanced product development and certification efforts for the first Part 23 hydrogen aircraft are underway. UK-based operators (RVL Aviation, Loganair) are developing plans to introduce commercial operations powered by retrofitted gaseous hydrogen aircraft following regulatory approval.

The initial flight network will likely be limited to routes from a single hub, with the next natural progression being the addition of further routes at this hub, given the capital expenditure required to introduce storage and refuelling capabilities. Hydrogen flight operations are well-suited to fuel tankering, (carrying sufficient fuel for a return flight without refuelling). This is because carrying more fuel does not have the same weight and fuel burn penalty as kerosene-powered operations.

These initial operations will be limited, and the associated hydrogen demand is low in the national context. While on-site operations are relatively practical and cost-effective at this scale, the limited demand means hydrogen remains relatively expensive to procure. The costs of the very first aircraft engines and retrofit processes will also face peak cost which creates a commercial challenge for first-mover operators. The use of low-carbon hydrogen as an aviation fuel is eligible for reward under the Sustainable Aviation Fuels Mandate as it meets the sustainability criteria.

The knowledge, skills and capabilities gained from initial gaseous hydrogen operations at airports have fundamental value in supporting expansion of the airport and route network. It also underpins the establishment of liquid hydrogen infrastructure to support large aircraft.

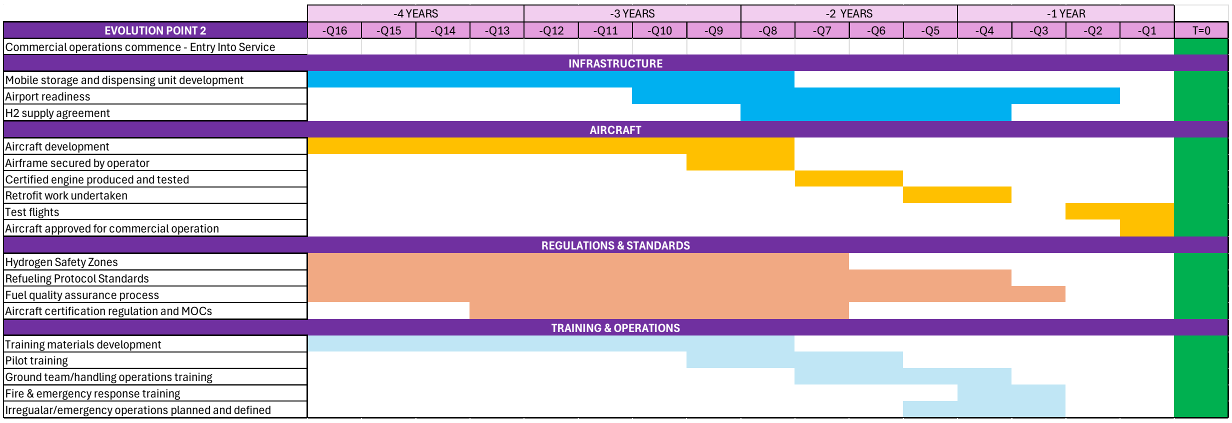
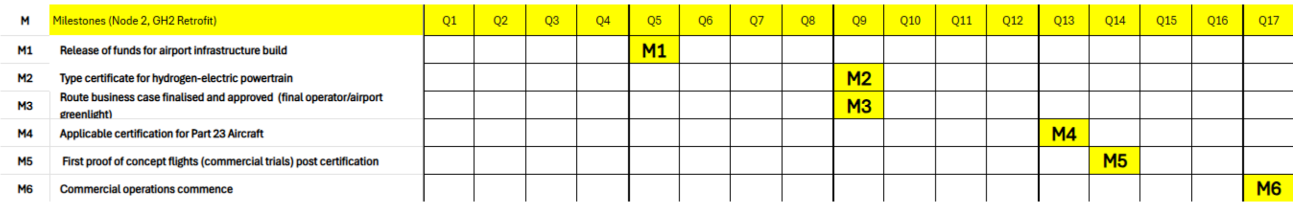


Figure 14: Summary roadmap for Evolution Point 2

Key Milestones

Six key milestones have been identified that lead to commercial operations of GH2 retrofit aircraft by the start of 2030, with commercial trials beginning in Q2 2029. The timeline is indicative, although much of the activity is already underway. There are areas for both acceleration and delay that could shorten or extend the timeline.



M	Milestones (Node 2, GH2 Retrofit)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17
M1	Release of funds for airport infrastructure build					M1												
M2	Type certificate for hydrogen-electric powertrain									M2								
M3	Route business case finalised and approved (final operator/airport greenlight)									M3								
M4	Applicable certification for Part 23 Aircraft													M4				
M5	First proof of concept flights (commercial trials) post certification														M5			
M6	Commercial operations commence																	M6

Figure 15: Key milestones for evolution point 2 - gaseous hydrogen retrofit aircraft

The key milestones identified are summarised below.

M1: Release of Funds for Airport Infrastructure Build - Secure funding to develop hydrogen refuelling and safety systems at selected spoke airports, enabling operational readiness.

- Mobile hydrogen storage and dispensing unit secured with <30 min refuelling time.
- Hydrogen supply agreement executed; fuel assurance process approved by HSE/CAA.
- Airport system design completed; planning applications and consents obtained.
- Operational readiness trials initiated, including RFFS training and emergency procedures.

M2: Type Certificate for Hydrogen-Electric Powertrain - Achieve certification of the hydrogen-electric propulsion system, validating its safety and performance for retrofit use.

- OEM Design Organisation Approval (DOA) awarded for hydrogen-electric system.
- Special Conditions and Certification Review Items agreed with CAA.
- Means of Compliance (MoCs) defined; testing data collection underway.

M3: Route Business Case Finalised and Approved - Complete commercial and operational feasibility studies; secure operator and airport commitment for the initial route/network.

- Route feasibility and commercial viability assessed; operator and airport greenlight secured.
- Detailed network mapping completed for 3-spoke model.
- Explore parallel use cases in other sectors or transport modes to support future scalability.
- Post-launch planning initiated for EP3 and EP4 infrastructure evolution.

M4: Applicable Certification for Part 23 Aircraft - Obtain necessary approvals for retrofitted aircraft under Part 23 regulations, enabling legal and safe operation.

- Airframe secured by operator and retrofit work completed.
- Aircraft tested and approved for commercial operation under Part 23.
- Refuelling protocol standards and hydrogen safety zones confirmed with regulators.
- Changes to airport operations agreed with the regulator (CAP791)
- emergency response & fire fighting competence & training fully implemented

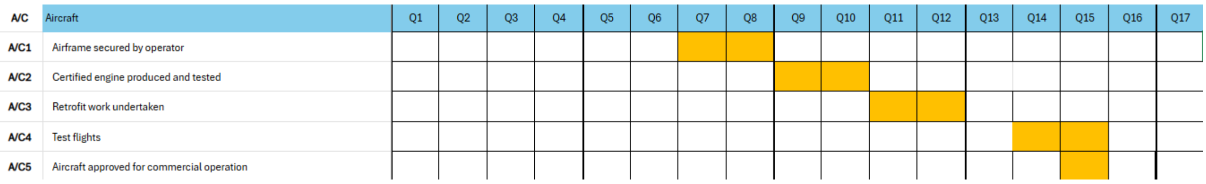
M5: First Proof-of-Concept Flights Post Certification - Conduct live demonstration flights across the network to validate performance, safety, and public acceptance.

- Pilot and ground handling teams trained for hydrogen operations.
- Irregular/emergency operations defined and rehearsed, including diversion airports.
- Proof-of-concept flights conducted across 3-spoke network.
- Performance, safety, and public acceptance data collected and reviewed.

M6: Commercial Operations Commence - Launch certified hydrogen-powered services on the 3-spoke network, marking the UK’s first commercial deployment of gaseous hydrogen aviation

- Commercial service launched with certified hydrogen-powered aircraft.
- On-site storage and fixed infrastructure planning initiated.
- Journey to cost parity and clean-sheet airframe development explored.
- COMAH implications assessed for >5 tonne hydrogen threshold.

Aircraft Development



A/C	Aircraft	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17
A/C1	Airframe secured by operator							🟨	🟨									
A/C2	Certified engine produced and tested									🟨	🟨							
A/C3	Retrofit work undertaken											🟨	🟨					
A/C4	Test flights														🟨	🟨		
A/C5	Aircraft approved for commercial operation															🟨		

Figure 16: Key aircraft readiness milestones

A number of UK-based R&D projects, many with ATI funding, have been developing hydrogen-electric powertrains for small aircraft, seeking to deliver electrification but negating the weight-penalty that makes current battery technology impractical for commercial operations.

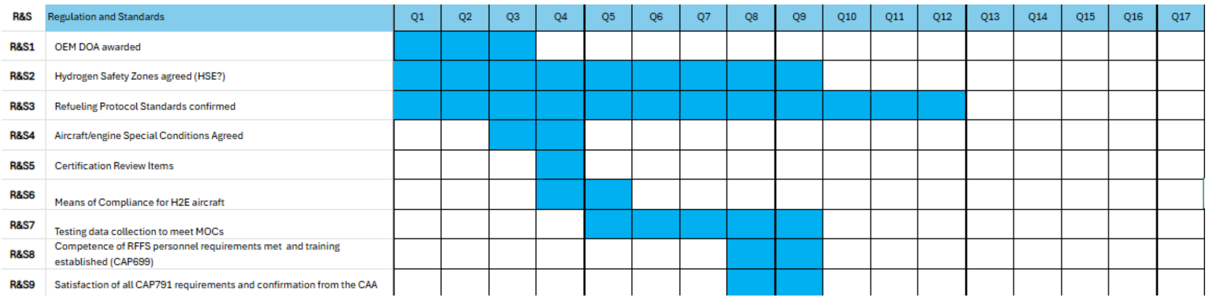
The necessary technologies for delivering these systems were collectively examined by the Hydrogen Task & Finish Group and considered to be at high TRL (TRL 6 or later), including Type IV gaseous hydrogen tanks, low-temperature PEM fuel cell systems, thermal management systems, electric motors, and inverters. In large part, this high readiness is a result of these technologies being widely deployed in the automotive sector and subsequent innovative work over recent years, particularly in the UK, to adapt them for aerospace applications. UK leadership in these technologies can create substantial export, growth, and job opportunities should certification and entry into service be achieved.

Work is now underway on certification of full powertrains and attention turns to the testing requirements. The anticipated pathway is for an engine OEM to obtain a Type Certificate (TC) with the CAA for a novel hydrogen-electric powertrain, before subsequently obtaining a Supplemental Type Certificate (STC) for retrofit of the aircraft. At least one engine OEM is currently working through an application process with the CAA and has secured Design Organisation Approval.

Means of compliance are yet to be agreed with hydrogen-electric engine developers, but the regulatory considerations expected are detailed in the subsequent section. Testing will need to show technologies meeting D-160 G requirements (the standard for environmental testing in aviation to ensure acceptable operation of systems in diverse conditions), and bonfire and crash/drop testing that will be needed to demonstrate safety of fuel systems was considered one of the more challenging aspects to complete.

Once the route feasibility and commercial viability have been assessed, and the operator and airport greenlight secured, the operator will need to finance and acquire the aircraft for retrofit conversion. Operators will likely lease aircraft from lessors specialising in the regional market, with a lead time before retrofit work is undertaken in order to allow time for training on the aircraft and operational preparations. Retrofit is expected to take around six months and proof-of-concept operations a further six months before full commercial launch takes place.

Regulation of Hydrogen Use in Aviation



R&S	Regulation and Standards	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17
R&S1	OEM DOA awarded	🟦	🟦	🟦														
R&S2	Hydrogen Safety Zones agreed (HSE?)	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦								
R&S3	Refueling Protocol Standards confirmed	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					
R&S4	Aircraft/engine Special Conditions Agreed			🟦	🟦													
R&S5	Certification Review Items				🟦													
R&S6	Means of Compliance for H2E aircraft				🟦	🟦												
R&S7	Testing data collection to meet MOCs					🟦	🟦	🟦	🟦	🟦								
R&S8	Competence of RFFS personnel requirements met and training established (CAP699)								🟦	🟦								
R&S9	Satisfaction of all CAP791 requirements and confirmation from the CAA								🟦	🟦								

Figure 17: Anticipated regulatory timeline

Aircraft Certification

The process for delivering certified aircraft systems is defined at high-level above in the Aircraft Development section. It is foreseen that the establishment of special conditions and means of compliance for type certificate of a hydrogen propulsion system would need to be achieved around three years in advance of entry-in-service. As mentioned, the process is underway with some OEMs, but the CAA to keep pace with industry in this area as a transformational step. Clearly safety is paramount and appropriately supplying the personnel and skills for well-paced certification activity is crucial.

While funding the Hydrogen Sandbox Challenge is welcomed, it focuses on fuel cell, combustion technology, cryogenic pipework, HAPS & UAVs using hydrogen, as well as airport use cases for hydrogen (providing helpful experience which has informed the next section). Similar initiatives are underway overseas with greater funding. As a minimum, the UK should aim to keep pace with the international competition in supporting zero-emission aircraft development.

The UK could propel the next stage and secure world-first certifications by multi-year funding to support resourcing type certificate and supplemental type certificate applications for zero-emission propulsion systems.

Recommendation – Additional funding for the CAA to support development of Means of Compliance for hydrogen and other zero-emission technologies

Airport Infrastructure

Introducing hydrogen airside at an airport is a multi-phase, high-stakes transformation that requires careful planning, regulatory alignment, and infrastructure investment.

Engagement with the aerodrome operators, hydrogen suppliers, OEM’s Ground Handling companies, the Rescue and Firefighting Service (RFFS) and UK CAA at an early stage is encouraged and has started on a good footing with the Government’s multi-round Hydrogen Sandbox Challenge.

CAP 791 Procedures for Changes to Aerodrome Infrastructure is a key Civil Aviation Authority (CAA) document that outlines how aerodrome operators must notify and engage with the CAA when making changes to infrastructure or management systems. It includes guidance to help ensure that changes comply with licensing and certification criteria and are managed safely. It covers four categories; development, changes, maintenance and management systems, all of which would impact on the introduction of hydrogen as a fuel airside.

While CAP 791 does not yet contain hydrogen-specific refuelling guidance, it does provide the procedural framework through which such changes, like introducing hydrogen refuelling, must be proposed and assessed.

Key elements that will need to be completed to ensure compliance in line with CAP 791 and other CAA requirements include:

- Conducting innovation trials for hydrogen aircraft fuelling systems
- Submission of a structured, evidence-based safety case to support the proposed introduction of hydrogen refuelling operations - as part of the aerodrome Safety Management System (SMS) and following CAP 760 and CAP 795 guidance
- Detailing location and design of hydrogen storage and refuelling points, control systems and safety barriers, separation distances from aircraft stands and terminals
- Preparing emergency response plans including updates to existing Rescue and Firefighting Services RFFS procedures and ensuring RFFS personnel receive specialist, role-specific training related to hydrogen operations and potential incidents (further detailed in Appendix 1.

As can be seen from the timeline, two major steps to unlock airport planning and timely delivery of hydrogen operations should be a priority for industry and regulator (CAA, HSE) engagement: enabling acceptable fuel quality assurance (and hydrogen purity) and defining gaseous hydrogen safety zones, covered in more detail below.

Hydrogen Fuel Quality Assurance

The introduction of hydrogen as an aviation fuel presents distinct challenges compared to traditional fuels such as AVGAS and Jet A-1. These challenges necessitate specialised handling procedures, enhanced safety measures, and rigorous fuel quality assurance throughout the supply chain.

Fuel assurance is particularly important because hydrogen purity needs to meet stringent requirements set by international standards, primarily ISO 14687. The presence of impurities, even at parts-per-billion (ppb) levels, can damage fuel cell performance, potentially impacting operation.

Currently, assurance requires sampling and lab-based validation. This may be sufficient for initial operations but as hydrogen use scales, it will be optimal to deliver production-line or in-line hydrogen purity testing. The National Physical Laboratory in Teddington is working on this technology, but the foundations for scaling hydrogen aviation could benefit from expediting this technology development (see Appendix 2).

Aerodrome operators with fuel storage facilities are required by the Air Navigation Order to include in their Aerodrome Manual procedures to ensure that aviation fuel is fit for use at all stages: receipt, storage, handling, and distribution.

Industry standards can help with the foundations of acceptable fuel assurance and SAE and EUROCAE have published AIR8466 on Hydrogen Fuelling Stations for Airports, with guidance on fuelling protocols for a range of aircraft types.

The Joint Inspection Group (JIG), the leading international body for aviation fuel standards, plays a role in ensuring the safe handling, quality control, and distribution of aviation fuels globally. As it stands today, there is no plan for them to publish hydrogen-specific standards but it is anticipated that they will align with emerging frameworks as hydrogen aviation infrastructure evolves.

Reliance on JIG creates a dependency which may delay the development of hydrogen aviation unless aviation & safety regulators take the lead on this topic.

Recommendation: Enabling a clear and agreed fuel assurance process for hydrogen is critical to the adoption of hydrogen flight and a key step for CAA action.

Although no formal hydrogen refuelling standard currently exists for aviation, automotive hydrogen standards and UK health and safety legislation provide a foundational reference. Relevant legislation includes:

- Health and Safety at Work Act 1974
- DSEAR (Dangerous Substances and Explosive Atmospheres Regulations)
- COMAH (Control of Major Accident Hazards)
- ATEX (Explosive Atmospheres Regulations)
- PSSR (Pressure Systems Safety Regulations)
- COSHH (Control of Substances Hazardous to Health)

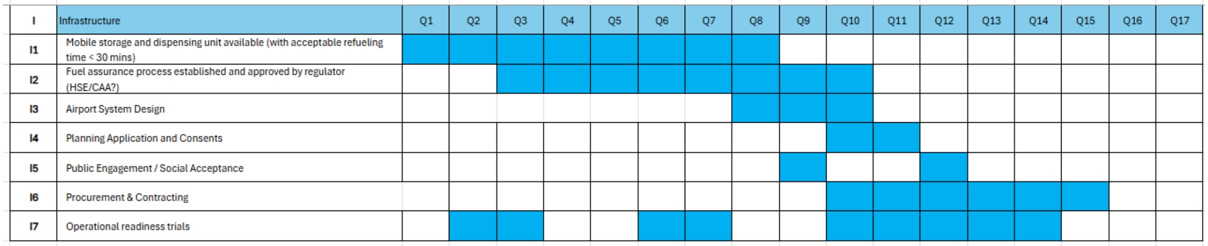
Hydrogen Safety Zones

The establishment of hydrogen safety zones is a fundamental requirement to ensure that gaseous hydrogen operations achieve and maintain an Acceptable Level of Safety (ALoS). These zones are designed to mitigate the risks associated with compressed hydrogen storage, transfer, and refuelling activities. This item was identified by the Task & Finish Group as having a two year or more duration, with a necessity to complete at least 18 months before planned entry-in-service to allow effective operations planning and training window.

Thankfully, extensive work is already underway within the regulator and industry standards groups. Ongoing industry and regulatory discussions have highlighted the need for clear, evidence-based criteria to define these zones, including their dimensions, classification, and the physical and procedural safeguards required. Safety zone definition will need to account for varying factors including location (e.g. indoor vs outdoor), system pressure and volume which influence potential severity and radius of a release event, and ventilation and environmental conditions.

Further information on hydrogen safety zone considerations can be found in Appendix 3.

Airport Planning and Readiness



I	Infrastructure	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17
I1	Mobile storage and dispensing unit available (with acceptable refueling time < 30 mins)	■	■	■	■	■	■	■	■									
I2	Fuel assurance process established and approved by regulator (HSE/CAA?)			■	■	■	■	■	■	■	■							
I3	Airport System Design								■	■	■							
I4	Planning Application and Consents										■	■						
I5	Public Engagement / Social Acceptance									■			■					
I6	Procurement & Contracting										■	■	■	■	■	■		
I7	Operational readiness trials		■	■			■	■			■	■	■	■	■			

Figure 18: Airport infrastructure readiness timeline

Technology Development and Integration

The use of hydrogen within airside environments has been successfully demonstrated at a number of airports, but at present is not in common usage. There is potential for airports to utilise hydrogen within their own operations and also offer refuelling for surface transport vehicles as part of wider hydrogen hub initiatives.

Airport operations rely upon a range of heavy equipment designed for use in a niche environment and hydrogen offers a potential fuel source to replace the use of diesel power.

In the UK, Bristol Airport has worked with Easyjet and others through Project Acorn to demonstrate airside refuelling and use of baggage trucks. In addition, Cranfield University Airport provided the infrastructure to de-risk and host a UK first commercial aircraft hydrogen turnaround. Furthermore, within the Tees Valley Transport Hydrogen Hub demonstration of hydrogen vehicles airside has taken place plus construction of a landside refueler for use by goods vehicles.

The UK is not alone in this endeavour. As examples of overseas activity, Hamburg Airport has been using hydrogen baggage trucks and, as part of the Tulip project, Amsterdam Schipol Airport has been trialling a range of vehicles operating airside using hydrogen.

There is strong evidence of the technological viability of using hydrogen for a variety of purposes at airports to help in the decarbonisation of their operations and as an enabler of the infrastructure and expertise required to handle hydrogen in aircraft operations. Commercial challenges remain given the need for airports to source low-carbon hydrogen at appropriate volumes. In addition, there are competing low-carbon technologies for some equipment such as battery-electric aircraft tugs, already in commercial operation. There are opportunities for UK companies to seize new market share from hydrogen ground support equipment, but they seek certainty on the pace at which airports will adopt greater use of hydrogen.

Our recommendation is that trial and demonstration activity continues with dissemination of findings between airports and with regulators such as the CAA. This should enable the continued evolution of standards and the regulatory environment to allow the handling of hydrogen at airports to be an increasingly mainstream activity.

Business Case

Making a successful business case for hydrogen infrastructure at an airport must consider both aviation and non-aviation offtakers, as broader demand can improve utilisation and financial viability. Airports typically operate within long funding cycles and structured approvals processes, often requiring alignment with master planning and stakeholder engagement. In order to meet ROI criteria, airports will have to be able to identify not only a viable scalable market opportunity but have a reasonable level of assurance in the timescales for delivery of other critical path items.

Investment decisions must also compete with other priorities and demonstrate a clear return on investment or alignment with sustainability goals. The contractual models for fuel provision whether airport owned, third-party operated, or hybrid affect risk allocation, revenue potential, and operational flexibility. Longer-term, infrastructure costs will be in part recovered through airline charges, potentially influencing ticket prices so affordable availability of both hydrogen and the infrastructure required will be critical. A robust business case must therefore balance technical feasibility, commercial structure, stakeholder alignment, and long-term sustainability outcomes.

The level of complexity foreseen above makes first airport adoptions dependent on a number of variables that can stymie or protract the process. It is therefore recommended that Government deploys catalysing, small-scale funding of initial airport hydrogen infrastructure and hydrogen transportation costs for the very first routes be established. This will enable the learnings that support development of viable business cases for expansion of the small-scale gaseous hydrogen aircraft routes, and ultimately foundational work that supports liquid hydrogen fuel and aircraft operations.

Recommendation – Establish funding mechanism for first airport infrastructure to unlock business case

System Design and ConOps

The introduction of hydrogen operations into an airport facility is a complex, multi-phase process that requires careful planning, coordination, and integration with existing airport systems and operations. The operation must be embedded both physically and operationally within the broader airport ecosystem. A key enabler to successful integration will be ongoing trials of new technology and practices in the operational environment. This will be even more critical for initial stages of development of the UK network and will require ongoing gradual learning and improvement from early stages to ensure commercial operations can be integrated as safely and efficiently as possible.

The system design phase required from early in the process must account for not only the technical aspects such as functional requirements, sizing for peak and future demand, dynamic modelling of hydrogen flow and storage, redundancy for critical systems, and rigorous safety and environmental assessments but also the operational realities of a busy airport. This includes ensuring minimal disruption to daily operations, aligning with airside and landside logistics, and maintaining compliance with aviation safety standards. The system will involve a mix of mobile and fixed components, such as hydrogen-powered ground support vehicles, refuelling trucks, stationary storage tanks, production units at some sites (e.g., electrolysers), and distribution infrastructure. These must be strategically located and designed to operate safely and efficiently within the airport's spatial and operational constraints.

Supporting subsystems including control systems for flow and pressure regulation, power systems for hydrogen production and compression, real-time monitoring for performance and leak detection and emergency response protocols must be seamlessly integrated with existing airport systems. This includes IT networks, energy grids, and emergency services.

Given the scale and complexity, this process should commence as early as possible involving stakeholder engagement, regulatory approvals, pilot testing and phased implementation. Collaboration will be essential to ensure that hydrogen infrastructure enhances, rather than disrupts, the airport's core functions and will ensure confidence is built in the early stages leading to a smoother implementation.

Integrating Hydrogen with key Airport Operators

Ground handling agents involved in aircraft fuelling must meet strict safety and competency standards set by IATA's ISAGO and Airport Handling Manual (AHM). They require initial and recurrent training on fuel properties, PPE, emergency procedures, and environmental protection. Operational responsibilities include preventing ignition sources, ensuring communication with flight crews, monitoring for leaks, and using certified equipment would have to be built into the overall integration into an airport operation.

The airport operator is responsible for oversight of fuelling operations, storage and dispensing and are required to ensure staff carrying out these oversight activities are competent for this responsibility. Availability of training material and appropriate training courses will be critical for both GHAs and Airports following publication of the regulations.

Gaseous Hydrogen Storage and Refuelling Technology for Initial Operations (Evolution Point 2)

During initial operations with gaseous hydrogen, the infrastructure requirements at participating airports are expected to be relatively modest. Gaseous hydrogen storage and fuelling systems are already in use for off-airport applications (eg hydrogen buses) and technology has been trialled in airport environment for GSE (as in Evolution Point 1). These proven systems can provide safe, reliable storage of the limited hydrogen volumes anticipated in EP2, meaning that the capital outlay and civil works for airports will be minimal at this stage.

It is anticipated that gaseous hydrogen will be delivered to airports by road tanker – and would either be stored on site in tankers or storage tanks located within secure airside compounds. From there, aircraft would be refuelled using mobile refuelling units.

Civil Infrastructure

The civil infrastructure required to support the delivery, storage and refuelling with gaseous hydrogen will vary dependent on specific airport site layout, condition and capacity of existing infrastructure

Practically, the first operations at Evolution Point 2 are unlikely to necessitate major civil infrastructure upgrades given the anticipated hydrogen volumes and planned delivery mechanism of limited tanker movements.

However, as gaseous hydrogen operations scale, at the first hub airport and as additional airport sites, civil infrastructure upgrades could include:

- Upgrades / extensions to landside and airside roads to provide tanker access to hydrogen storage areas, and parking for tankers and refuellers
- Civil works to accommodate storage and fuelling equipment, including security and physical protection in accordance with safety zoning requirements
- Upgrades to utilities infrastructure (eg power, control systems) to support marginal increases in demand

The scale and complexity of these civil works would generally be at a level that would routinely be undertaken by most airport development teams and their supply chains. The development lead time would be driven by the typical business planning, stakeholder engagement and procurement processes that apply across airport development programmes.

Planning Applications and Consenting

The scale of development anticipated to support Evolution Point 2 operations is generally likely to be at a level that can be managed through permitted development rights, but subject to the project requirements and site location, may require approval through the town and country planning system – similar to most other capital development works on airport. Again, subject to scope and location of works, some level of environmental impact assessment may be required in order to support the consenting process.

Whilst in principal routine, these consenting processes take time and may be delayed by local planning considerations.

Operator Readiness

Fuel Contracts

Securing reliable and scalable GH2 supply is foundational to operational readiness. For initial operations, it is likely that operators will acquire fuel as part of a "power-by-the-hour" contract for the purchase of the retrofit propulsion system. This enables derisking of the fuel cost for operators and simplifies the business case, with the engine OEM working with hydrogen producers to secure fuel contracts.

However, longer-term scaling into different Evolution Points with higher hydrogen volumes required will mean operators striking longer-term agreements for the provision of hydrogen directly with hydrogen producers as the ecosystem grows.

Initial fuel agreements should include provisions for:

- Volume flexibility to accommodate scaling from pilot operations to full commercial service.
- On-site storage solutions, either via mobile storage and dispensing units or fixed storage tanks (depending on the size of the initial operations)
- Contingency supply planning to mitigate risks from production or logistics disruptions.

Coordination with airport authorities and infrastructure providers is essential to ensure that refuelling systems are compatible with aircraft requirements and meet regulatory standards.

Irregular/Emergency Operations

Route planning will need to extend to detailed contingencies for irregular and emergency operations. Given the relatively small distances involved, nearby airfields can serve as diverted landing sites, with the mobile, storage and dispensing vehicles used at the primary hub airport capable of driving to diverted aircraft to refill gaseous hydrogen when needed.

Training materials must be developed in line with CAP699 and other relevant CAA guidance, ensuring that ground teams, flight crews, and emergency responders are proficient in GH_2-specific scenarios. Regular drills and proficiency checks should be embedded into operational routines.

Trials

The Jet Zero Hydrogen Roadmap identifies the need for a roughly half-year period of trials to ensure smooth operations of a retrofit hydrogen aircraft to test out fuelling processes, maintenance considerations, flight operations, RFFS drills and irregular and emergency operations. Key aspects of the trials should include:

- Ground handling and refuelling simulations, validating infrastructure, safety zones, and turnaround times. Ground crew will need to be trained and practised in hydrogen refuelling interfaces, hydrogen and high-voltage incident scenarios and specific human factors, including communication under stress, error prevention and situational awareness.
- Flight trials, assessing aircraft performance, fuel efficiency, and operational reliability under real-world conditions.

Trial data should be collected to support final stages of certification, refine operational procedures, and inform future infrastructure planning. Collaboration with regulators, OEMs, and research institutions will be critical to ensure trials meet both technical and policy objectives.

Flight Operations Administration and Training

Gaseous hydrogen operations require updates to flight operations manuals, crew training programmes, and scheduling systems. Key administrative tasks include:

- Integration of GH_2 specific procedures into standard operating manuals and dispatch protocols.
- Crew rostering and duty time adjustments, accounting for new turnaround and refuelling durations.
- Flight planning system updates, including fuel weight calculations, range modelling, and contingency planning.

Operators must also ensure that digital systems — including maintenance tracking, fuel usage monitoring, and performance analytics — are adapted to support retrofit hydrogen aircraft. Coordination with air traffic control and airport operations teams will be essential to manage any procedural changes.

With changes to cockpit orientation, instrumentation, flight controls and aircraft aerodynamics, pilot training and type rating on the STC aircraft will be required. This will necessitate simulator development matching the unique characteristics of the retrofit aircraft. Training materials development can begin in the early stages of the certification program.

Pilot and flight crew will also require training on basic hydrogen awareness and safety, fuel cell system fundamentals and refuelling principles.

Maintenance, Repair and Overhaul (MRO)

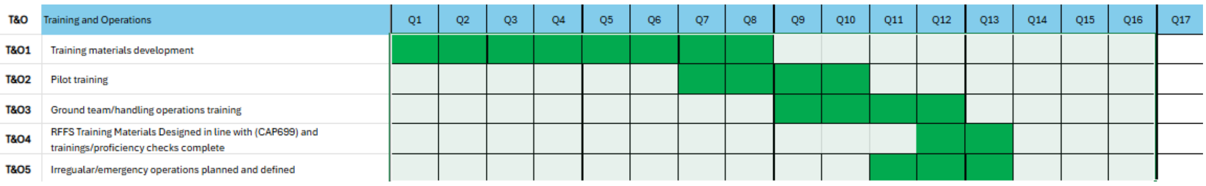
Hydrogen aircraft introduce new MRO requirements, particularly around high-pressure storage systems, hydrogen-specific requirements, fuel cell components and high-voltage electrical systems.

Airworthiness training and Maintenance, Repair & Overhaul (MRO) processes are already under development to support operator adoption. The primary goal will be to close the gap with operation and maintenance standards for existing technologies by developing guidance on operational procedures, maintenance protocols, and lifecycle management for the new technologies. The development of effective remote sensors and remote monitoring technologies (also underway) will enable optimised operations and simplified MRO, alongside the inherent benefits provided by fuel cells and electric motors in terms of low temperature, low pressure reactions and fewer moving parts.

Operators must:

- Establish hydrogen-capable maintenance facilities, including tooling, safety systems, and trained personnel.
- Develop inspection and servicing protocols for tanks, valves, insulation, fuel lines and high-voltage electrical components.
- Coordinate with OEMs and regulators to ensure compliance with evolving standards and certification pathways.

Training programmes for MRO staff must be developed in partnership with equipment manufacturers and regulatory bodies.



T&O	Training and Operations	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17
T&O1	Training materials development	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩									
T&O2	Pilot training							🟩	🟩	🟩	🟩							
T&O3	Ground team/handling operations training									🟩	🟩	🟩	🟩					
T&O4	RFFS Training Materials Designed in line with (CAP699) and trainings/proficiency checks complete												🟩	🟩				
T&O5	Irregualar/emergency operations planned and defined											🟩	🟩	🟩				

Figure 19: Anticipated key training and operations milestones

Marketing and Sales

Commercial success depends on public confidence and market demand. Operators must develop a marketing and sales strategy that:

- Communicates the environmental benefits of hydrogen-electric aviation, including zero-emission flight, long-term cost reductions, cleaner air and less noise for local communities, and the potential for increased connectivity based on these benefits
- Builds trust in safety and reliability, supported by transparent trial results and regulatory endorsements.
- Targets early adopters (aerospace/aircraft engineering enthusiasts and sustainability-focused customers). The introduction of these new systems may create a tourism boost for the selected destinations based on the enthusiast appetite and comparative lower trip emissions on these routes.

Sales teams should be trained to articulate the unique value proposition of hydrogen aviation, and digital platforms should be updated to reflect new aircraft capabilities, routes, and service features.

Safety and Compliance / Manual Development

Safety and regulatory compliance are central to hydrogen operations.

Foundational familiarisation training will be required for personnel involved in hydrogen-electric aircraft operations and maintenance to ensure that all staff have a baseline understanding of hydrogen and high-voltage/high-pressure systems prior to undertaking role-specific authorisations or operational duties. Records will need to be maintained in the operator's LMS, and completion is a prerequisite for progression to role-specific or authorisation-level training. Maintenance regimes will likely be less cumbersome and frequent, but with key differences, developing the necessary materials and curricula to satisfy the regulator remains a large task.

Operators must:

- Develop comprehensive manuals covering hydrogen handling, flight operations, ground procedures, and emergency response.
- Ensure alignment with CAP791, CAP699, and emerging hydrogen aviation standards.
- Establish internal audit and review processes to maintain compliance and support continuous improvement.

Coordination with the CAA, HSE, and international aviation bodies will be essential to ensure that manuals reflect best practice and evolving regulatory expectations. Operators should also contribute to industry working groups to help shape future standards and share lessons learned.

Summary and Conclusions – EP2

Delivering commercial flights in Part 23 aircraft will have limited overall decarbonisation impact in itself. However, it will underpin the promise of hydrogen aviation and provide market confidence that will unlock private investment in both technology R&D critical to delivering propulsion systems for large aircraft and also in the exponentially larger infrastructure investment required for a scaled liquid hydrogen aviation ecosystem.

Furthermore, while major differences exist between gaseous and liquid hydrogen (as will be documented in EP4-6), starting with gaseous operations is much simpler and achievable in a much shorter time horizon. Reaching EP2 will:

- Establish the regulatory frameworks necessary to ultimately bring Part 25 aircraft into UK operation
- Embed knowledge and develop capabilities and skills related to hydrogen systems and procedures that ease the transition to liquid hydrogen operations at EP4, ultimately reducing the costs of establishing these operations.
- Strengthen the case for investment in R&D in hydrogen systems for large aircraft, securing UK technology leadership as hydrogen aviation matures

Analysis of all the required steps across technology and skills development, airport and operator preparedness, and regulation reveals key dependencies that constrain the timeline, with many items underway and others requiring urgent attention.

To ensure the timely realisation of EP2, the Government should:

- Provide additional funding for the CAA to support certification programmes for hydrogen and other zero-emission technologies
- Establish a funding mechanism for first airport infrastructure to unlock the business case
- Direct the CAA to establish a clear and agreed fuel assurance process for hydrogen is critical to the adoption of hydrogen flight and a key step for CAA action
- Create additional funding programmes to support the establishment of hydrogen fuel infrastructure and/or transport of hydrogen

In the next section we explore the scaling of gaseous hydrogen aircraft operations to a broader array of airports, operators and routes.

Evolution Points 3 to 4 – Scaling Gaseous Hydrogen Operations and Preparing for LH2 introduction

Establishing Operational Readiness for Hydrogen Aviation

The deployment of gaseous hydrogen-powered retrofit aircraft under Part 23 regulations provides a critical first step in validating hydrogen as a viable aviation fuel. Through proof-of-concept flights and commercial operations across an initial single route or a multi-spoke network, the project will demonstrate safe refuelling, handling, and flight operations using mobile GH_2 infrastructure. These early deployments allow for real-world testing of hydrogen-specific protocols, including fuel quality assurance, emergency procedures, and airport readiness — all of which simplify the subsequent preparations for LH_2 introduction.

By embedding hydrogen operations into existing airport environments, the project builds familiarity and confidence among pilots, ground crews, regulators, and passengers. This operational foundation is vital for transitioning to LH_2, which will require more complex infrastructure and handling procedures.

Gaseous hydrogen operations are also a much lower barrier to entry and involve corresponding lower costs. This smaller scale investment will provide significant confidence to approach liquid hydrogen investments in Evolution Points 4, 5 and 6.

Building Regulatory and Certification Pathways

The GH_2 retrofit programme enables early engagement with the Civil Aviation Authority (CAA) and other regulators to define certification pathways for hydrogen propulsion systems. Achieving a type certificate for the hydrogen-electric powertrain and satisfying CAP791 (Procedures for changes to aerodrome infrastructure) requirements for Part 23 aircraft sets a precedent for future LH_2 aircraft certification under Part 25.

This process also helps establish regulatory frameworks for hydrogen safety zones, refuelling protocols, and emergency response standards — many of which will be directly applicable or adaptable to LH_2 operations. The collaborative work with the CAA, HSE, and OEMs during the GH_2 phase will streamline future approvals for clean-sheet LH_2 aircraft and larger commercial platforms.

Developing Scalable Infrastructure and Supply Chains

The network's use of mobile GH_2 storage and dispensing units allows for flexible deployment and testing of hydrogen logistics. These systems will inform the design and planning of fixed infrastructure required for LH_2, including cryogenic storage, high-volume dispensing, and potential integration with future pipelines.

Post-launch planning for EP3 and EP4 — which includes on-site GH_2 storage, LH_2 readiness, and COMAH compliance — will be based on lessons learned from the GH_2 phase. This staged approach ensures that infrastructure investment is de-risked and aligned with operational demand, regulatory thresholds, and future scalability.

Advancing Skills, Safety, and Public Confidence

Training programmes developed for GH_2 operations — including pilot certification, ground handling, and RFFS (Rescue and Fire Fighting Services within CAP699) — will serve as a blueprint for LH_2 workforce development. CAP699-aligned materials and proficiency checks will be expanded to cover LH_2-specific risks and procedures, ensuring continuity in safety culture and operational competence.

Public confidence will also be built through visible, successful GH_2 operations. Demonstration flights and commercial services will help engagement in hydrogen aviation, paving the way for broader acceptance of LH_2 aircraft. This step is essential for future adoption of more advanced hydrogen technologies.

Enabling Strategic Growth and Technology Transition

The EP2 GH_2 retrofit programme is not only a technical demonstration but a strategic enabler of long-term growth. It supports the development of business cases for hydrogen aviation, informs network mapping, and lays the groundwork for clean-sheet LH_2 aircraft designs. The transition from Part 23 to Part 25 aircraft — including potential conversion pathways and new multimodal use cases — will be shaped by data and experience gathered during the GH_2 phase.

Ultimately, this project bridges the gap between today's retrofit solutions and tomorrow's scalable, zero-emission aviation systems. It positions the UK as a global leader in hydrogen aviation, ready to move from pilot deployment to full commercialisation of LH_2-powered aircraft.

Progression to First Liquid Hydrogen Operations

The previous sections have set out the steps required to enable gaseous hydrogen (GH_2) operations as the first commercial application of hydrogen in aviation. This section looks ahead to the next phase: the introduction of liquid hydrogen (LH_2) operations.

Preparation for LH_2 must advance in parallel with the development of GH_2 operations. The technologies, infrastructure, and regulatory frameworks required for liquid hydrogen aviation have longer lead times and greater complexity and cannot be developed sequentially without risking delay to the overall transition. This section therefore outlines how the UK can establish early readiness for LH_2 operations, ensuring that national capability, safety frameworks, and infrastructure are in place as aircraft technologies mature.

Introducing Liquid Hydrogen Operations

Liquid hydrogen offers a step change in capability compared to gaseous hydrogen. Its higher energy density enables the operation of larger aircraft and longer routes, extending the reach of zero-carbon flight beyond regional networks. However, it brings significant new challenges. The cryogenic temperatures required to maintain hydrogen in liquid form necessitate specialist systems for storage, distribution, and refuelling, each of which must meet rigorous safety and reliability standards.

At the airport level, LH_2 operations imply a fundamental shift in the scale and nature of infrastructure. Larger storage facilities, enhanced safety management, and close integration with airport energy systems will be essential. Planning and development must consider siting, resilience, and compatibility with existing operations. As with GH_2, readiness for LH_2 depends on a whole-system approach, involving aircraft manufacturers, airlines, airports, fuel suppliers, logistics providers, and regulators working to a common framework.

The Case for Early Action

Preparations for liquid hydrogen aviation must begin now if the UK is to remain competitive and ensure timely deployment. The development and certification of the required technologies and infrastructure are long-cycle activities, often spanning a decade from concept to operation.

Key drivers for early action include:

Liquid hydrogen availability: Currently, there is no liquid hydrogen production in the UK, resulting in a dependence on imports. Although initial volumes will be small, if the UK does not have security of supply it creates a significant risk across the supply chain and for the drivers below.

Technical challenges: Although liquid hydrogen pumps and valves exist, they have not been validated or designed for aerospace applications. This is critical for the aircraft and refuelling systems. This requires early assessment and technology development to inform the viability of further actions.

Infrastructure and regulatory lead times: The design, permitting, and construction of cryogenic storage and refuelling systems, along with the establishment of associated safety frameworks, require extended timelines.

Early design integration: Coordination between aircraft developers, airports, airlines, and fuel suppliers is critical to align design assumptions and operational requirements from the outset.

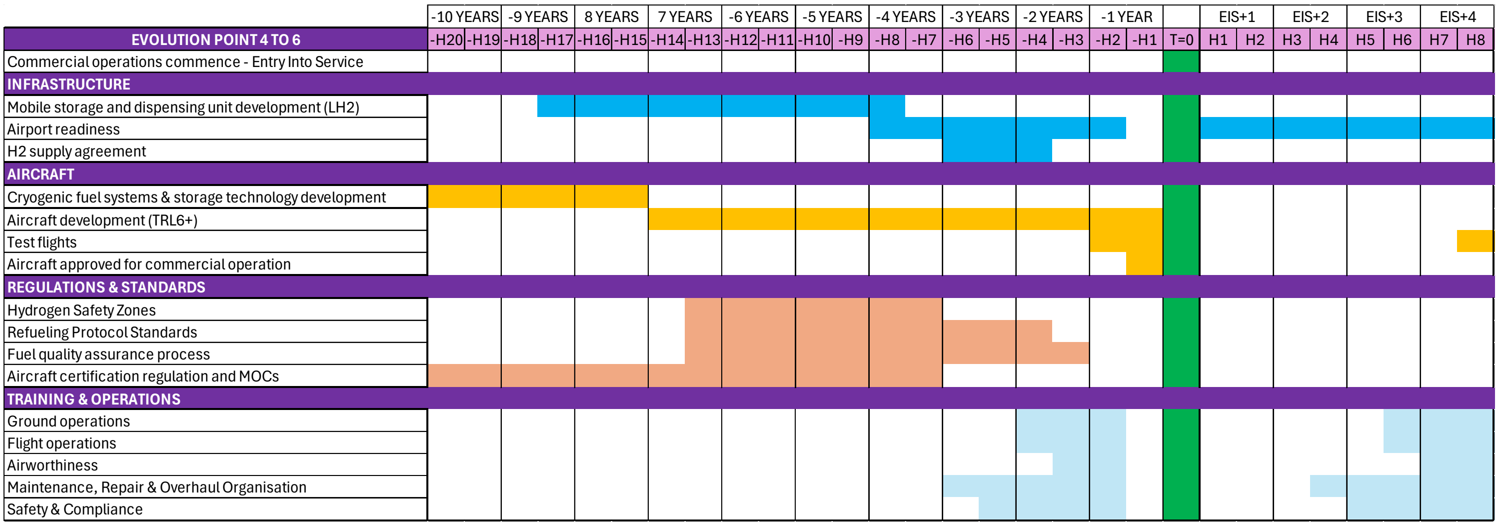
Global competition: Other regions, including the EU and Japan, are already investing in liquid hydrogen supply chains, airport trials, and aircraft integration. Maintaining alignment with international standards and partnerships will be crucial to safeguard the UK's leadership and export potential.

Industrial opportunity: Advancing LH_2 readiness alongside GH_2 creates continuity for the UK supply chain, building on existing hydrogen capabilities to capture value in cryogenic systems, safety technologies, and airport infrastructure services.

Without early and coordinated preparation, there is a risk that aircraft and infrastructure readiness will diverge, undermining the UK's ability to adopt and scale zero-emission flight at pace.

Overview of LH_2 Evolution Points (4–6)

Liquid hydrogen operations are presented through three progressive Evolution Points, reflecting the increasing maturity of aviation networks, infrastructure, and hydrogen demand. These stages are designed to overlap, with each building on the experience and learning of the previous phase.



	-10 YEARS		-9 YEARS		8 YEARS		7 YEARS		-6 YEARS		-5 YEARS		-4 YEARS		-3 YEARS		-2 YEARS		-1 YEAR			EIS+1		EIS+2		EIS+3		EIS+4	
EVOLUTION POINT 4 TO 6	-H20	-H19	-H18	-H17	-H16	-H15	-H14	-H13	-H12	-H11	-H10	-H9	-H8	-H7	-H6	-H5	-H4	-H3	-H2	-H1	T=0	H1	H2	H3	H4	H5	H6	H7	H8
Commercial operations commence - Entry Into Service																					🟩								
INFRASTRUCTURE																													
Mobile storage and dispensing unit development (LH2)				🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦								🟩								
Airport readiness													🟦	🟦	🟦	🟦	🟦	🟦	🟦		🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
H2 supply agreement															🟦	🟦	🟦				🟩								
AIRCRAFT																													
Cryogenic fuel systems & storage technology development	🟨	🟨	🟨	🟨	🟨	🟨															🟩								
Aircraft development (TRL6+)							🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩								
Test flights																			🟨	🟨	🟩								🟨
Aircraft approved for commercial operation																				🟨	🟩								
REGULATIONS & STANDARDS																													
Hydrogen Safety Zones								🟧	🟧	🟧	🟧	🟧	🟧	🟧							🟩								
Refueling Protocol Standards								🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧				🟩								
Fuel quality assurance process								🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧			🟩								
Aircraft certification regulation and MOCs	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧							🟩								
TRAINING & OPERATIONS																													
Ground operations																	🟦	🟦	🟦		🟩							🟦	🟦
Flight operations																	🟦	🟦	🟦		🟩						🟦	🟦	🟦
Airworthiness																		🟦	🟦		🟩							🟦	🟦
Maintenance, Repair & Overhaul Organisation															🟦	🟦	🟦	🟦	🟦		🟩				🟦	🟦	🟦	🟦	🟦
Safety & Compliance																🟦	🟦	🟦	🟦		🟩					🟦	🟦	🟦	🟦

Figure 20: Summary timeline for evolution points 4, 5 and 6

Evolution Point 4 – Initial LH_2 Operations

EP4 represents the first introduction of LH_2 aircraft at a limited number of early-adopter airports. Operations will be intentionally kept simple, with small volumes of liquid hydrogen to minimise initial investment and allow phased learning. Early regulatory, operational, and airport readiness activities will proceed in parallel with aircraft development to ensure that systems evolve together. This phase will validate safety cases, establish operating procedures, and build confidence across the sector.

Evolution Point 5 – Expanded LH_2 Operations

EP5 marks the transition to wider commercial operations. Hydrogen demand increases, driven by a broader range of aircraft and routes. Airports will require larger storage and distribution systems, with higher investment values and more complex logistics. Concept development and business case preparation can begin during EP4, ensuring continuity between phases. Lessons learned from initial operations will inform scalable, standardised approaches to infrastructure and safety management.

Evolution Point 6 – Mature LH_2 Operations

EP6 represents full operational maturity. At this stage, the quantities of hydrogen required by the aviation sector will necessitate on-site liquefaction at major airports, supplied by gaseous hydrogen pipelines. Some airports will transition from mobile refuelling to static hydrant systems, similar to today's jet fuel networks. Delivering this level of capability will involve major capital investment, long-lead technology development, and detailed integration with existing airport systems. Achieving EP6 readiness will signify that liquid hydrogen has become a routine, large-scale aviation fuel. Collectively, EP4–6 provide a structured pathway for scaling liquid hydrogen operations in the UK. Early progression through EP4 will enable the evidence base, standards, and industrial capacity needed to accelerate subsequent phases.

The following sections focus on the activities required to achieve EP4, with a brief explanation of the additional requirements for EPs 5 and 6 detailed in the final paragraphs.

Aircraft Development

The concept of a 'clean sheet' regional aircraft represents a fundamental rethink of aircraft design to incorporate hydrogen from the outset to achieve the goal of net-zero aviation. This ambition is heavily influenced by pioneering initiatives from Airbus (with its ZEROe project), GKN Aerospace, ATI FlyZero, ZeroAvia and Rolls-Royce. These programmes are driving the development of future regional aircraft with a strong focus on hydrogen as the primary energy source, with entry into service projected in the 2040s.

Key Research and Development and Industrialisation Steps

Cryogenic Storage/Fuel Systems: A critical R&D block involves the design and manufacture of innovative cryogenic storage systems for liquid hydrogen, which needs to be safely stored at minus 253°C. This includes developing aerospace cryogenic capabilities, addressing material and sealing challenges, and establishing industry-wide standards. This is also applicable to aircraft fuelling systems.

Hydrogen Fuel Cell Technologies: The first liquid hydrogen aircraft is likely to be a regional aircraft (60-100 seats) powered by fuel cells. Airbus, through its ZEROe project, has selected hydrogen fuel cell technology for its future 100-seat aircraft, converting hydrogen into electricity through a chemical reaction with water as the only byproduct. This has advantages in terms of efficiency and tackling non-CO2 emissions. FlyZero also identified green liquid hydrogen as the most viable fuel, capable of powering aircraft using fuel cell, gas turbine, and hybrid systems. FlyZero presented a regional aircraft concept powered by fuel cells and carrying liquid hydrogen fuel.

To support the development of hydrogen-electric propulsion systems for aircraft in this range, fuel cells with specific power in excess of 2 kW/kg must be at TRL6 at the start of an aircraft development programme. Further work is needed to advance the power density of electric motors and inverter thermal management systems. With multiple existing ATI projects targeting components for multi-megawatt hydrogen-electric engines, the UK has a great opportunity to become a major supplier to this new propulsion segment and stimulate the global market by leading in adoption through establishment of early LH2 flight operations.

Aerodynamic Structures and Thermal Management: Revolutionary technology breakthroughs are required in aerodynamic structures and thermal management to optimise the efficiency and integration of hydrogen systems. Hydrogen-capable heat exchangers are a key technology in early stages of development.

Hydrogen Gas Turbines: While fuel cells are a focus, hydrogen gas turbines are also being explored, with combustor development identified as a key challenge.

From Design to Take-off: A Programme Overview

Preliminary Design: Preliminary design efforts involve conceptualising future highly efficient next-generation regional aircraft, considering various configurations such as 90-passenger turboprops. This phase explores the feasibility of different hydrogen propulsion concepts before narrowing down to the most promising pathways, such as fully electric powertrains for hydrogen-powered aircraft.

Detailed Design: The detailed design phase focuses on the specifics of the aircraft and its systems. For existing programmes, this phase has involved significant progress in technology maturation and the design of demonstrators, with detailed design now complete for full-scale demonstrators.

Flight Test Programme: A comprehensive flight test programme would be crucial to validate the new technologies. This could involve using flying test beds (modified existing aircraft) with turboprop engines for demonstration campaigns of air vehicle technologies. Ground and airborne demonstrations of cryogenic hydrogen fuel systems, gas turbines, and airframes are also essential.

Flight Sim Development: The development of advanced flight simulators will be vital for testing and refining the aircraft's performance, control systems, and operational procedures in a virtual environment before actual flight. This will also be critical for pilot training.

Certification: Achieving certification for a hydrogen-powered aircraft will require the establishment of new industry-wide aerospace standards and specifications for cryogenic hydrogen applications. This will be a collaborative effort involving aerospace companies, regulators, and other stakeholders.

Pilot Training: Pilot training programmes will need to be completely revised to account for the unique characteristics of hydrogen-powered aircraft, including new fuel systems, propulsion methods, and emergency procedures. This will likely involve extensive simulator training and specialised ground courses.

Retrofit: There is an alternative pathway to first liquid hydrogen operations and large regional aircraft that follows the retrofit approach taken for the gaseous hydrogen, Part 23 aircraft. The Task and Finish group’s roadmap has focused on cleansheet designs due to OEM plans, but a successful STC of a hydrogen-electric engine for existing, certified regional turboprop aircraft could significantly bring forward LH2 operations. Propulsion system timelines will be similar and with similar technical challenges which need to be overcome.

Regardless of the retrofit or cleansheet approach, all signs point towards a scaling up of fuel cell propulsion systems to support the first liquid hydrogen enabled aircraft. With large regional planes flying on hydrogen fuel cells, confidence will increase for fuel cell/combustion or pure combustion concepts to enable appropriate investment in these development projects and unlock hydrogen for narrowbody and even widebody aircraft.

In the short term, the UK can build on its leadership in hydrogen fuel cell propulsion by investing in the key R&D blocks documented in this roadmap exercise and also in the ATI's FlyZero reports.

Regulation

Aircraft Certification

As explored above, retrofit of large regional turboprops is possible, following the same regulatory pathway as identified for Part 23 aircraft in Evolution Point 2, but subject to the more stringent criteria of Part 25, and with likely more complex airframe alterations complicating the STC process.

The Task and Finish Group decided to focus on the delivery of a clean sheet aircraft for the timelines identified. In this case, the lead certification agency would likely be another major regulator in the airframers domestic market (EASA, FAA, etc).

Airport Infrastructure

Much of the preparation and requirements that will be met in Evolution Point 2, and expanded in Evolution Point 3, will lay the necessary foundations for more rapid adoption of LH2, but with several notable exceptions.

Handling companies the Rescue and Firefighting Service (RFFS) and UKCAA at an ear Introducing hydrogen airside at an airport is a multi-phase, high-stakes transformation that requires careful planning, regulatory alignment, and infrastructure investment.

Engagement with the Aerodrome Operator (AO), hydrogen suppliers, OEM's Ground ly stage is encouraged.

CAP 791 Procedures *for Changes to Aerodrome Infrastructure* is a key Civil Aviation Authority (CAA) document that outlines how aerodrome operators must notify and engage with the CAA when making changes to infrastructure or management systems.

It includes guidance to help ensure that changes comply with licensing and certification criteria and are managed safely. It covers four categories; development, changes, maintenance and management systems all of which would touch the introduction of hydrogen as a fuel airside.

While **CAP 791 does not yet contain hydrogen-specific refuelling guidance, it does provide the procedural framework** through which such changes like introducing hydrogen refuelling must be proposed and assessed.

The CAA policy team are cognisant of this fact and are currently updating the document expanding on a section under "infrastructure" changes required in ADR.OR.B.040(a)(1) relating to the certification basis and its supporting AMC, the CAA requires that the additional following changes will subject to prior approval:

Innovation trials including:

- Hydrogen and hybrid-electric aircraft fuelling systems
- Hydrogen and electric ground support equipment (GSE)
- Autonomous vehicle
- Robotic baggage handling
- Introduction of electric vertical take-off and landing (eVTOL) areas

Whenever a project is proposed, the proposal must detail:

- Location and design of hydrogen storage and refuelling points
- Storage tanks (gaseous or liquid)
- Refuelling vehicles or dispensers
- Control systems and safety barriers
- Separation distances from aircraft stands and terminals
- Emergency response plans (likely requiring updates to RFFS procedures)

In accordance with the Aerodrome Safety Management System (SMS) and its Management of Change (MoC) process, the Aerodrome Operator (AO) should submit a structured, evidence-based safety case to support the proposed introduction of hydrogen refuelling operations**.** This safety case must demonstrate how the associated safety risks—arising from new systems, operations, or infrastructure—are systematically identified, assessed, and controlled to a level that is as low as reasonably practicable (ALARP).

The development of the safety case should be guided by:

- **CAP 760 –** *Guidance on the Conduct of Hazard Identification, Risk Assessments and the Production of Safety Cases for Aerodrome Operators and Air Traffic Service Providers*, and
- **CAP 795 –** *Safety Management Systems*, which outlines the principles and expectations for effective safety risk management within aerodrome operations.

Specialist Training for RFFS: Emergency Preparedness for Hydrogen Incidents

Aerodrome operators must ensure that Rescue and Firefighting Services (RFFS) personnel receive specialist training to enable them to respond safely and effectively to incidents involving gaseous and liquid hydrogen.

The successful implementation of emergency procedures for hydrogen-related incidents depends on the development of robust, role-specific training programmes that address the unique risks and operational characteristics of alternative fuel systems. These requirements extend beyond the scope of conventional domestic or aircraft firefighting qualifications and demand:

- Specialised knowledge of hydrogen’s physical and chemical properties.
- Familiarity with advanced detection and monitoring technologies.
- Mastery of response techniques that differ significantly from those used in traditional aviation fuel emergencies.

Given the complexity of hydrogen systems and the potential for prolonged or high-risk emergency operations, training must integrate both technical understanding and practical application. This ensures that RFFS personnel are fully prepared to manage scenarios not typically addressed in standard aviation emergency response training.

Core Competency Requirements

Emergency response personnel must demonstrate the following core competencies specific to hydrogen and alternative fuel aircraft operations:

- A comprehensive understanding of hydrogen fuelling systems and their integration with conventional airport infrastructure.
- The ability to identify and assess hydrogen-specific hazards, including cryogenic risks, invisible flames, and rapid gas dispersion.

- Proficiency in implementing hydrogen-specific response procedures, including isolation, containment, and safe venting.
- Effective coordination with aircraft systems, ground support equipment, and hydrogen supply chain operators during emergency scenarios.

These competencies should be developed through structured training programmes that combine theoretical instruction with hands-on practical exercises.

National Standards and Regulatory Development

Recognising the need for a national framework, the RFFS Policy Specialist has submitted a draft National Occupational Standard (NOS) for hydrogen-related emergency response to Cogent, the organisation commissioned by the UK Government to review NOS for hydrogen and other emerging technologies.

Once agreed, this NOS will inform a comprehensive review of the CAA's CAP 699 – Framework for the Competence of Rescue and Fire Fighting Service Personnel. This review will expand CAP 699 to include all alternative fuels, including hydrogen, and will be conducted in collaboration with:

- Airports UK
- Aerodrome Operators
- Representative Associations
- RFFS Training Providers

Emergency Procedures

Airport operators and any third-party providers must establish clear emergency response procedures and ensure that all personnel are trained and fully familiar with them. This includes conducting regular drills and coordination with local emergency services.

Refuelling Protocol Standards for Hydrogen Operations

The introduction of hydrogen as an aviation fuel presents distinct challenges compared to traditional fuels such as AVGAS and Jet A-1. These challenges necessitate specialised handling procedures, enhanced safety measures, and rigorous fuel quality assurance throughout the supply chain.

The Joint Inspection Group (JIG) the leading international body for aviation fuel standards plays a critical role in ensuring the safe handling, quality control, and distribution of aviation fuels globally. While JIG has not yet published hydrogen-specific standards, it is anticipated that the organisation will align with or contribute to emerging frameworks as hydrogen aviation infrastructure evolves.

Regulatory Requirements and Compliance

Aerodrome operators with fuel storage facilities are required, under:

- Regulation (EU) No. 139/2014 (as retained and amended in UK law via the Retained EU Law (Revocation and Reform) Act 2023), and
- Schedule 12 of the Air Navigation Order (ANO) 2016),

to include in their Aerodrome Manual procedures that ensure aviation fuel is fit for use at all stages receipt, storage, handling, and distribution.

Although no formal hydrogen refuelling standard currently exists for aviation, automotive hydrogen standards and UK health and safety legislation provide a foundational reference. Relevant legislation includes:

- Health and Safety at Work Act 1974
- DSEAR (Dangerous Substances and Explosive Atmospheres Regulations)
- COMAH (Control of Major Accident Hazards)
- ATEX (Explosive Atmospheres Regulations)
- PSSR (Pressure Systems Safety Regulations)
- COSHH (Control of Substances Hazardous to Health)

These frameworks can inform the development of a dedicated CAP: Hydrogen Operations Guidance for UK aerodromes.

Emerging Technical Standards

A key reference document is:

SAE AIR8466 – Hydrogen Fuelling Stations for Airports

Published by SAE International and EUROCAE, this foundational document addresses both gaseous and liquid hydrogen fuelling infrastructure and includes guidance on:

- Fuelling protocols for a range of aircraft types (from eVTOLs to wide-body jets)
- Safety parameters, storage capacities, and turnaround time considerations
- Coupling sizes, ambient conditions, and fuelling speeds

This standard provides a technical and operational baseline for aerodromes transitioning to hydrogen, ensuring safety and fuel integrity in line with UK regulations.

Alignment with UK Aviation Law

Hydrogen refuelling operations must also comply with Article 220 of the UK Air Navigation Order, which governs aircraft refuelling activities. This ensures that all operations meet the required standards for:

- Safety
- Environmental protection
- Fuel quality assurance

Hydrogen Safety Zones

The establishment of hydrogen safety zones is a fundamental requirement to ensure that aerodrome operations involving hydrogen fuel whether gaseous or liquid achieve and maintain an Acceptable Level of Safety (ALoS). These zones are designed to mitigate the risks associated with hydrogen storage, transfer, and refuelling activities.

Ongoing industry and regulatory discussions have highlighted the need for clear, evidence-based criteria to define these zones, including their dimensions, classification, and the physical and procedural safeguards required.

Key Considerations for Safety Zone Definition

- When determining the extent and configuration of a hydrogen safety zone, the following factors must be assessed:
- Location of fuelling activity: Indoor operations (e.g. within hangars or enclosed maintenance facilities) present different risk profiles compared to outdoor ramp or apron fuelling.
- Form of hydrogen: Liquid hydrogen (LH_2) introduces cryogenic and boil-off hazards, while gaseous hydrogen (GH_2) presents high-pressure release and dispersion risks.
- System pressure and volume: These influence the potential severity and radius of a release event.
- Ventilation and environmental conditions: Wind, temperature, and enclosure geometry affect gas dispersion and ignition potential.

Regulatory Approaches

Two primary regulatory models are under consideration for defining hydrogen safety zones:

Prescriptive Model

- The regulator (e.g. CAA) defines fixed separation distances and mandatory safety measures.
- Ensures consistency and clarity across aerodromes.
- May reference international standards such as NFPA 2 or ISO 19880-1.

Performance-Based Model

- The aerodrome operator and fuelling provider conduct a site-specific risk assessment.
- Safety zones are defined based on quantitative risk analysis (QRA) and operational context.
- Offers flexibility but requires a robust safety case and regulatory engagement.

Each model has implications for:

- Consistency of implementation
- Accountability for safety outcomes
- Adaptability to diverse aerodrome environments

Hazardous Area Classification

- Hazardous areas should be classified using established methodologies that consider:
- Release scenarios (e.g. full-bore rupture, venting, boil-off)
- System pressure and flow rate
- **Ignition probability and consequence modelling**

These classifications inform:

- Minimum separation distances
- Zoning for ATEX compliance
- Placement of detection and mitigation systems

Codified Safety Distances

International standards such as NFPA 2: Hydrogen Technologies Code (2023 Edition) provide guidance on minimum separation distances between hydrogen systems and:

- Aircraft and ground support equipment
- Other fuel systems (e.g. Jet A-1)
- Buildings, public areas, and critical infrastructure

Indicative setback distances include:

- Gaseous Hydrogen: 7.6 – 15 metres (depending on pressure and volume)
- Liquid Hydrogen: 15 – 25+ metres (due to cryogenic and BLEVE risks)

Physical and Procedural Safety Measures

Hydrogen safety zones must be clearly defined and protected through a combination of physical infrastructure and operational controls, including:

- Signage: Clear, multilingual hazard warnings and access restrictions.
- Physical barriers: Fencing, bollards, or controlled access gates to prevent unauthorised entry.
- Monitoring systems: Hydrogen gas detectors, thermal imaging, and pressure sensors.
- Emergency shut-off systems: Integrated with fuelling and storage infrastructure.
- Access control: Only trained and authorised personnel permitted within the zone.

Airport Planning and Readiness

Liquid Hydrogen Storage and Refuelling Technology for Initial Operations (Evolution Point 4)

During initial liquid hydrogen (LH_2) operations, the infrastructure requirements at participating airports are expected to remain modest. Existing small-scale LH_2 storage and handling technologies, already in use across various sectors such as research, energy, and space, are sufficient to support early aviation trials and demonstration flights. These proven systems can provide safe, reliable storage of the limited hydrogen volumes anticipated in EP4, meaning that the capital outlay and civil works for airports will be minimal at this stage.

It is anticipated that liquid hydrogen will be delivered to airports by road tanker, in much the same way that other cryogenic liquids are currently transported. The fuel would then be transferred into on-site storage tanks located within secure airside compounds. From there, aircraft would be refuelled using mobile refuelling units, which provide flexibility and avoid the need for fixed underground hydrant infrastructure.

Several technology providers are already progressing the development of these systems. Companies such as ZeroAvia are designing and testing prototype liquid hydrogen refuellers capable of safe, efficient aircraft fuelling under operational conditions. These innovations build directly on existing cryogenic handling expertise and, with the right support, could be commercially available in time to support early LH_2 flight trials.

While liquid hydrogen handling remains technically complex due to its cryogenic nature, the infrastructure needed for EP4 can be deployed using well-established industrial practices. The primary focus at this stage will be on supporting the development, validation, and certification of refuelling technologies, establishing operating procedures, and training personnel.

In essence, the transition to initial LH_2 operations is less about large-scale infrastructure investment and more about enabling technology and regulatory readiness. By facilitating demonstration activity and early partnerships between airports, fuel suppliers, and technology developers, the UK can ensure that refuelling systems are proven and available when the first liquid hydrogen aircraft enter service.

Airport system design and ConOps

Moving from gaseous to liquid hydrogen (LH2) use at an airport is a significant step. Although some skills are transferable, there are limited opportunities to use or upgrade any existing gaseous infrastructure for liquid, which requires cryogenic storage and other new infrastructure.

At the earliest stage, LH2 is expected to be delivered by tanker, when demand is low. For many small airports this supply method may remain the preferred option indefinitely. From storage, LH2 would be delivered to aircraft via a loading station and a tanker.

The Connected Places Catapult's 'Zero Emission Airports 2040' transition plan (commissioned by DfT) identifies gaps in the regulations and standards facing airports and begins to consider the operational and safety considerations. Known challenges include the lack of skilled personnel, understanding for Rescue and Fire Fighting Service, and, critically, the handling of refuelling.

Refuelling of aircraft using Jet A1 is integrated into existing turnarounds, taking place alongside baggage, catering etc. LH2 refuelling may require dedicated or remote parking facilities, reducing airport and apron capacity, or alternatively changes to the infrastructure required on stands.

Although many of the key operational and safety challenges, such as boil-off of LH2, have been identified, real-life demonstrations of the technologies listed above will be required to assess the safest and most cost-effective ways to integrate them into existing airport operations.

Planning and consenting

Planning and consenting for hydrogen aviation raises practical and policy challenges for airports and local authorities that pose a significant risk to the costs and timescales of deploying new infrastructure.

The UK Government's Aviation Policy Framework recommends that airports produce master plans for their long-term development, updating them every five years. Although this has no statutory basis, larger airports do follow this system so that future development is given due consideration in the planning system – including within local authority's Local Plans.

At this stage, liquid hydrogen storage requirements will be modest but planning permission will need to be sought from local authorities. Like all infrastructure projects of this size, planning permission can be an unpredictable, costly and time-consuming process. Although liquid hydrogen storage is an established technology, it will be novel for most local authorities, who are highly likely to lack the experience and knowledge to handle a planning application.

These risks can be negated through central government guidance for both airports and local authorities. Any future updates to the Aviation Policy Framework should include guidance for airports to identify land for liquid hydrogen storage and associated infrastructure in the master plans, drawing on the guidance provided in the Connected Places Catapult's 'Zero Emission Airports 2040' document. Support will be needed for local authorities and/or mayoral authorities to avoid delays in the planning system.

Finally, negative community reaction is a risk given the novel nature of liquid hydrogen. Meaningful early engagement, clear safety evidence, and integration into airport master plans are therefore essential to reduce opposition and shorten consenting times.

Civil Infrastructure

The civil infrastructure required to support the delivery, storage and refuelling with liquid hydrogen will again vary depending on specific airport site layout, condition and capacity of existing infrastructure, but could include:

- Upgrades/extensions to landside and airside roads to provide tanker access to hydrogen storage areas, and parking for tankers and refuellers – with scale and impact of works needed increasing as the LH2 operations increase.
- Civil works to accommodate storage and fuelling equipment, including security and physical protection in accordance with safety zoning requirements
- Upgrades to utilities infrastructure (eg power, control systems) to support the handling and storage of liquid hydrogen. The potentially significant increase to overall electrical demand may lead to requirements for upgrades to both on- and off-site power systems.

The scale and complexity of the on-site civil works would generally still be at a level that would routinely be undertaken by most airport development teams and their supply chains – but the works on installation of LH2 handling and storage, and any off-site utilities upgrades might require additional capabilities and resources. The development lead time would be driven by the typical business planning, stakeholder engagement and procurement processes that apply across airport development programmes.

Operator Readiness for First LH_2 Operations: Strategic Overview

The transition to liquid hydrogen (LH_2) aviation represents a transformative step in decarbonising regional air transport. For operators preparing to launch first LH_2-powered flights, readiness must span across commercial, technical, regulatory, and operational domains. This section outlines the key components of operator readiness, focusing on fuel contracts, emergency planning, trials, flight operations, maintenance, marketing, and safety compliance.

Fuel Contracts

Securing reliable and scalable LH_2 supply is foundational to operational readiness. Operators must establish long-term contracts with hydrogen producers or distributors capable of meeting aviation-grade purity standards and delivery schedules. These agreements should include provisions for:

- Volume flexibility to accommodate scaling from pilot operations to full commercial service.
- On-site storage solutions, including cryogenic tanks and boil-off management systems.
- Contingency supply planning to mitigate risks from production or logistics disruptions.

Coordination with airport authorities and infrastructure providers is essential to ensure that refuelling systems are compatible with aircraft requirements and meet regulatory standards. Fuel contracts should also align with broader hydrogen ecosystem development, including potential integration with national pipeline or port-based supply chains.

Currently, no liquid hydrogen supply is available at any meaningful scale in the UK, something that must be addressed before larger aircraft can feasibly operate commercially, or even in test environments.

Irregular/Emergency Operations

LH_2 introduces new safety and operational risks that must be addressed through robust emergency planning. Operators must develop and validate procedures for:

- Leak detection and containment, including sensor systems and emergency shutdown protocols.
- Fire suppression and cryogenic hazard response, in coordination with airport Rescue and Fire Fighting Services (RFFS).
- Passenger and crew evacuation protocols tailored to LH_2 aircraft configurations.

Training materials must be developed in line with CAP699 and other relevant CAA guidance, ensuring that ground teams, flight crews, and emergency responders are proficient in LH_2-specific scenarios. Regular drills and proficiency checks should be embedded into operational routines.

Trials

Before commercial launch, operators must conduct a structured programme of LH_2 trials. These should include:

- Ground handling and refuelling simulations, validating infrastructure, safety zones, and turnaround times.
- Flight trials, assessing aircraft performance, fuel efficiency, and operational reliability under real-world conditions.
- Passenger experience pilots, if applicable, to gauge public perception and refine service delivery.

Trial data should be collected to support certification, refine operational procedures, and inform future infrastructure planning. Collaboration with regulators, OEMs, and research institutions will be critical to ensure trials meet both technical and policy objectives.

Flight Operations Administration

LH_2 operations require updates to flight operations manuals, crew training programmes, and scheduling systems. Key administrative tasks include:

- Integration of LH_2-specific procedures into standard operating manuals and dispatch protocols.
- Crew rostering and duty time adjustments, accounting for new turnaround and refuelling durations.
- Flight planning system updates, including fuel weight calculations, range modelling, and contingency planning.

Operators must also ensure that digital systems — including maintenance tracking, fuel usage monitoring, and performance analytics — are adapted to support LH_2 aircraft. Coordination with air traffic control and airport operations teams will be essential to manage any procedural changes.

Maintenance, Repair and Overhaul (MRO)

LH_2 aircraft introduce new MRO requirements, particularly around cryogenic systems and fuel cell components. Operators must:

- Establish LH_2-capable maintenance facilities, including tooling, safety systems, and trained personnel. This may include new or adapted hangars that are designed for hydrogen safety (avoiding gas accumulating in the event of a leak, for example)
- Develop inspection and servicing protocols for tanks, valves, insulation, and fuel lines.
- Coordinate with OEMs and regulators to ensure compliance with evolving standards and certification pathways.

Training programmes for MRO staff must be developed in partnership with equipment manufacturers and regulatory bodies. Long-term planning should also consider the transition to clean-sheet LH_2 aircraft and the implications for spare parts, diagnostics, and lifecycle management.

Marketing and Sales

Commercial success depends on public confidence and market demand. Operators must develop a marketing and sales strategy that:

- Communicates the environmental benefits of LH_2 aviation, including zero-emission flight and contribution to Net Zero goals.
- Builds trust in safety and reliability, supported by transparent trial results and regulatory endorsements.
- Targets early adopters and sustainability-focused customers, including regional governments, tourism boards, and corporate travel buyers.

Sales teams should be trained to articulate the unique value proposition of LH_2 aviation, and digital platforms should be updated to reflect new aircraft capabilities, routes, and service features.

With regulatory approvals in place, the public confidence gap between GH2 and LH2 operations is likely to be significantly less marked than will likely be seen for the introduction of the first GH2 flights. Therefore, establishing multiple years and hundreds of thousands of flight hours of hydrogen aircraft operations under Evolution Points 2 and 3 will significantly derisk the introduction of LH2 operations from a commercial standpoint for large aircraft. Regonal operators and small aircraft will derisk the commercial introduction for larger players.

Safety and Compliance / Manual Development

Safety and regulatory compliance are central to LH_2 operations. Operators must:

- Develop comprehensive manuals covering LH_2 handling, flight operations, ground procedures, and emergency response.
- Ensure alignment with CAP791, CAP699, and emerging hydrogen aviation standards.
- Establish internal audit and review processes to maintain compliance and support continuous improvement.

Coordination with the CAA, HSE, and international aviation bodies will be essential to ensure that manuals reflect best practice and evolving regulatory expectations. Operators should also contribute to industry working groups to help shape future standards and share lessons learned.

Evolution Point 5 – LH2 expansion (2-4 airports)

As liquid hydrogen (LH_2) operations expand, airport infrastructure requirements will increase significantly compared with the initial phase. Storage capacity will need to be scaled up, driving the need for larger cryogenic tanks, associated safety systems, and greater segregation within the airfield layout. These developments will involve more extensive civil works and higher capital investment, as well as careful planning to minimise disruption to ongoing airport operations.

Given the long lead-in times for securing land and consents, airports will need to plan for future land requirements to avoid stranded assets. Research carried out by Jacobs for Bristol Airport identifies that land requirements for LH2 storage will be significant, much greater than for traditional Jet A1 fuel. For some airports, including Bristol, their current sites are either too small or the land is too valuable for storage requirements, so adjacent land will have to be purchased.

Despite the increase in capacity, LH_2 is expected to continue being delivered by road tanker during this phase, with fuel transferred into on-site storage and aircraft refuelled using mobile refuelling units. However, the larger quantities involved may require storage solutions to be designed specifically for individual airports, reflecting variations in site layout, flight schedules, and throughput.

From an operational perspective, EP5 will see both the introduction of LH_2 aircraft by new airline operators and the expansion of networks by those already experienced with hydrogen operations. Airlines adopting LH_2 aircraft for the first time will need to complete the full suite of preparatory activities defined in EP4, including pilot training, ground-handling procedures, and operational readiness assessments. For existing operators, the emphasis will shift towards scaling capability rather than introducing new processes. This will include expanding pilot training programmes to accommodate a larger fleet, developing recurrent training modules, and securing additional hangarage or maintenance facilities to enable routine line maintenance under cryogenic safety conditions.

Overall, EP5 represents a period of incremental expansion and consolidation. While the technical and operational principles established in EP4 remain valid, the scale of activity increases, requiring greater investment, coordination, and regulatory oversight to ensure that early success transitions smoothly into broader, commercially sustainable LH_2 operations.

Evolution Point 6 – full network

EP represents the point at which liquid hydrogen (LH_2) aviation becomes fully embedded within major airport operations. The transition to this phase will be driven by the scale of hydrogen demand and the associated logistical pressures. As the number of LH_2-powered aircraft and flight movements increases, some airports will reach the practical limits of road-based hydrogen delivery, constrained by congestion, safety considerations, and the sheer volume of liquid hydrogen required.

The first step in EP 6 will therefore be the introduction of on-site or near-site liquefaction, with hydrogen supplied in gaseous form via a dedicated pipeline. This change fundamentally alters the airport's role within the hydrogen value chain — from being a recipient of delivered liquid hydrogen to becoming an integral part of the national hydrogen transmission and liquefaction network. The design, permitting, and construction of such facilities will require extensive planning, cross-sector coordination, and significant investment. Early engagement with network operators, energy suppliers, and regulators will be essential to define siting, safety zones, and integration with local energy infrastructure.

In the early stages of EP6, aircraft refuelling may continue to be performed using mobile refuellers, consistent with previous phases. However, as throughput volumes rise, operational efficiency and turnaround requirements will necessitate a shift to fixed liquid hydrogen hydrant systems, allowing automated or semi-automated refuelling directly at the stand. LH2 hydrants would move the fuel around the airport to transfer tanks and/or a dispenser vehicle. Transfer tanks adjust the pressure of the LH2 to match the requirements of the aircraft. This represents the final and most technically demanding step in the evolution of hydrogen refuelling technology. Developing safe, reliable, and cost-effective cryogenic pipelines and hydrant systems capable of operating in an airport environment presents major engineering challenges.

Whereas LH2 storage and liquefaction are established technologies, an airfield hydrant system, transfer tanks, and refuelling/dispenser vehicles all have low TRL levels. This creates a high degree of uncertainty about how they would be integrated with existing airport operations. The design, testing, and demonstration of these technologies is anticipated to take up to seven years, according to a Connected Places Catapult report.[1]

At present, liquid hydrogen delivery and hydrant technologies remain at a very early stage of development worldwide. Progress is unlikely without a targeted national effort. A coordinated technology strategy, supported by focused funding, standards development, and collaboration between government, industry, and academia, will be essential to de-risk these systems and enable future deployment.

While demanding, this challenge presents a significant opportunity for the UK. Establishing onshore capability in liquid hydrogen distribution and hydrant technologies could create a valuable industrial niche, supporting exportable products and expertise across the emerging global hydrogen aviation market.

Given the long development timelines and complex safety requirements, work to define this technology pathway must begin immediately. Early actions should include mapping the technology development roadmap, identifying the research priorities and industrial partnerships required, and determining the funding mechanisms needed to act as a catalyst for innovation.

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[1] https://cp-catapult.s3.amazonaws.com/uploads/2025/01/ZEFI-Transition-Plan.pdf.

Proactive investment at this stage will ensure that the UK is prepared to deliver EP 6 capability in line with future aircraft demand, maintaining its leadership position in zero-carbon aviation.

Summary and Conclusions: Evolution Points 4-6

The transition to liquid hydrogen (LH_2) aviation marks a defining stage in the UK's journey toward net-zero flight. Evolution Points 4-6 provide a clear pathway from early LH_2 demonstration to full commercial maturity, scaling operations from initial trials to widespread adoption across major airports. This progression will require coordinated investment, technology development and readiness, and regulatory alignment, all building on lessons learned, procedures established and skills developed from preceding gaseous hydrogen operations (EP1-3).

To realise this opportunity, the government should:

a) **Launch a national zero emission aviation programme** to coordinate airport readiness, safety regulation, fuel supply and refuelling technologies, alongside aircraft development and operational requirements – working in lockstep with European and global peers to ensure interoperability and shared/aligned standards
b) **Invest strategically to de-risk critical fuelling technologies** such as cryogenic storage, mobile hydrogen refuellers and high-throughput hydrant systems. By developing solutions that can be deployed globally, the UK can establish a strong export position and long-term economic return from early leadership in liquid hydrogen aviation
c) **Provide clear planning and consenting guidance** to local authorities and airports to streamline hydrogen infrastructure deployment and ensure regional readiness
d) **Accelerate regulatory and training frameworks** through the CAA, HSE and standards bodies to ensure safety, certification and emergency preparedness evolve in parallel with technology

Delivering these actions will secure the UK's position at the forefront of hydrogen aviation, turning early innovation into industrial strength and setting the foundation for a globally competitive, zero-emission air transport system.

Overall Summary

Hydrogen propulsion – both gaseous (GH_2) and liquid (LH_2) - forms the cornerstone of the UK's route to zero-emission flight. Early GH_2 operations are the essential first step: they will prove operational concepts, surface-test ground handling and emergency response procedures and build the practical skills, supply chain capability and public confidence that LH_2 adoption will rely on. Crucially, GH_2 deployment also requires the development of new, hydrogen-specific regulatory and safety frameworks; these must be advanced in parallel with trials so that certification, operational rules and emergency preparedness are in place from the outset.

Experience gained through GH_2 operations will lay the groundwork for the transition to LH_2 but liquid hydrogen will introduce additional and more demanding requirements in technology, infrastructure and regulation – it will require cryogenic storage and transfer systems, enhanced safety zoning and handling procedures and entirely new certification standards to manage its unique physical properties. It is therefore crucial that early work to develop LH_2 technology, infrastructure and safety standards is carried out alongside the deployment of GH_2, giving industry and regulators the confidence, competence and evidence based needed to scale safety into LH_2 operations.

To capture this opportunity, the UK now needs a national zero-emission flight programme that unites GH_2 demonstrations and initial operations, LH_2 technology development, airport readiness and regulatory evolution under one strategic framework. This integrated programme should prioritise early trials across the ecosystem rather than, for example, an isolated flight demonstration. It should target R&D to create exportable UK capability, streamline planning and consenting guidance for airports and local authorities, and accelerate deployment of hydrogen-specific safety, training and emergency response procedures. With coordinated policy and investment, the UK can deliver an end-to-end zero emissions aviation ecosystem and secure long-term industrial and climate benefits.

Workstream 3 – Aviation Hydrogen Demand in the UK

Introduction

Hydrogen has potential applications across multiple sectors. In many cases, such as the chemical industry, there is no alternative to using hydrogen. As a result, there will be demand for a sustainable production route, and priority should be given to hard-to-decarbonise sectors which cannot use other avenues such as electrification. In aviation, hydrogen demand can be divided into two categories: direct and indirect demand. Direct demand relates to hydrogen used as a fuel, whereas indirect demand is hydrogen used in the production of fuels such as biofuel, or e-fuels (also known as Power to Liquid (PtL)).

Hydrogen production via electrolysis (also known as green hydrogen) is the most sustainable method of production. Other sustainable sources of hydrogen, such as natural hydrogen, may play a role; however, it is expected that these pathways will only account for a small fraction of the overall demand. According to a Royal Society report, the UK has ample amounts of the rocks known to generate natural hydrogen, but it is not yet known whether it occurs in economic quantities.

Indirect aviation demand for hydrogen is expected to significantly exceed the capacity for green hydrogen production in the next 10-20 years. Blue hydrogen could be utilised to bridge the gap between supply and demand, but this relies on the development of a carbon capture and storage process. Most projections show that a mixture of green and blue hydrogen will be required.

Producing green hydrogen at scale via electrolysis also requires a large amount of energy. This demand is likely to be large enough that it will need to be factored into the planning of national electrical infrastructure. Demand forecasting is therefore essential due to the long lead times associated with adapting national infrastructure.

As of today, liquid hydrogen is not available in the UK. Where it is required, it is shipped from mainland Europe by tanker. If aviation is to scale up to the Evolution Points using liquid hydrogen, domestic production capabilities will be needed.

UK Aviation Direct Hydrogen Demand Forecast

Direct demand forecasts depend on multiple factors. The point of entry-into-service for hydrogen aircraft, the type and size of aircraft, production rates and market penetration all play a role. Recent announcements have delayed the *entry into service of large commercial hydrogen aircraft. This is reflected in a delay in the ramp-up of hydrogen demand.*

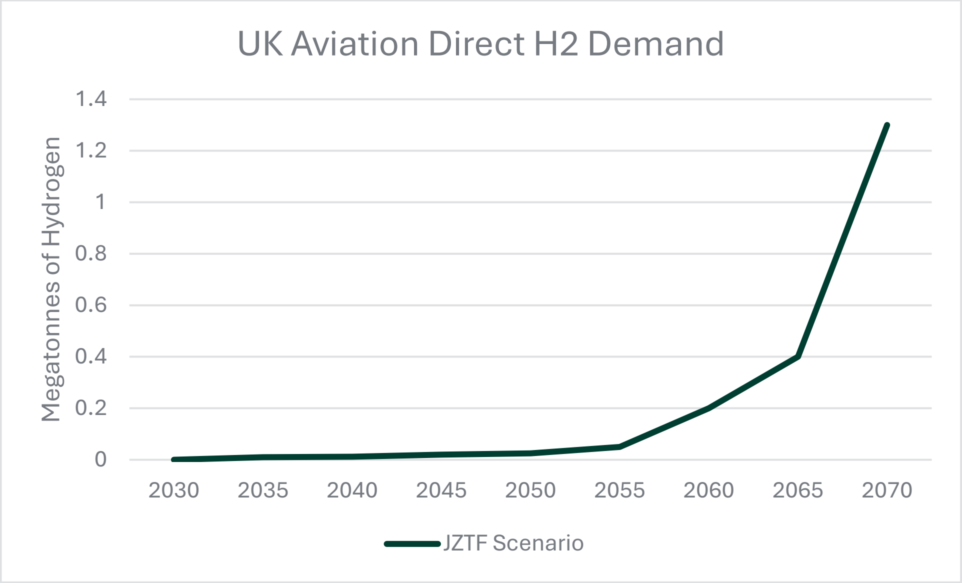

Figure 21 shows the total UK direct demand projected from the JZTF market forecast from Workstream 1.

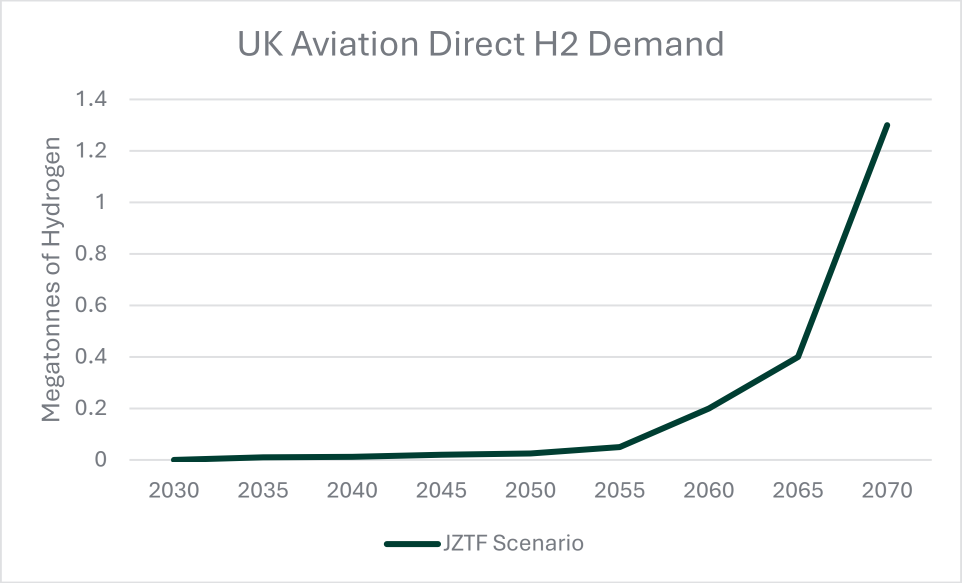

Figure 21: UK aviation direct hydrogen demand

UK domestic demand is based on flights within the UK. Total UK demand includes all departing flights from the UK, regardless of destination. The majority of this demand comes from large commercial aircraft, which will require liquid hydrogen. This is because gaseous hydrogen has a significantly lower energy density as part of a pressurised storage system, which makes it impractical for larger aircraft. If hydrogen aviation is successful in reaching EP6, then direct demand would be expected to continue increasing significantly after 2070.

UK Indirect Demand Forecast

Sustainable Aviation Fuels (SAFs) can be used in the existing aircraft fleet, and hence they can play an essential role in decarbonising aviation. Most SAFs require hydrogen as part of the fuel production process, including biofuels such as HEFA. E-fuels, in particular, require large amounts of hydrogen. As SAF usage increases as a percentage of overall aviation fuel demand, this in turn generates a significant increase in hydrogen demand, partly due to expected market growth. The UK and and EU have SAF mandates setting clear targets for SAF introduction over the coming years.

% of total fuel	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**Comments**
Europe: All SAF (%)	2	6	20	34	42	70	Ref. ReFuelEU Aviation
Europe: PtL (%)	0	1.2	5	10	15	35	
UK: All SAF (%)	2	10	15	22	42	70	Ref. UKGov SAF Mandates
UK: PtL (%)	0	0.5	2.0	3.5	7	15	

Table 11: EU and SAF mandate requirements. UK numbers projected beyond 2040 by the Hydrogen in Aviation Alliance

To estimate the UK aviation indirect hydrogen demand, a projection of SAF demand using the market scenario defined in section 1 of this report was used in combination with the UK SAF mandate numbers from table 11. While the UK SAF mandate does not extend past 2040, the numbers have been projected based on the ReFuel EU mandate, as it is expected that Europe and the UK will remain closely tied in this domain. To extend the projection to 2070, the ATAG waypoint 2050 projection of SAF availability was used.

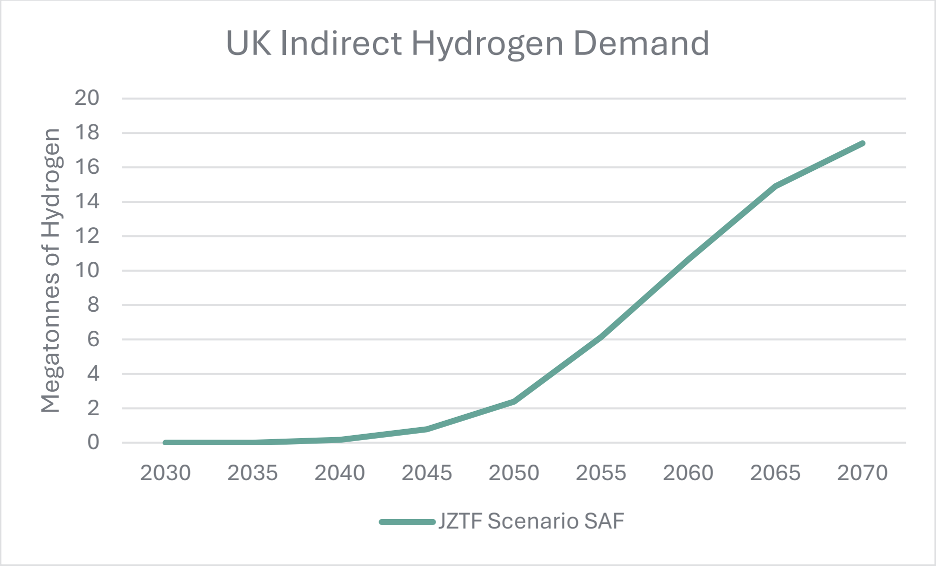

Figure 22: UK indirect aviation demand

Aviation Demand vs UK Production

Various estimates exist for UK aviation hydrogen demand. A 2023 DESNZ study estimated total hydrogen demand in aviation, including direct and indirect estimates. The lower 2050 hydrogen estimate assumed high availability of biomass for SAF, with very little e-fuel needed to meet the mandate. The higher end assumed high reliance on e-fuel SAF, with minimal direct demand.

The forecast for hydrogen production in the UK has been estimated as part of the task and finish group activity from a range of data inputs, as shown in Figure 5. It has been extrapolated to 2070, using the CCC target of 20–30% of UK energy demand being available for hydrogen production.

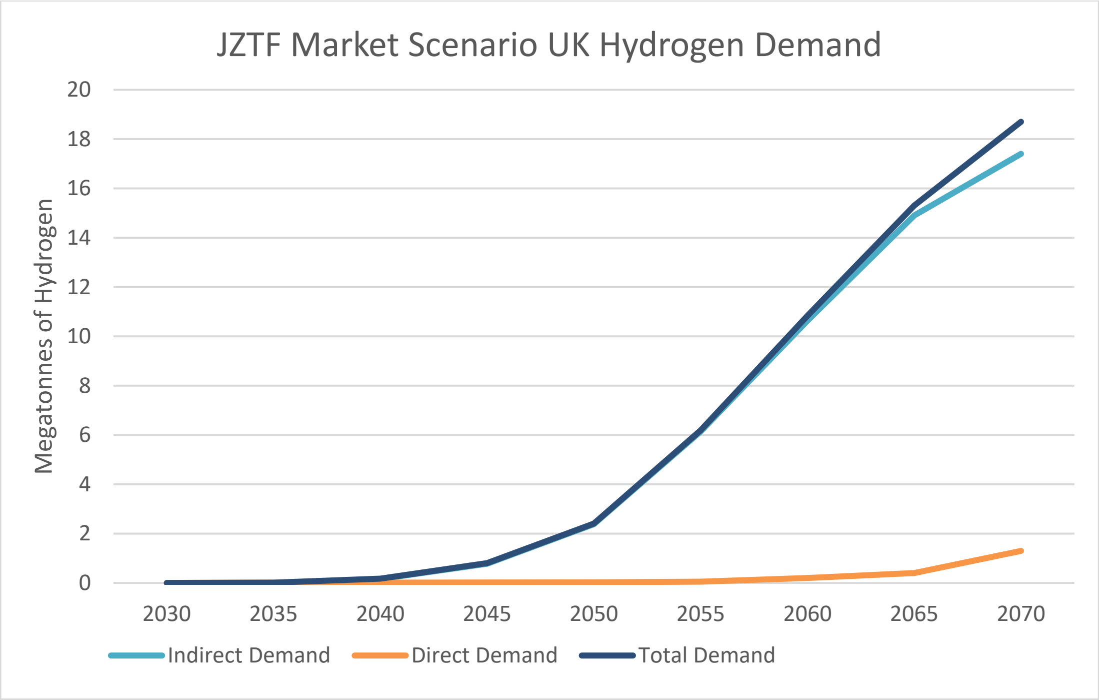

Figure 23: JZTF market scenario total UK H2 demand

2023 ambition	2024 ambition	2025 ambition	2030 ambition	2050 ambition
-Decision on blending up to 20% hydrogen into natural gas grid -Award first business model contracts to electrolytic and CCUS-enabled hydrogen projects -Hydrogen heating neighbourhood trial begins	Allocate second round of business model contracts to electrolytic hydrogen projects.	-Up to 1GW electrolytic 'green' hydrogen and up to 1GW of CCUS-enabled 'blue' operational or in construction by 2025 -Hydrogen Transport & Storage business models designed -Hydrogen heating village trial begins and plan for town pilot -Hydrogen certification scheme set up	- Up to 10GW low carbon hydrogen production capacity, double previous 5GW ambition - Hydrogen Transport and Storage business models in place	240 to 500 TWh low carbon hydrogen supply by 2050

Table 12: Hydrogen production ambition using various data sources, including British energy security strategy - GOV.UK

Estimates vary for the amount of hydrogen that aviation can expect to receive in the UK. The IEA suggests aviation will receive around 9% of total generation, whereas DESNZ estimates that the UK aviation sector will receive around 16% of total hydrogen generated. Figure 24 shows the projected production capacity alongside the demand projections. This indicates that the current DESNZ estimate is sufficient to meet demand until 2050. After 2050, however, aviation hydrogen demand scales up rapidly, mainly driven by indirect demand. If this demand is to be met, then either UK aviation will need the majority of hydrogen generated in the UK, or production capacity will need to be increased. Note the units have been converted to terraWatt hours rather than megatonnes.

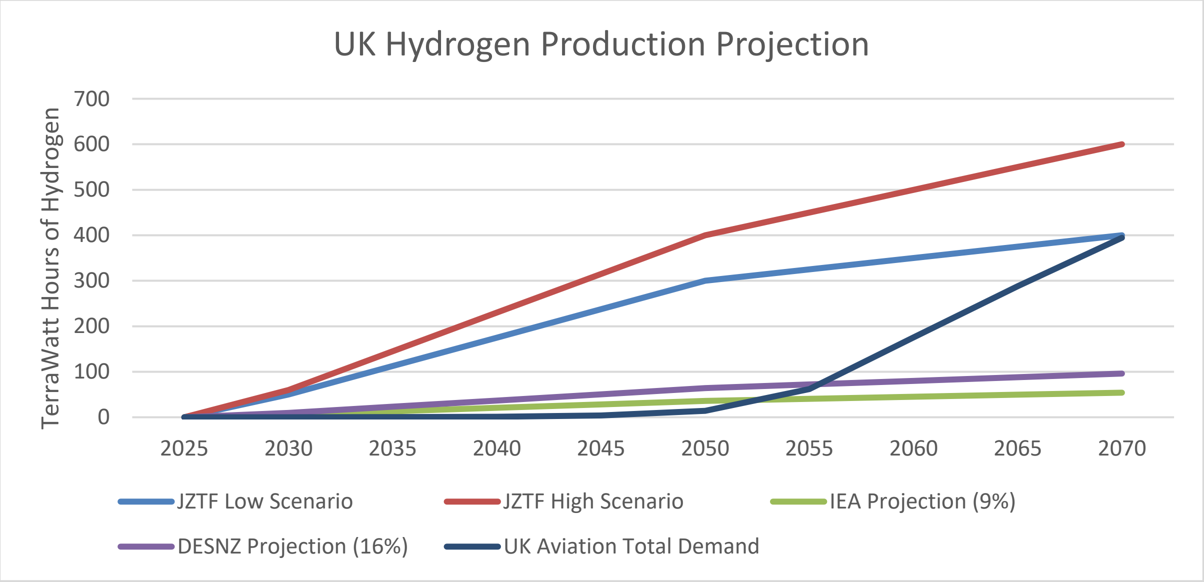

Figure 24: UK hydrogen production vs demand projection

In conclusion, continued investment in increasing low-carbon energy production is a critical strategy for the UK. If the JZTF scenario targets for hydrogen production are achieved, and these are based on stated UK government targets, then there is likely to be sufficient hydrogen to meet aviation demand until 2050. However, as aviation demand increases rapidly after 2050, infrastructure decisions will need to be taken around 2035-2040 to ensure sufficient time for the required infrastructure to be delivered. The infrastructure and operational procedures for liquid hydrogen operations must also be carefully planned.

Appendices

Appendix 1: Specialist Training for RFFS: Emergency Preparedness for Hydrogen Incidents

Aerodrome operators must ensure that Rescue and Firefighting Services (RFFS) personnel receive specialist training to enable them to respond safely and effectively to incidents involving gaseous and liquid hydrogen.

The successful implementation of emergency procedures for hydrogen-related incidents depends on the development of robust, role-specific training programmes that address the unique risks and operational characteristics of alternative fuel systems. These requirements extend beyond the scope of conventional domestic or aircraft firefighting qualifications and demand:

- Specialised knowledge of hydrogen’s physical and chemical properties.
- Familiarity with advanced detection and monitoring technologies.
- Mastery of response techniques that differ significantly from those used in traditional aviation fuel emergencies.

Given the complexity of hydrogen systems and the potential for prolonged or high-risk emergency operations, training must integrate both technical understanding and practical application. This ensures that RFFS personnel are fully prepared to manage scenarios not typically addressed in standard aviation emergency response training.

Core Competency Requirements

Emergency response personnel must demonstrate the following core competencies specific to hydrogen and alternative fuel aircraft operations:

- A comprehensive understanding of hydrogen fuelling systems and their integration with conventional airport infrastructure.
- The ability to identify and assess hydrogen-specific hazards, including cryogenic risks, invisible flames, and rapid gas dispersion.
- Proficiency in implementing hydrogen-specific response procedures, including isolation, containment, and safe venting.
- Effective coordination with aircraft systems, ground support equipment, and hydrogen supply chain operators during emergency scenarios.

These competencies should be developed through structured training programmes that combine theoretical instruction with hands-on practical exercises.

National Standards and Regulatory Development

Recognising the need for a national framework, the RFFS Policy Specialist has submitted a draft National Occupational Standard (NOS) for hydrogen-related emergency response to Cogent, the organisation commissioned by the UK Government to review NOS for hydrogen and other emerging technologies.

Once agreed, this NOS will inform a comprehensive review of the CAA's CAP 699 – Framework for the Competence of Rescue and Fire Fighting Service Personnel. This review will expand CAP 699 to include all alternative fuels, including hydrogen, and will be conducted in collaboration with:

- Airports UK
- Aerodrome Operators
- Representative Associations
- RFFS Training Providers

Emergency Procedures

Airport operators and any third-party providers must establish clear emergency response procedures and ensure that all personnel are trained and fully familiar with them. This includes conducting regular drills and coordination with local emergency services.

Appendix 2: Hydrogen Purity Testing

The core of this process is ensuring that hydrogen purity meets the stringent requirements set by international standards, primarily ISO 14687. The presence of impurities, even at parts-per-billion (ppb) levels, can severely damage fuel cell performance.

The analytical process is rigorous and methodical:

1. **Sampling:** The process begins with obtaining a representative sample from a production facility, storage tank, or refuelling station. Many target impurities, such as sulphur compounds, are reactive and unstable. This requires the use of passivated sampling vessels and careful handling to prevent the adsorption of components onto sample lines and equipment, which would lead to inaccurate results. This is a critical step where specialized, non-reactive equipment must be used to prevent contamination from the sampling apparatus itself. Recognizing that analysis is only as good as the sample taken, National Physical Laboratories has developed and validated novel sampling systems known as NPL DirSAM. This apparatus allows for the direct and uncontaminated collection of hydrogen from high-pressure refuelling stations, a critical step for verifying real-world fuel quality.
2. **Analysis**: Samples are typically transported to a specialized laboratory for analysis against the full list of ISO 14687 contaminants. This list includes substances like carbon monoxide (CO), sulphur compounds (e.g., H_2S), halogenated compounds, ammonia (NH_3), formaldehyde (HCHO), and various hydrocarbons. National Physical Laboratories (NPL) are at the forefront of moving analysis from the lab to the production line. They have developed a novel, non-speciating electrochemical hydrogen quality alarm. This low-cost technology is designed for mass deployment to provide a real-time, continuous check on hydrogen purity, flagging any deviation from standards instantly.
3. **Certification**: Upon successful analysis confirming that all contaminant levels are below the specified thresholds, a batch of hydrogen is certified for use. This process ensures the longevity and performance of fuel cells and is essential for commercial viability.

Available Technologies

A multi-instrument approach is necessary to detect the diverse range of potential contaminants at the required parts-per-billion (ppb) sensitivity. No single device can perform the complete analysis. The current technological suite includes:

- **Gas Chromatography (GC):** This is the most widely used technique and a cornerstone of hydrogen analysis. Different detector configurations are used to target specific compounds.
- **Cavity Ring-Down Spectroscopy (CRDS):** This technology offers exceptionally high sensitivity and stability for measuring specific impurities like moisture (H_2O), carbon monoxide (CO), and carbon dioxide (CO_2). Its rapid response time makes it a powerful tool.
- **Fourier-Transform Infrared Spectroscopy (FTIR):** Used to detect and quantify a range of gaseous molecules, particularly useful for CO, CO_2, and some hydrocarbons.

- **Inductively Coupled Plasma Mass Spectrometry (ICP-MS):** This technique is applied to detect any metallic or particulate matter that might be present in the gas stream.

Research and Development Roadmap

The current lab-based model, while reliable, is time-consuming and expensive. The R&D community is aggressively pursuing a paradigm shift towards real-time, in-line analysis to ensure quality at every point in the supply chain. Key areas of development include:

- **Advanced Sensor Integration:** The primary goal is to develop robust, low-cost, and highly selective sensors that can be integrated directly into hydrogen dispensers. These "smart" dispensers would provide instantaneous quality assurance at the final point of delivery.
- **Process Analytical Technology (PAT):** R&D is focused on implementing PAT solutions, allowing for continuous online monitoring during hydrogen production. This would enable producers to identify and rectify quality issues instantly, reducing the risk of producing non-compliant gas.
- **Novel Detection Methods:** Research into next-generation technologies like micro-GCs, optical sensors, and electrochemical methods aims to reduce the size, cost, and complexity of analytical hardware without compromising sensitivity.

In conclusion, while the current state of hydrogen purity testing is robust and well-defined, the future lies in embedding intelligence and analytical capabilities directly within the hydrogen infrastructure.

Appendix 3: Key Considerations for Safety Zone Definition of Gaseous Hydrogen

- When determining the extent and configuration of a hydrogen safety zone, the following factors must be assessed:
- Location of fuelling activity: Indoor operations (e.g. within hangars or enclosed maintenance facilities) present different risk profiles compared to outdoor ramp or apron fuelling.
- System pressure and volume: Gaseous hydrogen (GH_2) presents high-pressure release and dispersion risks which must be mitigated. System pressure and volume influence the potential severity and radius of a release event.
- Ventilation and environmental conditions: Wind, temperature, and enclosure geometry affect gas dispersion and ignition potential.

Regulatory Approaches

Two primary regulatory models are under consideration for defining hydrogen safety zones:

- Prescriptive Model
    - The CAA defines fixed separation distances and mandatory safety measures.
    - Ensures consistency and clarity across aerodromes.
    - May reference international standards such as NFPA 2 or ISO 19880-1.
- Performance-Based Model
    - The aerodrome operator and fuelling provider conduct a site-specific risk assessment.
    - Safety zones are defined based on quantitative risk analysis (QRA) and operational context.
    - Offers flexibility but requires a robust safety case and regulatory engagement.

Each of these models has implications for the consistency of implementation, the accountability for safety outcomes and adaptability to diverse aerodrome environments. The CAA may choose to implement a performance-based model for the very first gaseous hydrogen implementation given that the flexibility provided can help expedite the introduction and subsequent scaling. The regulator could then move to a prescriptive model as the number of operations, routes and hubs expands.

Hazardous Area Classification

- Hazardous areas should be classified using established methodologies that consider:
- Release scenarios (e.g. full-bore rupture, venting)
- System pressure and flow rate
- Ignition probability and consequence modelling

These classifications inform:

- Minimum separation distances
- Zoning for ATEX compliance
- Placement of detection and mitigation systems

Codified Safety Distances

International standards such as NFPA 2: Hydrogen Technologies Code (2023 Edition) provide guidance on minimum separation distances between hydrogen systems and:

- Aircraft and ground support equipment
- Other fuel systems (e.g. Jet A-1)
- Buildings, public areas, and critical infrastructure
- Indicative setback distances include:
- Gaseous Hydrogen: 7.6 – 15 metres (depending on pressure and volume)

Physical and Procedural Safety Measures

Hydrogen safety zones must be clearly defined and protected through a combination of physical infrastructure and operational controls, including:

- Signage: Clear, multilingual hazard warnings and access restrictions.
- Physical barriers: Fencing, bollards, or controlled access gates to prevent unauthorised entry.
- Monitoring systems: Hydrogen gas detectors, thermal imaging, and pressure sensors.
- Emergency shut-off systems: Integrated with fuelling and storage infrastructure.
- Access control: Only trained and authorised personnel permitted within the zone.

Appendix 4: Detailed roadmap data

Swimlane	Item Definition (Enabler)	Start Date	Expected Duration	Expected Delivery Date	Dependencies	Risks	Delivery Risk	Impact	Criticality	EP Applicability	EP simplified	Key Enabling Steps (Intervention)	Sources/ References
Propulsion Technology	Fuel cell specific power (system level) sufficient for Part 23 aircraft (TRL6). >1.4 kW/kg	2020	4 years	Complete	n/a	- non-UK competition advancing	Low	High	Medium	Step towards EP 2	EP 2 - GH2 First Ops	n/a	- ZeroAvia ZA600 certification programme - ATI Fly Zero Roadmap Report (target 2026 +1.5kW/kg)
	Fuel cell specific power (system level) sufficient for large regional turboprops (TRL6)- 2-2.5 kW/kg	Ongoing	5 years	2030	- Success/continued progress of Part 23 powertrain technology and UK/global hydrogen production and airport infrastructure (support tech R&D investment case) - Advances in higher temperature fuel cell system designs (durability/supply chain)	- funding for R&D around advanced fuel cell systems	Medium	Medium	Medium	Step towards EP 4	EP 4 - LH2 First Ops	- continued focus in ATI programme on advancing fuel cell systems (see recent investments in Intelligent Energy and ZeroAvia's AFCAD programme)	- - ATI Fly Zero report Fuel Cell Roadmap ("HTPEM stacks at TRL6 in 2030") - ZeroAvia HTPEM dev timeline per AFCAD project strand 1 targets >2kg/kW by 2027. Strand 2 targets >3.5 kw/kg in the same timeframe.D1 - ATI Fly Zero Fuel Cell Roadmap (LTPEM circa 2030, HTPEM circa J4). https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0033-Fuel-Cells-Roadmap-Report.pdf

	Fuel cell specific power (system level) sufficient for narrowbody aircraft (TRL6) > 4 kW/kg	2030	10 years	2040	- Advanced reactant flow field development in HTPEM - Continued evolution of HTPEM fuel cell air systems	technical challenges slowing pace of high temperature fuel cell development	High	Low	Medium	Step towards EP 5	EP 5 - LH2 Basic network	- R&D funding for HTPEM advances - Existing programmes tackling some of the technical challenges in HTPEM development (i.e. AFCAD) - ARIA/ATI/EPSRC partnership to focus on "moonshot" technologies? E.g. HTPEM for narrowbody aircraft	- https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0033-Fuel-Cells-Roadmap-Report.pdf Predicts move from 3 kW/kg to 5-6 kW/kg between 2035 and 2050
	Type IV gaseous tank aviation TRL6 maturity (Part 23)	Now	1 year	2026	- testing to meet G5 - aviation specific testing D-160 G and aviation-specific bonfire testing to demonstrate safety - crash/drop testing F4	- Gathering data for CAA cert	Low	Medium	Medium	Step towards EP 2	EP 2 - GH2 First Ops	- enhanced funding to allow parallel testing regime	- ZeroAvia HyFlyer II demonstration; Universal Hydrogen demonstration
	Electric motor power density at ~5 kW/kg (Part 23) - (TRL 6)	Complete	Complete	Complete	n/a		Low	High	Medium	EP 2	EP 2 - GH2 First Ops		- ZeroAvia 600kW motor datasheet referencing motor at 4.5 kW/kg, in certification testing

	Electric motor power density at 13 kW/kg (RTP) - (TRL 6)	Ongoing	5 years	2030	- High speed gearbox maturity and integration	- Reduced pace of OEM development of multi-MW motor design architectures	High	High	Low	EP 4	EP 4 - LH2 First Ops	- Derisking funding to support industry R&D	- ATI Fly Zero EPS roadmap - 23kw/Kg by 2030 - ZeroAvia motor development (10kW/kg target by 2027)
	Electric motor power density at 23kW/kg (narrowbody) - (TRL 6)	2030	10 years	2040	- advances in superconducting motors for substantial lightweighting - Cost and scalability of High Temp Superconducting (HTS) materials - ability to leverage Abingdon superconducting test facility	- Reduced pace of OEM development of multi-MW motor design architectures	High	Low	Low	EP 5	EP 5 - LH2 Basic network	- Collaboration between EPSRC, ATI and industry to advance nascent breakthrough technologies	- ATI Fly Zero EPS roadmap - NASA six-year technical challenge to develop and demonstrate a 5 MW cryogenic motor system (motor, power electronics, and motor controller) for large transport aircraft.
	Inverter power density at 22 kW/kg (Part 23)	Ongoing	1 year	2026	n/a	n/a	Low	Medium	Medium	EP 2	EP 2 - GH2 First Ops		- ATI Fly Zero EPS Roadmap - ZeroAvia invertor tested at 20 kW/kg (further progress expected)
	Inverter power density at 40 kW/kg (regional turboprop)	2030	5 years	2035	- successful functional integration, demonstrating inverter as motor controller - wide range of voltage operation to simplify overall architecture and reduce weight - integration with on board cryogenics and superconducting motors to enable enhanced efficiency	- lack of ongoing, funded comprehensive multiMW powertrain development programme (tight integration with motor development and cryogenic fuel storage development programmes to drive towards Fly Zero 2050 target/estimate of 60 kW/kg)	High	Medium	Low	EP 4	EP 4 - LH2 First Ops	- Industry and ATI to work towards re-establishing larger, integrated programmes targeting multi-MW powertrains (e.g. deprecated programmes such as GKN H2 FlyGHT)	- ATI Fly Zero EPS Roadmap = 2030 (industry consensus of later delivery 2032-2035)

	Testing & qualification of aluminium alloys and stainless steels under prolonged exposure to cryogenic hydrogen conditions	Ongoing	5 years	2030	- Progression of academic research addressing fundamental questions (University of Manchester, Cranfield University, University of Southampton, University of Nottingham)	- Late identification of requirements by regulator jeopardising start date - Slowing of pace of academic/industry collaboration	Medium	High	Medium	EP 4	EP 4 - LH2 First Ops	- See M11: University of Nottingham was exploring this question with industry as part of deprecated ATI programme	https://www.findaphd.com/phds/project/fse-bicentenary-phd-an-investigation-into-the-potential-of-aluminium-alloys-for-the-cryo-compressed-hydrogen-transmission-and-storage/?p188688 Cryogenic mechanical behaviour and hydrogen compatibility of stainless steels for next-generation hydrogen infrastructure | University of Southampton
	LH2 metallic tank mass fraction of 40%+ to support viable system for large RTP (TRL 6)	Ongoing	4 years	2029	- UK facilities for material testing at cryogenic temperatures in a hydrogen environment - Scaling up LH2 aluminium tank testing - (100+kg tank safety validation)	- limited skills and testing capabilities in the UK to understand the behaviour of liquid hydrogen	Medium	High	Medium	Step towards EP 4	EP 4 - LH2 First Ops	- Funding for R&D and testing programmes	Cryogenic Roadmap: Fly Zero Report predicts 47% mass efficiency of tank/fuel storage for regional concept by 2026 (at TRL6). https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-MAP-0026-Cryogenic-Hydrogen-Fuel-System-and-Storage-Roadmap.pdf

	LH2 tank mass fraction of 60%+ to support viable system for narrowbody aircraft	2028	10 years	2038	- Composite tank integrity/cycling - TRL maturation - Continued R&D investment - UK facilities for material testing at cryogenic temperatures in a hydrogen environment - slick conops/aircraft operation for refuelling processes to enable rapid refuelling (want to land with 20% LH2 tank volume to ensure low temp) - demonstrating commercially viable cycle (5 years plus)	- limited skills and testing capabilities in the UK to understand the behaviour of liquid hydrogen - overfocus on material science at academic research level	Medium	High	Medium	EP 5	EP 5 - LH2 Basic network	- MOD focus R&D - development of LH2 infra to reduce costs and build commercial case across aircraft sizes.	- ATI Fly Zero Cryogenic Hydrogen Fuel System & Storage predicts mass efficiency for regional aircraft concept of 61% by 2030 (66% for narrowbody concept) - GTL has tested LH2 composite dewar concepts up to 55% - https://www.gtlcompany.com/wp-content/uploads/2024/03/GTL-Composite-LH2-System-H2Symposium2024public.pdf - ZeroAvia 10kg composite tank testing
	LH2 composite management systems meeting defined acceptable rates of leakage standards	Ongoing	5 years	2030	- regulatory guidance from CAA - standard development within SAE/EUROCAE - exploration of failure modes	- Lack of availability of suitable testing facilities	Medium	High	Medium	EP 4	EP 4 - LH2 First Ops	- development of appropriate leakage management steps	- ZeroAvia LH-SIFT project

	Qualification of micro-crack resistant resins to ensure composites suitability for LH2 storage	Ongoing	20 years	2045	- very low TRL - sufficient UKRI EPSRC funding	- commercially viable possible without these developments, but huge economic benefits could be achieved.	Medium	Medium	Medium	EP 5	EP 4 - LH2 First Ops		- FlyZero Cryogenic Technology Roadmap Report
	Thermal management system efficiencies (across HEPS) - Part 23	2021	5 years	2026	- oil impingement cooling techniques, oil spray or dual phase cooling techniques (motor/fuel cell cooling - enabling higher temps and thus higher currents) - Appetite of avionics thermal management system providers to scale-up and support propulsion systems - Novel thermo-conducting composite materials (inverters) - ensuring compatibility of thermal management systems with high voltage DC architectures - Progress on establishing standards SAE AS74/99 -- ED 296 - Requirement for high integrity hydrogen fuel cell heat exchangers to prevent mixing of H2/coolant - growth in microtube radiator suppliers	- Dependence on intercooler technologies - very thin supply chain for microtube heat exchangers as an alternative	Medium	Medium	Medium	EP 2	EP 2 - GH2 First Ops	- IUK assessment of supply chain and efforts to upskill/connect to aerospace players	- Industry discussions

	Thermal management system efficiencies (across HEPS) - RTP	2023	5 years	2028	- commercial and technical progress of thermal management systems in RTP to justify investment (managing increased flow rates, supporting power density constraints) - SAE AS74/99 -- ED 296 progress in part 23 advancing thermal management system understanding for larger systems	- Lack of sufficient advancement in Part 23 technologies to provide confidence for investment	High	Medium	Low	EP 4	EP 4 - LH2 First Ops	- Connecting R&D programmes at Row 17 to follow on development projects	- Industry discussions
	Thermal management system efficiencies (across HEPS) - Narrowbody	2028	7 years	2035	- commercial progress of thermal management system efficiencies in Part 23 and RTP to justify investment	- Lack of sufficient advancement in Part 23 and RTP relevant technologies to provide confidence for investment	High	Low	Low	EP 5	EP 5 - LH2 Basic network	- Connecting R&D programmes at Row 17 to follow on development projects	- Industry discussions
	Thermal management systems for gas injection into H2 Gas Turbine engines @TRL 6+	Ongoing	Ongoing	2027	- "A low pressure drop heat exchanger in the exhaust gas path (a recuperator) provides effective heating and desirable gas turbine performance gains."		Low	High	High	Step towards EP 6	EP 6 - LH2 Full scale		- Fly Zero - https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-IST-MAP-0012-FlyZero-Technology-Roadmaps.pdf

	Open propulsor architectures (support NB fuel cell aircraft)	2021	15 years	2036	- Ensuring durability and damage tolerance under real-world conditions, including Foreign Object Ingestion risks. Large scale testing is required. - Development of resin-transfer-moulded composite blades, ceramic matrix composites, etc (tech maturity and supply chain)	- Non-UK project means less control of project outcomes/timelines - Noise impacts remain unproven. If projections can't be met, could mean slowing/shuttering of concept (re-1980s)	High	Low	Low	EP 5	EP 5 - LH2 Basic network	- ATI and Clean Aviation continued engagement to track development and consider potential UK contribution to future R&D - Support for potential UK suppliers (e.g. Dowty, Lentus, Barnes Aerospace)	https://www.cfmaeroengines.com/rise
	Design maturity (cert programme readiness) of H2E propulsion system for Part 23	2020	4 years	2024	See above Part 23 related building blocks	- Interdependencies of building block tech - Engine OEM investment	Low	Medium	Medium	Step towards EP 2	EP 2 - GH2 First Ops	Mid-to-late TRL (5+) stage development funding support for full engine systems	- ZeroAvia
	Design maturity (cert programme readiness) of H2E propulsion system for Part 25 (regional TP)	2022	6 years	2028	See above Part 25 H2E building blocks	- Interdependencies of building block tech - Engine OEM investment - Success of Part 23 engine designs and progress through the certification journey	Medium	Medium	Medium	Step towards EP 4	EP 4 - LH2 First Ops	- Support of CAA resource to take mature Part 23 designs through cert programme (derisk more advanced H2E developments) - Continued R&D investment in building block technologies (multiMW fuel cell systems and EPS, LH2 storage systems)	- ATI Fly Zero Report/Industry discussions

	Design maturity of H2 gas turbine for Part 25 (NB)	2028	7 years	2035	See above GT building blocks	- Interdependencies of building block tech (notably high pressure LH2 fuel systems - see row 27) - Engine OEM investment	Medium	High	Medium	Step towards EP 6	EP 6 - LH2 Full scale		
	Design maturity of H2 fuel cell propulsion system for Part 25 (NB)	2028	7 years	2035	See above narrowbody H2E building blocks	- Interdependencies of building block tech - Engine OEM investment	High	High	Medium	Step towards EP 5	EP 5 - LH2 Basic network	- Continued R&D investment in building block technologies (multiMW fuel cell systems and EPS, LH2 storage systems) - Moonshot investment (higher gearing, further derisking for industry): ATI partnership with ARIA	
	Design maturity of H2 gas turbine for Part 25 (Widebody)	2028	7 years	2035	See above GT building blocks	- Interdependencies of building block tech - Engine OEM investment	Medium	High	Medium	Step towards EP 6	EP 6 - LH2 Full scale		

	Design maturity for a high-pressure LH2 fuel system	Ongoing	10	2035	- Engine maker / Airframer collaboration & airframer pull, as the architecture & installation opportunities are vital to the tech choices.	- OEM appetite for programme	High	Medium	Low	Step towards EP 6	EP 6 - LH2 Full scale	- joint R&D investment by OEM and Government (ATI programme)	
Aircraft Structures & Systems	Dry wing technology for new H2 airframes: TRL 6	2030	5 years	2035	- Aeroelastic and loads breakthroughs to offset the loss of wing fuel's inertial relief - strut bracing technologies - Advanced load-alleviation techniques	- Lack of UK development hinders UK content on new airframe. Impact on retrofit programmes.	Medium	High	Medium	Step towards EP 5	EP 5 - LH2 Basic network		
	Fueldraulic replacement systems	2040	5 years	2045	- Development of a dedicated electrical system, suitable for high temperature H2 GT engine environments	- Lack of UK development hinders UK content on new airframe. Impact on retrofit programmes.	High	High	Medium	Step towards EP 5	EP 5 - LH2 Basic network	Establishment of a UK systems network comprising systems suppliers, academia and the end customer(s) for the sharing of information, development of systems requirements and the exploitation of system integration opportunities.	https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIR-REP-0013-Aircraft-Systems.pdf

	Folding wing-tip designs	2030	5 years	2035	- semi aero-elastic hinge technology maturity	- if not achieved, high aspect ratio performance improvements are precluded by airport gate limits	High	High	Low	Step towards EP 5	EP 5 - LH2 Basic network	Prioritisation of dry wing related technology development as part of ATI Roadmap, building on NCC work in collaboration with industry	https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIR-COM-0016-Aerodynamic-Structures-Roadmap-Report.pdf https://www.nccuk.com/media/gijonfgu/xwing-case-study-final.pdf
	Inerting systems	2030	5 years	2035	- certification basis for liquid hydrogen aircraft and associated definition of standard fit inerting systems - sufficient electric power provision within designs to support parasitic demand	- Lack of UK development hinders UK content on new airframe. Impact on retrofit programmes. - Jeopardising certification programme without viable systems at high TRL in advance.	High	High	Medium	Step towards EP 5	EP 5 - LH2 Basic network	Establishment of a UK systems network comprising systems suppliers, academia and the end customer(s) for the sharing of information, development of systems requirements and the exploitation of system integration opportunities.	https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIR-REP-0013-Aircraft-Systems.pdf

	Cryogenic hydrogen containment and fluid control	2025	5 years	2030	- Underlying supply chain "aerospace" maturity for pumps, filters, valves, seals, bearings, etc)	- Lack of UK development hinders UK content on new airframe. Impact on retrofit programmes.	Medium	High	Medium	Step towards EP 5	EP 5 - LH2 Basic network	Establishment of a UK systems network comprising systems suppliers, academia and the end customer(s) for the sharing of information, development of systems requirements and the exploitation of system integration opportunities.	https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIR-REP-0013-Aircraft-Systems.pdf
	Development of new regional aircraft (100 PAX) - delivery date = commencement of certification programme	2025	7 years	2032	- Early accumulation of operational data and issues to feed back into future product development - Data to underpin the business case i.e. performance, reliability, maintenance - Improved readiness of the whole aviation system to scale up - OEM commitment to project - Infrastructure progress: Success of earlier phase hydrogen at airports	- Hydrogen production/refuelling infrastructure and supply chain readiness to provide investment case for continued aircraft OEM programme	Medium	High	Medium	EP 5	EP 5 - LH2 Basic network	- delivery of retrofit Part 23 aircraft flights and airport hydrogen infrastructure	

Regulation	First application for TC part 23 H2E propulsion system (establishing cert baseline) underway	Complete	n/a	Complete	- Part 23 tech building blocks and design maturity achieved	- Lack of track record for hydrogen operation today	Low	Medium	Medium	Step towards EP 2	EP 2 - GH2 First Ops		
	First application for TC RTP H2E propulsion system (establishing cert baseline)	2026	3 years	2029	- Evidence of Part 23 to inform regulatory requirements and limitations - Establishing a sub-regional fleet soon will enable the industry and regulator to accumulate data that can support the development and introduction of future large aircraft	- Building block technologies slower to develop - Regulatory pace in Part 23 category creates hesitance to invest in cert programme for higher power engines	Medium	High	Medium	Step towards EP 4	EP 4 - LH2 First Ops	- CAA H2/new technologies resource support from DfT/HMT	
	First application for TC narrowbody H2E propulsion system (establishing cert baseline)	2030	5 years	2040	- Plans for viable narrowbody hydrogen-electric ready narrowbody with ~2040 entry G40 - Evidence from Part 23/RTP to inform regulatory requirements and limitations	- Regulatory resource in design and cert - GT/piston familiarity of certification personnel - Regulatory knowledge basis	High	High	Low	Step towards EP 6	EP 6 - LH2 Full scale	- Moonshot funding for rapid development of core development and scaling of early-stage technologies	
	First application for TC narrowbody H2G2 propulsion system (establishing cert baseline)	2040	3 years	2043	- Evidence from prior FC segments on LH2 management systems; airport refuelling operations	- Airframer investment/commitment to a programme	Medium	High	Medium	Step towards EP 6	EP 6 - LH2 Full scale		
	Standards (hydrogen specific) - WG-80 / SAE AE-7F - establishing best practices for the qualification and certification of hydrogen fuel cell systems in aerospace applications.	Ongoing	2 years	2026	- Strong industry participation and continued commitment - CAA focus on standards group work	- Technologies such as electric propulsion, autonomous systems, and AI-based flight control are evolving faster than the standards that govern them. Manufacturers often therefore face delays or must rely on special conditions or exemptions, which are not scalable.	Low	High	High	Step towards EP 2	EP 2 - GH2 First Ops	- CAA resource to shadow standards development	

	Standards (broader standards and means of compliance under development touching hydrogen technology development)	Ongoing	2 years	2026	- Strong industry participation and continued commitment - CAA focus on standards group work	- Pace of standards development trails industry tech advancement creating reliance of special conditions	Low	Medium	Low	Step towards EP 2	EP 2 - GH2 First Ops	- CAA resource to shadow standards development	
	Establishment of harmonized, end-to-end certification framework for hydrogen fuel cell systems based on standards	2025	4 years	2029	- learnings from Part 23 special conditions applied to live certification programmes	- Large bureaucratic exercise across different international authorities: can threaten pace of progress	High	Medium	Low	Step towards EP 2	EP 2 - GH2 First Ops		
	First TC part 23 H2E propulsion system	2023	5 years	2028	- Special Conditions for H2 aircraft established - Certification basis for new product complete established - Acceptable means of compliance - Execution of CAA onboarding strategy - Small scale testing in a laboratory, integrated ground rig testing and flight test on a representative flying test bed. - Availability of affordable outdoor DO-160 testing facilities capable of taking H2/LH2 for electric propulsion system vibration and environmental testing	- Lack of regulatory resource/expertise slows development - Familiarity bias creates slow pace on each step in the certification journey - UK lacks outdoor DO-160 ready testing facilities	Medium	High	High	Step towards EP 2	EP 2 - GH2 First Ops	- Compressed Design and Validation (utilising digital tools) - UK CAA resource investment	
	Follow on TCs for part 23	2028	4 years	2032	- Establishing certification specification following first TC	- Slow speed to move to certification specification creates overdependence on special conditions (not scalable/affordable way to continue operating)	Medium	Low	Low	Step towards EP 2	EP 2 - GH2 First Ops	n/a	

	First TC for part 25 H2E propulsion system	2026	5 years	2031	- Regulator/OEM experience via Part 23 TC process - Clear investment case to move demonstrators into full cert programme -> example of hydrogen aircraft operations in place and H2 fuel production scaling up	- high burden of proof required - greater impact of failure creates hesitance to certify/approve	Medium	Medium	Medium	Step towards EP 4	EP 4 - LH2 First Ops	- Compressed Design and Validation (utilising digital tools) - UK CAA resource investment	
	First TC for part 25 H2 gas turbine engine	2043	7 years	2050	- Airframer/engine manufacturer joint commitment to development project - Advanced in high pressure LH2 fuel storage systems	- Without H2GT cert, large aircraft transition to zero carbon/H2 pushed further out (EP 6/full maturity delayed)	Medium	Medium	Medium	Step towards EP 6	EP 5 - LH2 Full scale	- Compressed Design and Validation (utilising digital tools) - UK CAA resource investment	
	STC retrofit Part 23	2026	1 year	2027	- Participation of airframe OEM to ensure access to important data to maintain pace	- Without STC allowing first commercial flight operations, knock-on impact of Part 23 on later stage R&D is slowed	Medium	High	Medium	EP 2	EP 2 - GH2 First Ops	- Further Hydrogen Sandbox Challenge investment focussed on STC/retrofit knowledge development	
	H2 gas turbine relight at altitude demonstration	2040	2 years	2042	- Airframer/engine manufacturer joint commitment to development project - Advanced in high pressure LH2 fuel storage systems	- no facility globally adapted for liquid hydrogen	Medium	High	Medium	Step towards EP 6	EP 5 - LH2 Full scale	- Assessment of UK test capability in line with H2 roadmap	*Fly Zero - https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-IST-MAP-0012-FlyZero-Technology-Roadmaps.pdf*
	Cleansheet RTP structures wind tunnel testing	2030	5 years	2035	- Airframer continued design progress - Available test infrastructure	- Without positive scaled structures testing, appropriately derisking Part 25 clean sheet cert programme is challenging	Medium	Medium	Medium	Step towards EP 5	EP 5 - LH2 Basic network	n/a	

	TC for cleansheet LH2 large regional aircraft	2032	7 years	2039	- OEM commitment to project - Success of earlier phase hydrogen at airports - Aerodynamic structures development (what programmes are in place?)	- missed delivery on TC for cleansheet aircraft causes significant business challenges within supply chain and with H2 production/infrastructure projects	Medium	High	Medium	Step towards EP 6	EP 6 - LH2 Full scale	CAA engagement with global counterparts to align on process for certifying inaugural H2-first airframe	- ATI bomber chart
	Delivery of suitable LH2 material and materials compatibility data to CAA	2026	3 years	2029	- establishment of active dialogue between industry and regulator	- without confidence in materials science, testing requirements for LH2 system cert become highly challenging	High	High	Medium	Step towards EP 4	EP 4 - LH2 First Ops	- Hydrogen Sandbox Challenge legs covering this specific requirement	
	STC retrofit Large RTP	2031	3 years	2034	- TC for H2E propulsion system for large RTP	- missed delivery increases dependence on cleansheet aircraft with longer timelines	Medium	Medium	Medium	EP 4	EP 4 - LH2 First Ops	- Increased CAA resource around hydrogen systems to support UK-first cert of STC for retrofit	
	Establishment of hydrogen knowledge within the continued air worthiness process as part of air operators' certificate	2025	2 years	2027	- development of CAA guidance and related training materials - committed plans for launch of operations, dependent in turn on cost parity with kerosene operations	- EIS delayed by lack of clear guidance or methods to successfully embed within operations	Low	High	High	Step towards EP 2	EP 2 - GH2 First Ops	- EIS projects established to enable close collaboration between OEM, Operator and CAA	
	Operator maintenance organisation approvals	2027	1 year	2028	- Appropriate training materials developed in support of first TC systems	- EIS delayed by lack of clear guidance or methods to successfully embed within operations	Low	High	High	EP 2	EP 2 - GH2 First Ops		
	CAA to establish a safety group on H2 to monitor ongoing safety	2026	1 year	2027	- CAA available resource	- Without appropriate monitoring/engagement beyond the Sandbox/Challenge work, future cert programmes slowed by need to come up to speed on baseline hydrogen safety questions	Medium	Medium	Medium	EP 2	EP 2 - GH2 First Ops	- Review of the offshore heli example	

	Establishment of standards on hydrogen purity and/or agreed fuel sample process established with CAA/HSE	2026	2 years	2028	- Requirement to ensure that hydrogen purity meets the stringent requirements set by international standards, primarily ISO 14687 - Development of technologies for in-line H2 fuel purity testing AND/OR - Agreement of lab testing protocols with associated safety case	- lack of clarity on standards and impacts of impurities may cause overregulation	Medium	High	Medium	EP 2	EP 2 - GH2 First Ops	- Support for National Physical Laboratory in bringing forward novel hydrogen quality alarm in collaboration with industry, government and regulator (establishing additional unique UK capability)	
	Establishment of safety zones for GH2 aircraft refuelling & GH2 storage	Ongoing	2 years	2028	- Developing aviation relevant use cases for international standards such as NFPA 2: Hydrogen Technologies Code - Selecting prescriptive or performance-based regulatory approach	- prescriptive regulatory approach applied to early operations likely to be cumbersome	Medium	High	Medium	EP 2	EP 2 - GH2 First Ops	- support a performance-based regulatory approach on safety distances with prescriptive rules developed based on derisked early operations	
	Establishment of safety zones for LH2 aircraft refuelling & LH2 storage	2028	2 years	2030	- Assessment of BLEVE and cryogenic risks and typical safety distances in airport operations context	- impacts operational safety distances - delay to EIS roll-out if acceptable level of safety not agreed	Low	Medium	Medium	EP 4	EP 4 - LH2 First Ops	- Hydrogen Sandbox/Challenge projects	
	Risk-based, location specific fire, emergency response protocols for GH2 aircraft agreed & training carried out	2027	1 year	2028	- Formalisation of learning from existing airfield uses of hydrogen to date (Kemble/Cranfield/Bristol)	- Delay to EIS if not established - Potential adverse impact incident response if established with errors	Low	Medium	Medium	EP 2	EP 2 - GH2 First Ops		

	National, standardised fire, emergency response protocols for GH2 aircraft agreed & training carried out	2028	3 years	2031	- Successful delivery of risk-based, location specific RFFS protocols	- Stymieing of scaling GH2 network if not achieved	Low	Medium	Medium	EP 3	EP 3 - GH2 Full scale		
	Risk-based, location specific fire, emergency response protocols for LH2 aircraft agreed & training carried out	2029	1 year	2030	- early-stage demonstrations with LH2 to provide initial frameworks (e.g. ZeroAvia testing LH2 refuelling and flight at Cotswold Airport)	- availability of LH2 and related testing facilities for test programmes that can provide learnings for first LH2 operations	Low	Medium	Medium	EP 4	EP 4 - LH2 First Ops	- Hydrogen Sandbox Challenge focus on LH2 safe operations - Establishment of UK domestic liquefaction capability and testing infrastructure	
	National, standardised fire, emergency response protocols for LH2 aircraft agreed & training carried out	2031	3 years	2034	- Successful delivery of risk-based, location specific RFFS protocols related to LH2	- Scaling network requires effective training rollout	Low	Medium	Medium	EP 5	EP 5 - LH2 Basic network	- Establishment of UK domestic liquefaction capability and testing infrastructure	
Airport &	Refuelling turnaround time of sub 20 minutes for Large Regional Turboprop Part 25 aircraft - LH2	2025	5 Years	2030	Enablement of operational environment to allow trials	Increased turnaround times will challenge commercial viability	High	High	Medium	EP 4	EP 4 - LH2 First Ops	ZEF Programme including network of test beds & simulation capabilities	

	First airport readiness for first GH2 hydrogen operations for aircraft	2025	2 years	2027	- Training for airport fire and appropriate equipping - changes in airport operations signed off with CAA & HSE - airport infrastructure in place for storage, refuelling & on-airport transportation - Successful operation of gaseous hydrogen fuelling in airport environments to reduce public concern	- Public opposition based upon misinformation - airport business approval - commercial viability of low-level operations	High	High	Low	EP 2	EP 2 - GH2 First Ops	- Survey major airports to identify space and requirements for hydrogen infrastructure. - Larger study of public attitudes/acceptance/tolerance to establish blockers - ZeroAvia and CPC have together developed good levels of knowledge on conops for GH2 and associated fire training through work with both Cranfield and Cotswold airport - government support to bridge commercial gap between first & BAU operations	
	Refuelling turnaround time of sub 20 minutes for Small Regional Turboprop Part 23 aircraft - GH2	Ongoing	2 Years	2027	Enablement of operational environment to allow trials	Increased turnaround times will challenge commercial viability of high-utilisation operations	Medium	High	Medium	EP 2	EP 2 - GH2 First Ops	ZEF Programme including network of test beds & simulation capabilities	

	First airport readiness for first LH2 hydrogen operations for aircraft	2027	9 years	2036	- Training for airport fire and appropriate equipping - changes in airport operations signed off with CAA & HSE - airport infrastructure in place for storage, refuelling & on-airport transportation - Successful operation of liquid hydrogen fuelling in airport environments to reduce public concern	- Public opposition based upon misinformation - airport business approval - commercial viability of low-level operations	High	High	Low	EP 4	EP 4 - LH2 First Ops	- government support to bridge commercial gap between first & BAU operations	
	Compressed hydrogen storage technology	Available	n/a	Available	System level safety case, regulation, reliability/redundancy for application	Lack of clarity/alignment on safety cases, etc.	Low	High	High	EP 1	EP 1 - GH2 Ground Ops	Grant funded technology development programme for ZEF refuelling & storage technologies	
	Liquid hydrogen storage technology	Available	n/a	Available	System level safety case, regulation, reliability/redundancy for application	Lack of clarity/alignment on safety cases, etc.	Low	High	High	EP 4	EP 4 - LH2 First Ops	Grant funded technology development and demonstration programme for ZEF refuelling & storage technologies	- ZeroAvia VHytta project (mobile storage and dispensing technology) - Air Liquide mobile hydrogen storage
	Liquefaction - increasing capacity/efficiency for scaling LH2 network	2026	4 years	2030	Although liquefiers are in common use these are not at the scale required for future aviation requirements. Operational experience at a larger scale needs to be gained. System level safety case, regulation. Reliability/redundancy for application	LH2 will need to be imported, increasing the cost and security of supply beyond that which is commercially viable	High	High	Low	EP 5/6	EP 5 - LH2 Basic network	Hydrogen & energy strategy that enables cost effective green LH2 to be produced in the UK and readily available at volume	

	Compressors	Available	n/a	Available	System level safety case, regulation, reliability/redundancy for application	n/a	Low	High	High	EP 1	EP 1 - GH2 Ground Ops	Grant funded technology development and demonstration programme for ZEF refuelling & storage technologies	
	Vaporisers	Available	n/a	Available	System level safety case, regulation, reliability/redundancy for application	n/a	Low	High	High	EP 4	EP 4 - LH2 First Ops	Grant funded technology development and demonstration programme for ZEF refuelling & storage technologies	
	Hydrogen unloading station - GH2	Available	n/a	Available	System level safety case, regulation, reliability/redundancy for application	n/a	Low	High	High	EP 3	EP 3 - GH2 Full scale	Grant funded technology development programme for ZEF refuelling & storage technologies	
	Hydrogen unloading station - LH2	2030	5 years	2035	Low frequency LH2 unloading stations exist but design of high frequency stations would need to be developed, including boil off capture technology. System level safety case, regulation, reliability/redundancy for application	- Slowing in development of underlying hydrogen technologies in non-aviation sectors (particularly LH2).	High	High	Low	EP 4	EP 4 - LH2 First Ops	Grant funded technology development programme for ZEF refuelling & storage technologies	

	Gas pipeline connecting production to UK hub airport	2026	5 years	2031	Pipelines transporting 100% hydrogen gas are used within industrial regions (Texas, Ontario). Long-distance transmission GH2 pipe networks are being planned in the EU (EU hydrogen backbone) and the UK (Project Union). Scale up & expansion of network required along with regulation & the development of relationships with supplementary offtakes	Not necessarily within aviation's gift to deliver	Medium	Medium	Medium	EP 5/6	EP 5 - LH2 Basic network	Project Union plans - https://www.nationalgas.com/future-energy/hydrogen/project-union-energising-britain	
	LH2 hydrant system	2030	10 years	2040	Cryogenic pipes for LH2 are common in the space and gas sectors. However, there are differences in an airport, e.g. maintaining pressure and preventing boil-off with many branches from a backbone pipe. Analysis required to model an LH2 pipe network operation at an airport. A demonstration network would need to be built and tested to determined how the integration with the main storage tank would be managed.	Without national technology roadmap, development of this may not happen, or will happen organically and not linked to any government or industry strategy	High	Medium	Low	EP 6	EP 6 - LH2 Full scale	Grant funded technology development programme for ZEF refuelling & storage technologies	
	LH2 hydrant system - transfer tanks	tbc	tbc	tbc	The use of a transfer tank is not new, the design of a below ground tank suitable for use in an airport does not currently exist A demonstration tank would be needed to be and tested through multiple refill cycles to determine the projected reliability and lifetime of the tank, in parallel to the operational concepts of refuelling the aircraft.	Without national technology roadmap, development of this may not happen, or will happen organically and not linked to any government or industry strategy	High	Medium	Low	EP 6	EP 6 - LH2 Full scale	Grant funded technology development programme for ZEF refuelling & storage technologies	

	LH2 hydrant system - mobile dispenser vehicle	2026	5 years	2031	A mobile refueller that can be used to connect and disconnect the refuelling hose(s) to the aircraft using robotic automation, purge the aircraft tank and refuelling hoses, pressurise the transfer tank, and avoid leaks does not exist. Much of the hydrogen technology with the vehicles already exists. However, there will be a lot of systems integration and automated control software that will need to be developed. A demonstration vehicle will need to be developed and tested through a comprehensive set of operational scenarios.	Without national technology roadmap, development of this may not happen, or will happen organically and not linked to any government or industry strategy	High	Medium	Low	EP 6	EP 6 - LH2 Full scale	Grant funded technology development programme for ZEF refuelling & storage technologies.	
	LH2 hydrant system - overall design	2030	5 years	2035	Nothing on the scale of the system needed for an airport has been developed. A considerable amount of system design, integration and testing work needs to be undertaken. A demonstration system will need to be built and tested through a comprehensive set of operational scenarios.	Without national technology roadmap, development of this may not happen, or will happen organically and not linked to any government or industry strategy	High	Medium	Low	EP 6	EP 6 - LH2 Full scale	Grant funded technology development programme for ZEF refuelling & storage technologies	
	GH2 refuelling vehicle	Ongoing	2 years	2027	Additional technology will be needed in relation to the control systems to manage the refuelling process that are not present on GH2 delivery trucks.	Without national technology roadmap, development of this may not happen, or will happen organically and not linked to any government or industry strategy (reducing UK export potential and roadmap control)	Medium	High	Medium	EP 2	EP 2 - GH2 First Ops	Grant funded technology development programme for ZEF refuelling & storage technologies	

	LH2 refuelling vehicle	Ongoing	5 years	2030	Additional technology in relation controls and boil off gas management technology will need to be developed.	Without national technology roadmap, development of this may not happen, or will happen organically and not linked to any government or industry strategy (reducing UK export potential and roadmap control)	Medium	High	Medium	EP 4	EP 4 - LH2 First Ops	Grant funded technology development programme for ZEF refuelling & storage technologies	ZeroAvia project VHyTTA
	Boil off gas (BOG)/Flash gas/displacement gas recovery or management solution (re LH2 storage)	Ongoing	5 years	2030	Technology development and bolstered R&D investment	Without national technology roadmap, development of this may not happen, or will happen organically and not linked to any government or industry strategy	High	High	Low	EP 4	EP 4 - LH2 First Ops	Grant funded technology development programme for ZEF refuelling & storage technologies	
	In-situ fuel purity testing technology	Ongoing	2 years	2027	Real-time continuous monitoring systems are not currently commercially available by are in development (i.e. SGS). However, it is not clear if these would be necessary (see Row 57). Quality control regime needs to be determined for an aviation application. For LH2 testing, it's likely that a LH2 sample will be taken then vaporised for testing as a gas. Sampling technology already available from LNG sector	Clarity of regulation/standards/process for fuel assurance is urgently required as this will drive the need for technology development to support it	High	High	Low	EP 1/2	EP 1 - GH2 Ground Ops	Grant funded technology development programme for ZEF refuelling & storage technologies	

	Integrated GH2 system	2026	2 years	2028	Preliminary System Design needs to be undertaken which will include: Perform sizing calculations (tank volumes, pipeline diameters, electrolysis size) Refine safety and control strategy (sensor placement, emergency shutdown logic) Develop preliminary layouts (site plans showing equipment zones and flow paths) System design process needs to be integrated with the development of feasible CONOPS, particularly in relation to H2 delivery & aircraft refuelling	Airport specific in the main - relies on individual airports to develop. Without central co-ordination/incentives, risk that this won't happen in a timely enough manner	Medium	High	Medium	EP 2	EP 2 - GH2 First Ops	Incentives/government support for pioneer airports supporting first hydrogen services	
	Integrated LH2 system	2026	5 years	2031	Concept Design and Preliminary System Design for a liquid hydrogen hydrant system needs to be undertaken. Preliminary System Design for a non-hydrant system needs to be undertaken. System design process needs to be integrated with the development of feasible CONOPS particularly in relation to H2 delivery & aircraft refuelling	Airport specific in the main - relies on individual airports to develop. Without central co-ordination/incentives, risk that this won't happen in a timely enough manner	Medium	High	Medium	EP 4	EP 4 - LH2 First Ops	Incentives/government support for pioneer airports supporting first hydrogen services	
	Establishment of indigenous capability for machining and tooling to support UK supply chain for cleansheet RTP and propulsion/fuel systems	Now	10 years	2035	- OEM demand signal for suppliers - Support for new aerospace suppliers from automotive and other sectors	- Dependence on volatile global supply chains if not achieved - Ceding tech leadership and future market share of global hydrogen aviation supply chain	Medium	High	Medium	EP 5	EP 5 - LH2 Basic network	- R&D funding via ATI SME Programme directed to H2 tech - Support programmes via HVMC, AMRC, NCC etc ("Fit for Hydrogen Aviation")	

	Qualification of new manufacturing techniques and inspection processes for LH2 storage vessels driven by material developments (composites)	Ongoing	5 years	2030	- Continuation of grant funding to advance projects towards manufacturability	Jeopardising UK opportunity to build strategic niche in LH2 sector with focus on aircraft storage vessels.	Medium	Medium	Medium	EP 4	EP 4 - LH2 First Ops	- Collaboration between industry, research centres and academia with support from by the NCC, High Value Manufacturing Catapult, EPSRC, Innovate UK and the Aerospace Technology Institute. - funding and support to help build pilot lines	- ATI Fly Zero Cryogenic Roadmap Report, Manufacturing report
	Establishment of manufacturing and treatment facilities capable of building and storing large size tanks (> 4 m in diameter) at industrial rates	2030	5 years	2035	- Clear demand signal from OEMs/industry - H2 ecosystem development	Jeopardising UK opportunity to build strategic niche in LH2 sector with focus on aircraft storage vessels.				EP 5	EP 5 - LH2 Basic network		- ATI Fly Zero Cryogenic Roadmap Report
	Availability of components and materials for hydrogen aviation systems (supply chain maturity) - Part 23	2026	4 years	2030	- Certification progress of Part 23 H2E systems	UK market share in global market forH2 aviation at risk if high supply chain preparedness not prioritised				EP 3	EP 3 - GH2 Full scale		
	Availability of components and materials for hydrogen aviation systems (supply chain maturity) - RTP	Ongoing	4 years	2029	- OEM demand signal for suppliers - Support for new aerospace suppliers from automotive and other sectors	UK market share in global market forH2 aviation at risk if high supply chain preparedness not prioritised	High	High	Low	EP 5	EP 5 - LH2 Basic network		

	Availability of components and materials for hydrogen aviation systems (supply chain maturity) - H2E narrowbody	2035	5 years	2040	- Success in regional segments to provide confidence for suppliers - technological maturity of propulsion technology bricks	UK market share in global market forH2 aviation at risk if high supply chain preparedness not prioritised	Medium	High	Medium	EP 6	EP 6 - LH2 Full scale		
	Availability of components and materials for hydrogen aviation systems (supply chain maturity) - H2 GT Narrowbody	tbc	tbc	tbc			High	High	Low	EP 6	EP 6 - LH2 Full scale		
	Pilot line established for manufacture of H2E propulsion systems for Part 23	2027	1 year	2028	- Certification progress of Part 23 H2E systems - Capital availability to fund pilot line establishment	- First system production face delays impacting overall timeline given criticality of first H2 flight	Low	High	High	EP 2	EP 2 - GH2 First Ops	- Collaboration between industry, research centres and academia with support from by the NCC, High Value Manufacturing Catapult, EPSRC, Innovate UK and the Aerospace Technology Institute. - funding and support to help build pilot lines	

	High-rate manufacture for H2E propulsion systems for Part 23	2028	2 years	2030	- Certification progress of Part 23 H2E systems - Capital availability to scale production capacity	- scaling GH2 network prevented by production pace to meet demand	Medium	Medium	Medium	EP 3	EP 3 - GH2 Full scale	- Mirroring of Automation Transformation Fund support for production - Leveraging vehicles like Repayable Launch Investment to enable public investment to derisk market entry	
MRO Procedures and Capacity	Closing gaps in operational and maintenance standards	2025	5 years	2030	- Development of guidance on operational procedures, maintenance protocols, and lifecycle management for new technologies.		Medium	High	Medium	Step towards EP 2	EP 2 - GH2 First Ops		
	Effective monitoring systems for first hydrogen-electric engines	Ongoing	2 years	2027	- Integrated sensors to enable remote diagnostics and maintenance of fuel cells - delivery of next generation diagnostics and maintenance		Medium	Medium	Medium	EP 2	EP 2 - GH2 First Ops		

	LH2 Storage Systems Maintenance at 17,000 flight cycles for regional, 20,000 for narrowbody	Ongoing	5 years	2030	- Materials development and demonstration - Regulatory approvals	- Setting maintenance requirement higher impacts economic case and slows transition	Medium	Medium	Medium	EP 4	EP 4 - LH2 First Ops		- Initially components and tanks should achieve a minimum life of an aircraft heavy maintenance interval (D-Check) to minimise maintenance burden and maximise aircraft availability. (ATI Fly Zero Report, Cryogenic Roadmap)
	LH2 Storage Systems Maintenance at 70,000 flight cycles for regional, 60,000 for narrowbody	2030	6-8 years	2037	- Flight cycles logged in first aircraft in service - Materials development and demonstration		Medium	Medium	Medium	EP 6	EP 6 - LH2 Full scale		
Economics	Parity of H2E Part 23 with cost per seat mile of kerosene Part 23	Ongoing	2 years	2028	- Government support to overcome sub-scale infrastructure and H2 transportation costs - Ability to connect to Hydrogen Allocation Round projects	Price premium creates first mover disadvantage that prevents adoption	Low	High	High	EP 2	EP 2 - GH2 First Ops	Catalysing funding programme to establish first flight routes, overcoming any initial cost premium in comparison to kerosene operations	
	Parity of H2E RTP with cost per seat mile of kerosene RTP	Ongoing	10 years	2035	- Government support to overcome sub-scale infrastructure costs - Access to affordable LH2 delivery and or liquefier technology	Delayed transition from GH2 to LH2 preventing realisation of wider economic, climate, environmental benefit	Medium	High	Medium	EP 4	EP 4 - LH2 First Ops	Focus on development of UK domestic LH2 supply	
	Parity of H2 GT NB with cost per seat mile of kerosene narrowbody	Ongoing	25 years	2050	- Timely shift to pipeline H2 distribution to airport use - Efficiency equation with combustion compared to fuel cells makes economic more challenging and dependent on further decline in LH2 cost	- Economics detract push from OEMs and pull from airlines, slow development	Medium	High	Medium	EP 6	EP 6 - LH2 Full scale	Focus on development of UK domestic LH2 supply	

	Parity of H2E NB with cost per seat mile of kerosene narrowbody	Ongoing	20 years	2045	- Timely shift to pipeline H2 distribution to airport use	- Large technology leaps needed to deliver required power output (may need to be derisked in this timeline with hydrogen-electric/GT hybrid, which has less efficiency and inferior economic case)	High	High	Low	EP 5	EP 5 - LH2 Basic network	Focus on development of UK domestic LH2 supply	
Routes	Part 23 launch route (10 seat - 250 nm)	2026	2 years	2028	- funding capex for retrofit and hydrogen refuelling infrastructure - Ensuring cost competitiveness with kerosene to enable first operator to commit	- Cert timeline: powertrain TC and airframe STC	Medium	High	Medium	EP 2	EP 2 - GH2 First Ops	Catalysing funding programme to establish first flight routes, overcoming any initial cost premium in comparison to kerosene operations	
	Part 23: 2-5 routes (10-20 seats - 250 nm)	2028	2 years	2030	- funding capex for retrofit and hydrogen refuelling infrastructure - Operator business case Proofpoint from 1st route	- Cert timeline: powertrain TC and airframe STC	Medium	High	Medium	Ongoing EP 2	EP 2 - GH2 First Ops	Catalysing funding programme to establish first flight routes, overcoming any initial cost premium in comparison to kerosene operations	

	RTP (LH2) first route launch (60 seat - 500 nm)	2025	10 years	2035	- funding capex for retrofit and liquid hydrogen refuelling infrastructure - Operator business case Proofpoint from Part 23 flights - RFFS and operational readiness	- Cert timeline: powertrain TC and airframe STC for retrofit. Delay risks dependence on non-UK cleansheet aircraft programme	Medium	High	Medium	EP 4	EP 4 - LH2 First Ops	- Technology R&D/commercialisation funding programme re-LH2 fuelling technologies - Coordinated programme/guidance on planning/consenting LH2 production, storage and refuelling infrastructure - Development of regulatory approach under Part 23 and extension into LH2	
	RTP (LH2): 2-5 routes (60 seat - 500 nm)	2035	3 years	2038	- Successful operations of scaled up Part 23 network and first RTP route - Cost competitive operation	- Cert timeline: powertrain TC and airframe STC for retrofit. Delay risks dependence on non-UK cleansheet aircraft programme and/or slowing of that subsequent programme (which is critical to scale)	Medium	High	Medium	Ongoing EP 4	EP 4 - LH2 First Ops	- Technology R&D/commercialisation funding programme re-LH2 fuelling technologies - Coordinated programme/guidance on planning/consenting LH2 production, storage and refuelling infrastructure - Development of regulatory approach under Part 23 and extension into LH2	

	H2 cleansheet (regional) EIS 1st route adoption (100 seat - 1000 nm)	2025	14 years	2039	- Industry business case proven by H2E operation in retrofit Part 23/regional turboprop segments (enabling major aerospace OEMs and Tier 1s to invest in programme acceleration) - Accumulation of operational data from preceding segments to feed back into future product development, data to underpin the business case i.e. performance, reliability, maintenance, etc.	- Lack of available airframes risks stranded assets in terms of airport infra development	Medium	High	Medium	EP 5	EP 5 - LH2 Basic network	- National zero-emission aviation programme that seeks to map infrastructure development to aircraft availability, providing OEM certainty	
	~10 regional routes adopted with H2 cleansheet regional platform	2039	3 years	2042	- scaling of LH2 refuelling infrastructure at UK airports - Economic performance of first routes	Slow scaling of network impacts ROI and emissions reduction ahead of 2050	Medium	High	Medium	Ongoing EP 5	EP 5 - LH2 Basic network	- National zero-emission aviation programme that seeks to map infrastructure development to aircraft availability, providing OEM certainty	
Skills & Training	HVMC and ATI commissioned to develop a National Skills Framework for Hydrogen Aviation, enabling coordination cross-sector	2026	1 year	2027	- Government funding and focus	- Lack of available funding to support programme in either Catapult Network or ATI	High	Medium	Low	All EPs	All EPs	Per item definition	- ATI Fly Zero Workforce Roadmap Report
	Skills England to conduct a full fore sighting assessment of skills requirements (following Skills Value Chain approach)	2026	0.5 years	2026 (Q3)	- Skills England capacity/direction from DWP in collaboration with DBT	- failure of cross-governmental collaboration leads to incomplete picture of skills needs/resources	Medium	Medium	Medium	All EPs	All EPs	Per item definition	

	Establishment of short course CPD / degree course curricula / apprenticeship programmes to enable skills development	2027	2 years	2029	- Industry participation/clear demand signals - Confidence in viability and urgency of investment, driven by "industrial business case" (first segment operations - Part 23 - represent key unlock) - Fore sighting exercise (row 118)	- Skills gap precludes rapid adoption of technology, adds significant cost and complexity to starting operations	Medium	Medium	Medium	All EPs	All EPs	- Skills assessment and curricula development (supported by Skills England, Innovate UK, ATI, HVMC, AMRC etc)	
	Home Office make work visas available to experts in hydrogen, cryogenics and electrical engineering	2027	1 year	2028	- Political will	- Anti-immigration sentiment and more restrictive government policy	Medium	Medium	Medium	EPs 3+	EPs 3 +	- Prioritisation of zero-emission flight progress as part of Government's plan for airport expansion and jet zero	
	Dozens of materials scientists developing novel material applications e.g. magnetic materials, electrical insulation and fuel cell membranes.	Ongoing	5 years	2030	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	Medium	Medium	Medium	EPs 3+	EPs 3 +	- EPSRC investment in core technology areas, in line with Industrial Strategy focus on aerospace advanced manufacturing	

	Low 100s of specialists required who understand advanced electrical motors, superconductivity and thermal management.	Ongoing	5 years	2030	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	Medium	Medium	Medium	EPs 3+	EPs 3 +	- EPSRC investment in core technology areas, in line with Industrial Strategy focus on aerospace advanced manufacturing	
	Low 100s of engineers with an understanding of integration of fuel cell and electrical systems onto aircraft.	Ongoing	5 years	2030	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	High	Medium	Medium	EPs 3+	EPs 3 +	- Skills assessment and curricula development (supported by Skills England, Innovate UK, ATI, HVMC, AMRC etc)	
	Low 100s of chemists and fluid dynamics specialists to develop modelling capability and support system design	Ongoing	5 years	2030	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	High	Medium	Medium	EPs 3+	EPs 3 +	Development and delivery of National Skills Framework for H2 Aviation	

	Low 100s of design, development and test engineers for cryogenic fuel distribution systems, hydrogen heat exchangers and...	Ongoing	5 years	2030	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	High	Medium	Medium	EPs 3+	EPs 3 +	- Establishment of LH2 testing facilities for industry and academia learning, product development and facility design - identifying baseline skills (GH2/liquid nitrogen)	
	Low 100s of Systems and automation engineers to develop refuelling solutions, hydrogen detection and fire suppression systems.	Ongoing	5 years	2030	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	High	Medium	Medium	EPs 3+	EPs 3 +	Development and delivery of National Skills Framework for H2 Aviation	
	Low 100s materials specialists developing new alloys or composites, potentially using new processes providing higher performance.	Ongoing	5 years	2030	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	High	Medium	Medium	EPs 3+	EPs 3 +	Development and delivery of National Skills Framework for H2 Aviation	
	Low 100s of engineers who understand safe handling and storage of liquid hydrogen for design, validation and testing.	Ongoing	5 years	2030	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	High	Medium	Medium	EPs 3+	EPs 3 +	Development and delivery of National Skills Framework for H2 Aviation	

	Low hundreds of manufacturing and maintenance specialists required to bring in new process technologies, particularly for combustor components and heat exchangers.	2030	5 years	2035	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	Medium	Medium	Medium	EPs 3+	EPs 3 +	Development and delivery of National Skills Framework for H2 Aviation	
	Low 100s of process specialists identifying advanced technologies for electrical system and component manufacture.	2030	5 years	2035	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	Medium	Medium	Medium	EPs 3+	EPs 3 +	Development and delivery of National Skills Framework for H2 Aviation	
	Low 100s of automation engineers and manufacturing specialists with knowledge of fuel cell products and safe working with chemicals.	2030	5 years	2035	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	Medium	Medium	Medium	EPs 3+	EPs 3 +	Development and delivery of National Skills Framework for H2 Aviation	
	Dozens of maintenance engineers and technicians who understand fuel cells and electrical systems.	2025	5 years	2030	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	Medium	Medium	Medium	EPs 3+	EPs 3 +	Development and delivery of National Skills Framework for H2 Aviation	

	Low 100s of manufacturing and repair specialists who can embed and maintain integrated sensors.	2030	7 years	2037	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	Medium	Medium	Medium	EPs 3+	EPs 3 +	Development and delivery of National Skills Framework for H2 Aviation	
	Low 100s of manufacturing and maintenance specialists experienced at working with liquid hydrogen and vacuums (for e.g., dual-walled fuel system pipes).	2030	5 years	2035	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	Medium	Medium	Medium	EPs 3+	EPs 3 +	Development and delivery of National Skills Framework for H2 Aviation	
	Dozens of manufacturing and maintenance specialists experienced at working with liquid hydrogen and vacuums (for e.g., dual-walled fuel system pipes).	2025	5 years	2030	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	Medium	Medium	Medium	EPs 3+	EPs 3 +	Development and delivery of National Skills Framework for H2 Aviation	
	Dozens of manufacturing specialists developing manufacturing technologies for dry wings	2030	5 years	2035	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	Medium	Medium	Medium	EPs 3+	EPs 3 +	Development and delivery of National Skills Framework for H2 Aviation	

	100s of manufacturing and maintenance specialists experienced at working with liquid hydrogen, vacuums (for e.g., dual-walled tanks) and composite repairs.	2030	10 years	2035	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	Medium	Medium	Medium	EPs 3+	EPs 3 +	Development and delivery of National Skills Framework for H2 Aviation	
	Dozens of manufacturing and maintenance engineers skilled in working with integrated systems, including electrification	2025	5 years	2030	- University programme development support hydrogen aviation roadmap - Faculty capability in UK Universities - Appropriate CPD short courses established (via Catapult network?)	- UK brain drain based on university funding and restrictive visa processes - Low starting point based on general shortage of relevant UK based scientists/engineering skills	Medium	Medium	Medium	EPs 3+	EPs 3 +	Development and delivery of National Skills Framework for H2 Aviation	
	Pilot Training	2026	2 years	2028	- Training syllabus development - Training manuals - Training organisation partnerships - Training requirements	- Training organisation adoption	Medium	Medium	Medium	EPs 3+	EPs 3 +	- CAA engagement (Hydrogen Sandbox)	