Hydrogen Aviation: A Regulatory Roadmap to 2050

Date
May 2026

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1 Executive Summary

The Hydrogen Aviation Regulatory Roadmap to 2050 sets out how the UK can enable the safe, timely and scalable introduction of hydrogen powered flight. It has been developed by the Civil Aviation Authority (CAA), as part of the Hydrogen Challenge with input from a range of stakeholders. The roadmap supports UK decarbonisation policy objectives, including the delivery of net zero UK aviation by 2050, by setting out the regulatory sequencing and evidence required while reflecting the CAA's core role: protecting people and enabling aerospace through proportionate, evidence-led safety regulation.

The CAA's Hydrogen Challenge receives funding from the Department for Transport (DfT). The opinions expressed within the roadmap are solely those of the authors.

Purpose and focus

This roadmap provides a structured sequence of activities that support safe progression from early trials to routine operations, with clear decision points and enabling work across aircraft, fuel, aerodromes, operations, and airspace. It does not commit to deployment outcomes or dates given these rely on the progress of industry. Instead, it identifies the regulatory, operational and infrastructure enablers that must be in place at each stage to allow safe progress as evidence and capabilities mature.

The regulatory roadmap also builds upon several activities such as the Hydrogen Challenge have been underway for several years.

To support consistent planning, the regulatory roadmap is structured around three maturity-based time periods, starting from the current day, which are used in the report:

- **Demonstrate (2026-2030):** Trials, demonstrations and evidence generation using small or modified aircraft under controlled conditions, with both low and high-powered propulsion systems <1MW and >1MW. Early aerodrome activity focuses on initial GH_2 refuelling trials at selected sites. Activity is enabled through the Hydrogen Challenge programme with evidence informing regulatory gap assessments, early Special Conditions (SCs) and draft guidance developed in parallel.

- **Prove (2030-2035):** Repeatable certification, operational and infrastructure frameworks are developed and applied to support initial, limited commercial operations on suitable routes and aerodromes. Hydrogen specific regulatory material and guidance are consolidated, and aerodrome arrangements mature toward more standardised, business as usual approaches.

- **Scale and sustain (2035 onwards):** Hydrogen aviation is embedded within routine regulatory oversight and operations, aligned with technology maturity, aerodrome investment cycles and wider energy system readiness. Training, emergency response and oversight become established as normal activities, supported by stable domestic frameworks compatible with international obligations.

These periods reflect regulatory and system readiness rather than technology promises or market forecasts. Regulatory readiness is a pre-requisite ahead of any future certified product.

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Roadmap structure

Hydrogen aviation introduces tightly coupled dependencies across the aviation system. To manage these, the regulatory roadmap is organised into five interdependent domains, each with defined regulatory and technical milestones plus enabling actions:

- **Aircraft and Propulsion Systems:** Developing and certifying safe entry into service (EIS) for hydrogen-powered aircraft, from early experimental propulsion systems (both low power <1MW and high power >1MW) and technologies to larger commercial classes as evidence accumulates.

- **Energy (hydrogen fuel production and supply):** Aviation-grade hydrogen supply, fuel quality, and logistics readiness for gaseous hydrogen (GH_2) and liquid hydrogen (LH_2) aligned to aviation operational needs.

- **Aerodromes:** Hydrogen storage and refuelling capability, hazard management, emergency response, and integration into aerodrome safety management systems.

- **Operations and Safety Management:** Operational concepts, continuing airworthiness and maintenance readiness, competence frameworks, and safety assurance for hydrogen operations.

- **Airspace and Flight Procedures:** Flight planning, diversion/alternate considerations, publication and procedures to integrate hydrogen operations safely into UK airspace.

Factors influencing the roadmap

Successful delivery of the roadmap depends on several critical factors:

- **Sequencing and interdependencies:** The roadmap emphasises cross domain sequencing. Progress in one area alone is insufficient; all the domains must mature in sequence. The roadmap therefore focuses on managing critical dependencies, avoiding misalignment and reducing the risk of fragmented investment, regulatory bottlenecks or avoidable safety risks, including the timely development of regulatory capability and fuel assurance arrangements for hydrogen.

- **External factors:** The roadmap explores its sequencing against three external scenarios (high ambition, central and low ambition) and through a structured PESTLE analysis highlighting how Policy, Economics, Social, Technological, Legal and Environmental domains could either constrain or accelerate hydrogen aviation and where stakeholder action can most influence outcomes.

- **Enablers and governance:** Delivery depends on coordinated progress across evidence generation, regulatory developments, aircraft and infrastructure readiness, and competence development. The roadmap sets out how these enablers progress together, how dependencies are managed through governance and how periodic review is used to adapt to evolving evidence. External taskforce reporting highlights the importance of sufficient regulatory capability and funding, alongside cross-government and international coordination as enablers of timely hydrogen aviation progress.

Next steps: Immediate priorities focus on mobilisation. These include governance and delivery management, prioritising critical-path activities and maintaining structured engagement across government, regulators and industry. This builds on recent scale-up of the CAA's Hydrogen Challenge sandbox activity, supported by DfT funding.

2 Introduction

Roadmap aim: *Enable the safe, timely, and scalable adoption of hydrogen-powered flight in UK civil aviation, aligned with the Government's decarbonisation objectives, while upholding the highest standards of aviation safety and supporting the UK civil aerospace sector.*

This roadmap provides a domain-wide framework for enabling the safe integration of hydrogen into UK civil aviation across aircraft, fuel supply, aerodromes, operations (including safety management) and airspace. The roadmap is structured around three maturity-based time periods that reflect progressive stages of system maturity: Demonstrate (2026-2030); Prove (2030-2035); Scale and sustain (2035 onwards). These periods are used throughout the document to support coherent sequencing of enabling activities and readiness milestones. The roadmap does not make conditional commitments on deployment or technology outcomes; instead, it focuses on identifying the activities and dependencies that must be addressed to enable safe progress as evidence and capability develop.

This roadmap has been developed by the CAA, with input from DfT and wider stakeholders (see details in ***Section 2.6*** for breakdown). It is intended to inform the CAA and government stakeholders, industry participants across the hydrogen and aviation ecosystem, and relevant counterparts in other states where cooperation supports UK safety and operational objectives.

2.1 Objectives

The roadmap's objectives are to:

- Maintain aviation safety while enabling proportionate, evidence-led innovation in hydrogen aviation.
- Provide a coherent domain-level view of the regulatory, operational, infrastructure and competence enablers required to support hydrogen readiness in the UK.
- Support informed planning and investment by clarifying dependencies, sequencing, and critical enabling conditions across the aviation system.
- Align regulatory development with UK Government policy objectives, including on green aviation, without pre-judging technology pathways or market outcomes.
- Support international interoperability by maintaining compatibility with the UK's International Civil Aviation Organization (ICAO) obligations and enabling harmonisation where it serves UK safety and operational interests.

2.2 Context of the roadmap

Hydrogen is being explored as a decarbonisation pathway for parts of civil aviation alongside Sustainable Aviation Fuel (SAF), operational efficiencies and other methods. These options are complementary rather than interchangeable and each address different parts of the aviation system and present distinct technical, operational and regulatory challenges.

SAF provides near-term emissions reductions by leveraging existing aircraft and infrastructure and is expected to play a significant role in aviation decarbonisation. The UK mandates a proportion of SAF within the supply of UK jet fuel: 2% in 2025 increasing linearly to 10% in 2030 and 22% in 2040[1]. However, SAF does not eliminate all lifecycle emissions and relies on sustained availability of suitable feedstocks, production capacity and supply chains.

Operational and airspace efficiencies can further reduce emissions but are constrained by physical and operational limits. As a result, no single pathway on its own can deliver net zero aviation by 2050.

Hydrogen offers the potential for zero-carbon civil aircraft operations for certain use cases, particularly in short-haul and regional aviation. However, this potential comes with substantially higher system impact and uncertainty than other pathways. Hydrogen affects aircraft architectures, fuel production and logistics, aerodrome infrastructure, operational concepts, emergency response and regulatory frameworks. If these interdependencies are not addressed in a coordinated way, there is a risk of fragmented investment, misaligned readiness across the system, and avoidable safety and delivery risks.

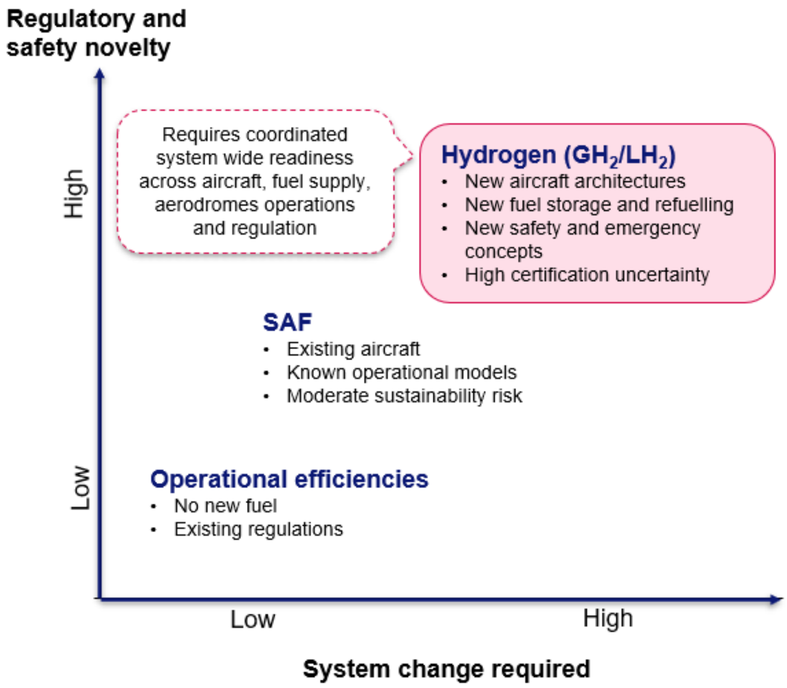

Figure 1:Relative system impact and regulatory novelty of aviation decarbonisation pathways for civil operations.

Due to the potential for zero emissions flight, public and private investment is being directed towards hydrogen aviation for civil operations. In the UK, this includes funding for early aircraft and ground-based trials, regulatory sandbox activity, and supporting

[1] Sustainable Aviation Fuel (SAF) Mandate - GOV.UK

research and capability development. This investment is intended to generate the evidence needed to determine whether, where and how hydrogen can be introduced safely and proportionately.

For the CAA, the central focus is safe integration. Hydrogen technologies must be introduced in a way that maintains or improves the current level of aviation safety, using operational evidence to inform proportionate regulatory approaches. Given the scale and novelty of the changes involved, progress cannot be managed through isolated approvals or incremental rule changes alone. Without a clear roadmap, there is a risk that aircraft development, infrastructure investment and regulatory readiness progress out of alignment, increasing cost, uncertainty and safety risk.

A dedicated hydrogen regulatory roadmap provides a structured way to manage these risks. It supports early investment by clarifying sequencing, dependencies and evidence needs. This ensures that regulatory and safety considerations are embedded from the outset and helps government and industry align activity across multiple domains. In doing so, the roadmap helps protect value for money, maintain safety, and keep future decarbonisation options open as evidence and technology maturity develop.

2.2.1 Current UK status

This section describes the current UK baseline from which the roadmap sequencing begins.

The UK's current position reflects an internationally early stage of hydrogen aviation maturity, with activity focused on regulatory innovation, evidence generation and early system learning, particularly for small or modified aircraft operating under controlled conditions, consistent with the approach being taken across leading aviation states.

The CAA's regulatory sandbox activity, including the Hydrogen Challenge, plays a central role in enabling early projects, testing novel technologies and operational concepts, and identifying where hydrogen introduces new or different safety considerations compared with conventional aviation.

These early programmes provide an essential foundation for structured progress, but domain-wide integration remains limited. Hydrogen fuel supply for aviation, aerodrome infrastructure, operational procedures, competence frameworks and emergency response arrangements are largely at exploratory or trial stage, and dependencies between domains are still emerging rather than resolved. Regulatory material specific to hydrogen aviation is developing, informed by early gap and impact assessments, but is not yet embedded as business-as-usual.

Table 1 summarises the current UK position across key readiness areas, highlighting where capability is active, emerging or at an initial stage.

Table 1: Summary of UK status

Readiness area	UK status	Examples
Regulatory innovation	Active	Hydrogen Challenge Sandbox[2]*:* first-of-kind regulatory sandbox for hydrogen aviation (since 2023) with 16 pilot projects including those of the Regulators' Pioneer Fund (fuel cell aircraft, H_2 retrofitted plane, H_2 airport ops). CAA has published gap analysis reports as interim guidance: • *CAP 3123/3124/3125:* Detailed gap analyses for small planes, large planes and engines recommending new SCs for H_2 fuel systems and engines (published 2025) • *CAP 3046:* Invitation to industry to test hydrogen tech and identify regulatory gaps.
Industry trials and technology system	Emerging	Early trials and demonstrations are proving both technology (fuel cell and combustion) and system (propulsion) concepts. Technology developments are at the following stage: • Hydrogen combustion Technical Readiness Level (TRL) level: 2-4 • <1MW Fuel cell TRL level: 3-5 • >1MW Fuel cell TRL level: 2-4 In November 2025, the CAA accredited ZeroAvia with design organisation approval (DOA), a critical milestone to certifying a hydrogen electric engine intended for Part 23 aircraft.[3]
Policy environment	Strong	The roadmap supports alignment with national policy targets including the Jet Zero Strategy[4] (net zero aviation by 2050) and national hydrogen strategies (E.g. UK Hydrogen Strategy and Jet Zero taskforce).
Infrastructure readiness	Initial exploration	Hydrogen storage and refuelling concept studies including at Cranfield University, Kemble, Exeter.

2.2.2 Technology readiness, certification readiness and aircraft classification framework

Below is interpreted using established TRL and Certification Readiness Level (CRL) frameworks (definitions provided in Glossary, ***Section 6.7***), together with explicit aircraft size and propulsion system classifications, to provide a consistent and transparent basis for assessing hydrogen aviation development across the roadmap.

[2] Regulating hydrogen use in aviation | UK Civil Aviation Authority
[3] ZeroAvia Receives Design Organisation Approval from UK CAA - ZeroAvia
[4] Jet Zero strategy: delivering net zero aviation by 2050 - GOV.UK

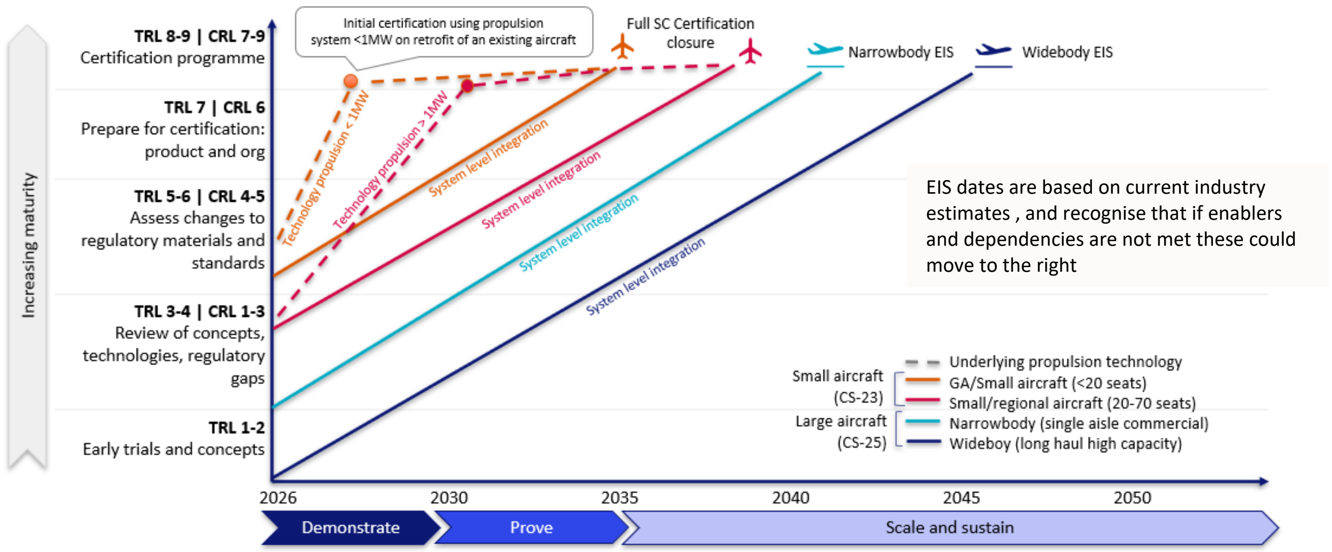

Figure 2: Illustrative simplified example of aircraft and technology classes in development to full certification and EIS

TRLs describe the maturity of individual technologies from early concept to operational use, while CRLs reflect the parallel progression of regulatory confidence, standards development, and certifiable product and organisational readiness. While related, technology maturity and certification readiness do not progress at the same pace, particularly for novel propulsion systems. Across development stages:

- Early phases (TRL 3-4 / CRL 1-3) focus on concept development, feasibility, and identification of regulatory gaps.
- Mid-stage development (TRL 5-6 / CRL 4-5) centres on component and subsystem validation, supported by increasing engagement with certification authorities.
- Later stages (TRL 7-9 / CRL 8-9) correspond to full-scale system demonstration, formal certification programmes, and EIS. Aircraft, propulsion system or products can only be considered 'certified' at CRL 8.

Development pathways are differentiated by aircraft class, reflecting increasing integration complexity, certification burden, and operational exposure as aircraft size increases:

- Underlying propulsion technologies such as hydrogen fuel cells are expected to develop earlier for smaller low-powered systems (<1MW) and on a longer timeline for higher powered systems (>1MW).
- General Aviation (GA) and small aircraft (<20 seats) provide the earliest opportunities for hydrogen systems demonstration and certification under CS-23.
- Small and regional aircraft (20-70 seats) follow with higher system-level and safety requirements, while enabling certification experience and regulatory material developed under CS-23 to be leveraged.
- Larger narrowbody and widebody aircraft developed under CS-25 face longer timelines due to full large aircraft certification, alignment with airline operational integration and supporting infrastructure dependencies. Later EIS for larger aircraft therefore reflect structural and regulatory factors rather than technology

performance alone.

Development pathways are also shaped by the hydrogen propulsion technology adopted. Hydrogen combustion, hydrogen fuel cells, liquid hydrogen, and hybrid systems involve distinct technical and certification challenges. Further, not all propulsion technologies are likely to be suitable for all aircraft classes, reinforcing the need for differentiated pathways.[5]

Certification for hydrogen aircraft does not progress as a single linear pathway. Early GA and small commercial aircraft can achieve certification through scoped SCs and operational limitations, while larger and more complex aircraft require progressively broader integration of hydrogen considerations across airworthiness, operations, aerodromes and regulatory oversight frameworks. Certification closure therefore occurs by aircraft class, as sufficient evidence, regulatory material and system-wide readiness accumulate.

A central distinction in the roadmap is between technology-level maturity and integrated propulsion system readiness. While hydrogen-related technologies, such as fuel cells, electric machines, gas turbines or storage systems, may achieve relatively high TRLs in isolation, integrated hydrogen propulsion systems mature more slowly due to system integration, safety validation and full-envelope certification requirements. This divergence increases with aircraft size and the associated propulsion technology and underpins the roadmap's sequenced approach, with smaller aircraft acting as lead platforms and larger commercial aircraft progressing over longer timescales from demonstration, through proof, to scaled and sustained operation.

2.2.3 International coordination

Hydrogen aviation involves cross-border design, operations, and supply chains, so international engagement supports safety, interoperability and efficiency. The UK's baseline obligation is compatibility with ICAO commitments and standards. The roadmap therefore supports ICAO-aligned outcomes and enables harmonisation where it is in the UK's interest to do so, recognising that different authorities may set different requirements within a broader safety continuum. Where relevant, the roadmap considers emerging definitions, classifications, certification specifications and regulatory approaches developed by other authorities, including the European Union Aviation Safety Agency (EASA) and the Federal Aviation Authority (FAA), to support interoperability and avoid unnecessary divergence. This approach aligns with recommendations by the Jet Zero Taskforce on coordinated international action to reduce regulatory fragmentation and support scalable zero-emission flight.[6]

[5] https://www.ati.org.uk/wp-content/uploads/2025/09/ATI-Tech-Strategy-2022-Destination-Zero.pdf
[6] Jet Zero Taskforce Hydrogen Task and Finish Group Report

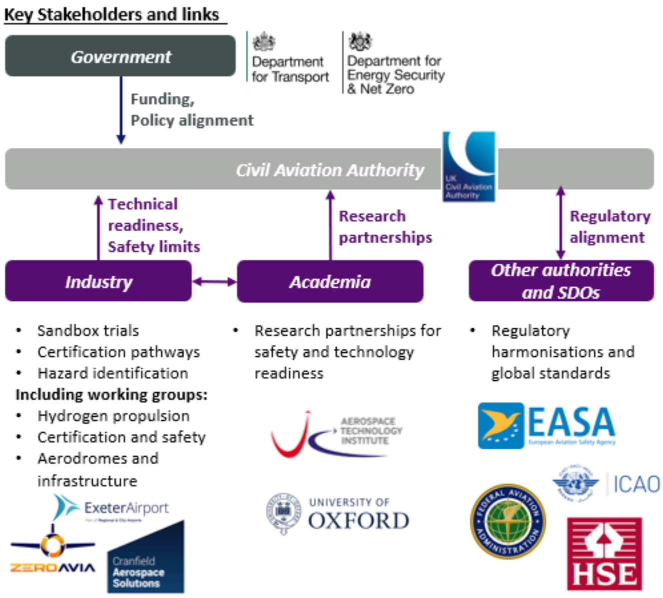

Figure 3: Key interdependencies and stakeholder map

2.3 Regulatory Roadmap approach

The regulatory roadmap adopts a domain-wide approach focused on sequencing, dependency management and critical-path identification, rather than prescribing outcomes or committing to specific deployment decisions. In practice, the roadmap:

- Sequences system readiness from early GH_2 ground operations through to LH_2-enabled commercial networks, recognising long lead times for infrastructure, certification, training and safety case development.
- Identifies critical path enablers that must be delivered ahead of aircraft EIS such as evidence from trials, fuel quality interfaces, safety zone principles, refuelling requirements and competence frameworks.
- Provides regulatory clarity for industry planning, including the progression from sandbox activity to formal guidance, SC and Means of Compliance (MoC).
- Allows coordinated scaling by aligning aircraft development timelines with aerodrome investment cycles, hydrogen production pathways and national planning processes.
- Supports early operational models (domestic routes, sub-regional networks, limited hubs) while paving the way for LH_2 hubs enabling narrowbody decarbonisation.

2.4 Scope and conceptual framework

System scope: Five-domain framework covering full aviation system required for safe integration of hydrogen operations into UK civil aviation systems (see ***Section 2.5*** for domains). Basic research and development activities and military applications are out of scope.

Time horizon: Extends to 2050, with near- to mid-term enabling actions structured across the three maturity-based roadmap periods Demonstrate, Prove Scale and sustain. Milestones are indicative and are intended to support sequencing and dependency management, recognising that timing depends on evidence, technology maturity, and delivery decisions by relevant parties.

Fuel pathway coverage: The CAA Hydrogen Challenge, and this roadmap, focus on hydrogen used as a direct aviation fuel, including hydrogen combustion and fuel-cell propulsion. It does not cover SAF produced via power-to-liquid pathways (using hydrogen), which are addressed through separate policy and regulatory frameworks. **Adaptability**: The roadmap is designed to be adaptive, with review points that allow priorities to be updated as evidence accumulates through trials, sandbox activity and early deployments. Scenario analysis and push/pull factors are included to stress-test sequencing and identify sensitivities that may influence the pace of adoption.

2.5 Segmentation

The roadmap is organised into five domain and corresponding subdomains that reflect the main parts of the aviation system that require regulatory readiness for hydrogen operations:

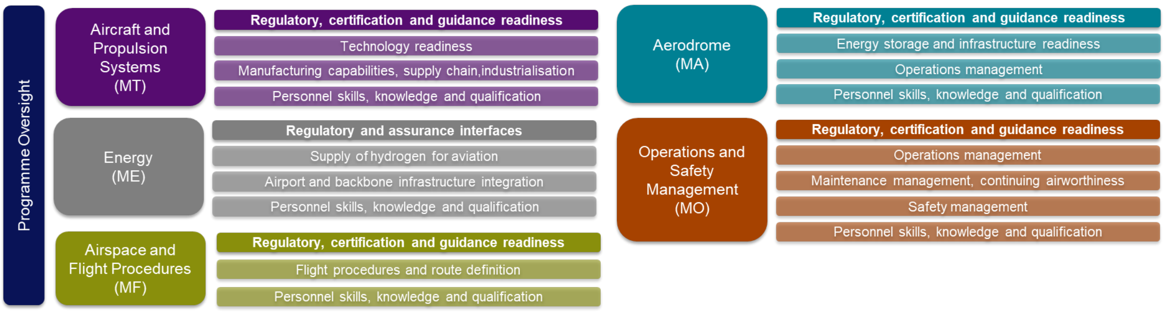

Figure 4: Domains and subdomains across the roadmap

- **Aircraft and Propulsion Systems:** Developing and certifying safe EIS for hydrogen-powered aircraft, from early experimental propulsion systems and technologies to larger commercial classes as evidence accumulates.
- **Energy (hydrogen fuel production and supply):** Aviation-grade hydrogen supply, fuel quality, and logistics readiness for GH_2 and liquid hydrogen LH_2 aligned to aviation operational needs.
- **Aerodromes:** Hydrogen storage and refuelling capability, hazard management, emergency response, and integration into aerodrome safety management systems.
- **Operations and Safety Management:** Operational concepts, continuing airworthiness and maintenance readiness, competence frameworks, and safety assurance for hydrogen operations.
- **Airspace and Flight Procedures:** Flight planning, diversion/alternate considerations, publication and procedures to integrate hydrogen operations safely into UK airspace.

Because these domains are interdependent, the roadmap emphasises sequencing, dependencies and primary enablers across domains, rather than parallel, uncoordinated progress.

Evidence → Regulatory material → Investable design basis → Scalable implementation

Figure 5: Illustrative sequencing pattern across domains

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2.6 Governance and stakeholder engagement

The roadmap reflects input gathered through structured workshops, targeted working groups and a CAA-issued survey. This engagement captures constraints, opportunities and enabling actions across aircraft developers, aerodromes, fuel and logistics providers, operators, safety and emergency response and academia stakeholders, plus relevant regulatory counterparts to address cross regime safety and assurance interfaces. It grounds the roadmap in practical delivery considerations and evidence needs, rather than aspirational statements.

Effective delivery will require a clear programme structure, robust governance framework and adaptive management approach to ensure coordination and oversight across domains and workstreams. DfT is expected to lead the overarching governance, providing strategic direction and cross-domain alignment, while the CAA retains primary responsibility for domains where it holds statutory duties, including aircraft certification production and oversight and airworthiness. Recent DfT-supported expansion of the CAA's Hydrogen Challenge sandbox illustrates the intent to scale evidence-generating trials to inform proportionate regulatory development. The 2025 Jet Zero taskforce Hydrogen Task & Finish Group report[7] identifies CAA regulatory capability and capacity as a critical enabler for timely hydrogen aviation deployment, alongside effective cross-government and international coordination.

2.7 Assumptions

The roadmap assumes a stable and predictable regulatory environment, including continuity in the CAA's mandate, resourcing and cross government and industry support for hydrogen aviation. Progress fundamentally depends on continued industry commitment to developing hydrogen aircraft and associated systems. Most government activity is focused on enabling and supporting industry led programmes (for example through trials, demonstration and regulatory engagement) and therefore relies on sustained industry action and investment. This includes sustained policy alignment with Government, consistent regulatory direction, and ongoing international coordination.

It also assumes that technology maturity and certification readiness progress broadly in parallel, without implying linear or automatic progression. Regulatory development is assumed to be evidence led, relying on operational data gathered through early trials and demonstrations, with certification frameworks, guidance material and oversight approaches evolving iteratively as service experience builds.

Key assumptions relate to:

1. The availability and pace of evidence generation from trials and demonstrations
2. The maturity of aircraft and fuel system technologies
3. Aerodrome investment and consenting timelines
4. The availability and logistics of aviation-grade hydrogen
5. The development of proportionate regulation and guidance informed by evidence

These assumptions are stress-tested through scenario analysis and push/pull factors, as described in ***Section 4***.

[7] Jet Zero Taskforce Hydrogen Task and Finish Group Report

3 Roadmap

This section sets out the core roadmap across the five domains, with milestone codes appearing as:

- MT = Aircraft and Propulsion Systems
- ME = Energy
- MA = Aerodromes
- MO = Operations and Safety Management
- MF = Airspace and Flight Procedures

Each domain includes a 2050 end-state description, key dependencies, and the enabling activities that support safe progression through the three time periods.

3.1 Roadmap and key milestones

Table 2: High level roadmap overview

Phase	**Demonstrate** 2026-2030	**Prove** 2030-2035	**Scale, sustain** 2035 onwards
Regulatory purpose	**Evidence gathering and gap identification**	**Regulatory material development, repeatable**	**Trend towards routine oversight and steady state regulation**
Milestone representation	Early trials, demonstrations and assessments generate sufficient safety evidence to understand hydrogen-specific hazards and identify gaps in existing regulation, guidance and oversight frameworks. Outcomes support structured regulatory decision-making rather than ad-hoc safety cases.	Hydrogen-specific regulatory tools are developed, consulted and applied, including SC, MoC and updates to guidance. Early deployments demonstrate that these tools can be used repeatably across more than one project, organisation or site.	Hydrogen aviation is supported through mature, stable regulatory frameworks and routine oversight activity. Hydrogen hazards are embedded within normal certification, operational and safety management processes, with periodic review and ICAO-compatible international engagement.
Milestone codes (see annex ***Section 6*** for details)	• **MT: 01, 03, 04a, 04b, 10 ,14** • **ME: 01,05 ,09, 13** • **MA: 01, 07, 08, 14, 15, 20** • **MO: 01, 03, 07, 11, 13** • **MF: 01, 07**	• **MT: 02, 05, 06a, 06b, 11, 15** • **ME: 02, 06, 10, 14** • **MA: 02, 03, 04, 08, 09, 10, 16, 17, 21** • **MO: 02, 04, 08, 14** • **MF: 02, 03, 04, 05, 08**	• **MT: 07, 08, 09, 12, 13, 16** • **ME: 03, 04, 07, 08, 11, 15** • **MA: 05, 11, 12, 13, 18, 19, 22, 23** • **MO: 05, 06, 09, 10, 12, 15** • **MF: 06, 09**

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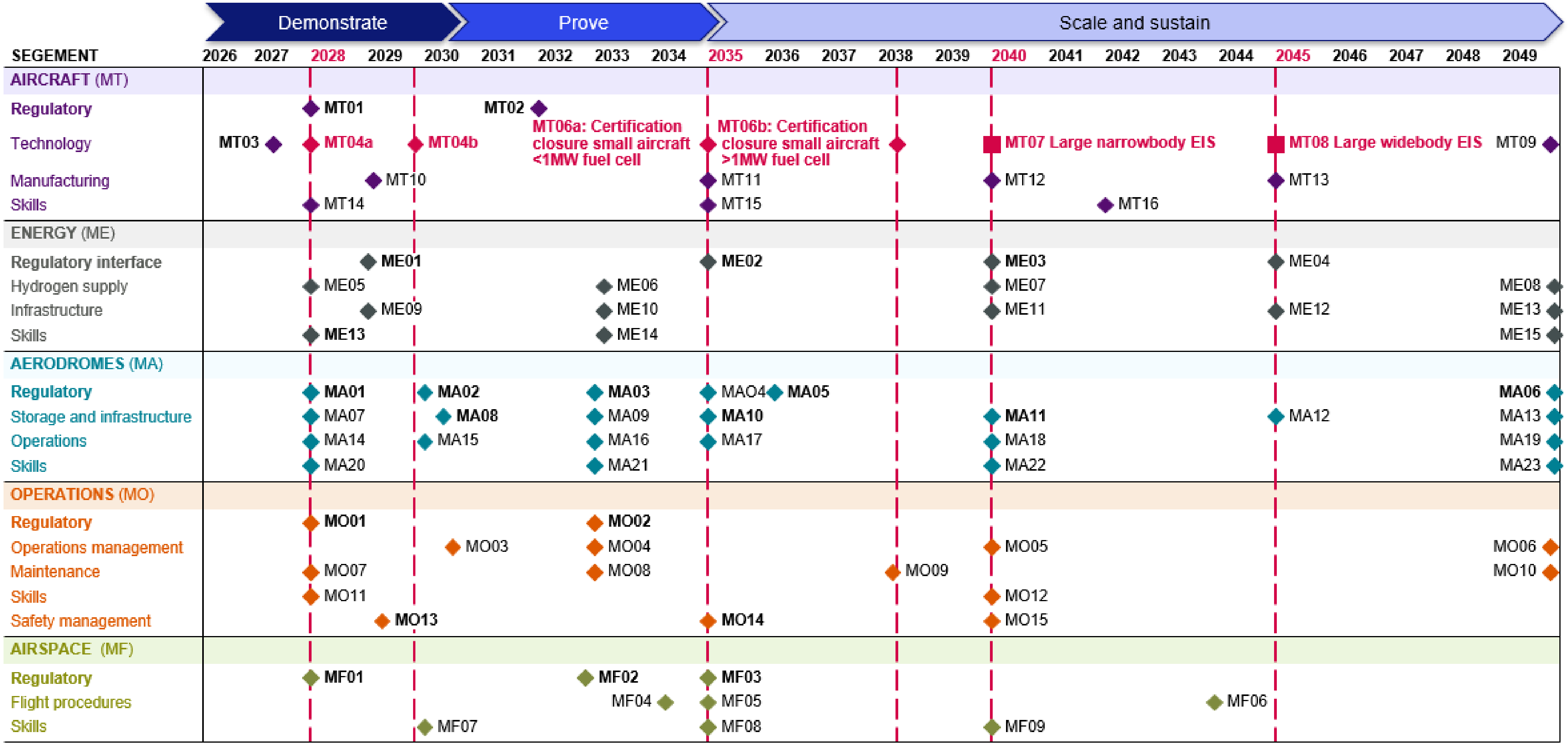

Figure 6: Detailed regulatory roadmap overview

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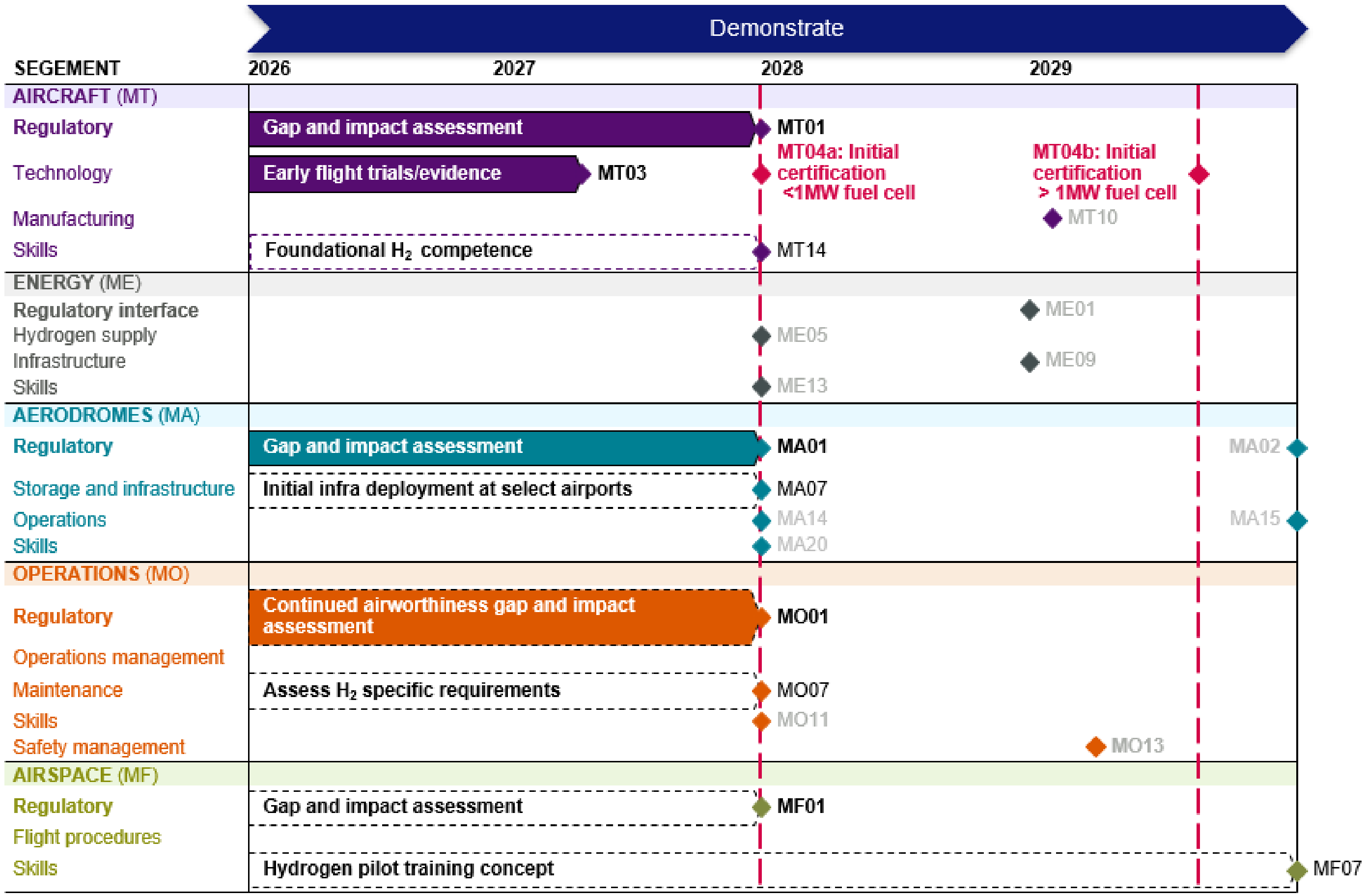

Primary dependency

Enabler

Critical path to MT04a/b: Initial certification of first small H_2 aircraft by 2028 with small and large propulsion system <1MW

Evidence -> Experimental certification

Primary Dependencies

Trial evidence: MT03 supports the main foundation for safety and performance validation.

Certification basis: **MT01, MA01**, **MO01**, ensuring that at least one aerodrome can support hydrogen flights with an acceptable safety case, defining acceptable criteria, and establishing credible maintenance under experimental certification.

Enablers (likely critical if missing)

MO07, MA07, MT14, preliminary MF07, and MF01, which facilitate conducting repeatable trials, ensuring safe operations, and supporting regulatory and industry competence necessary for approvals.

Other milestones in this phase

- ME01: GH_2 fuel quality and assurance interfaces defined
- ME13, MA20: Foundational hydrogen competence
- MT10: Prototype and low-rate production
- MA02: Safety zone and Refuelling frameworks defined
- MA14: Initial H_2 ConOps and QA framework
- MA15: Define provisional safety zones/refuelling protocols
- MO11: Identification of H_2 specific maintenance competencies
- MO13: Identification of H_2 specific Hazards

Figure 7: Demonstrate period key milestone and dependencies

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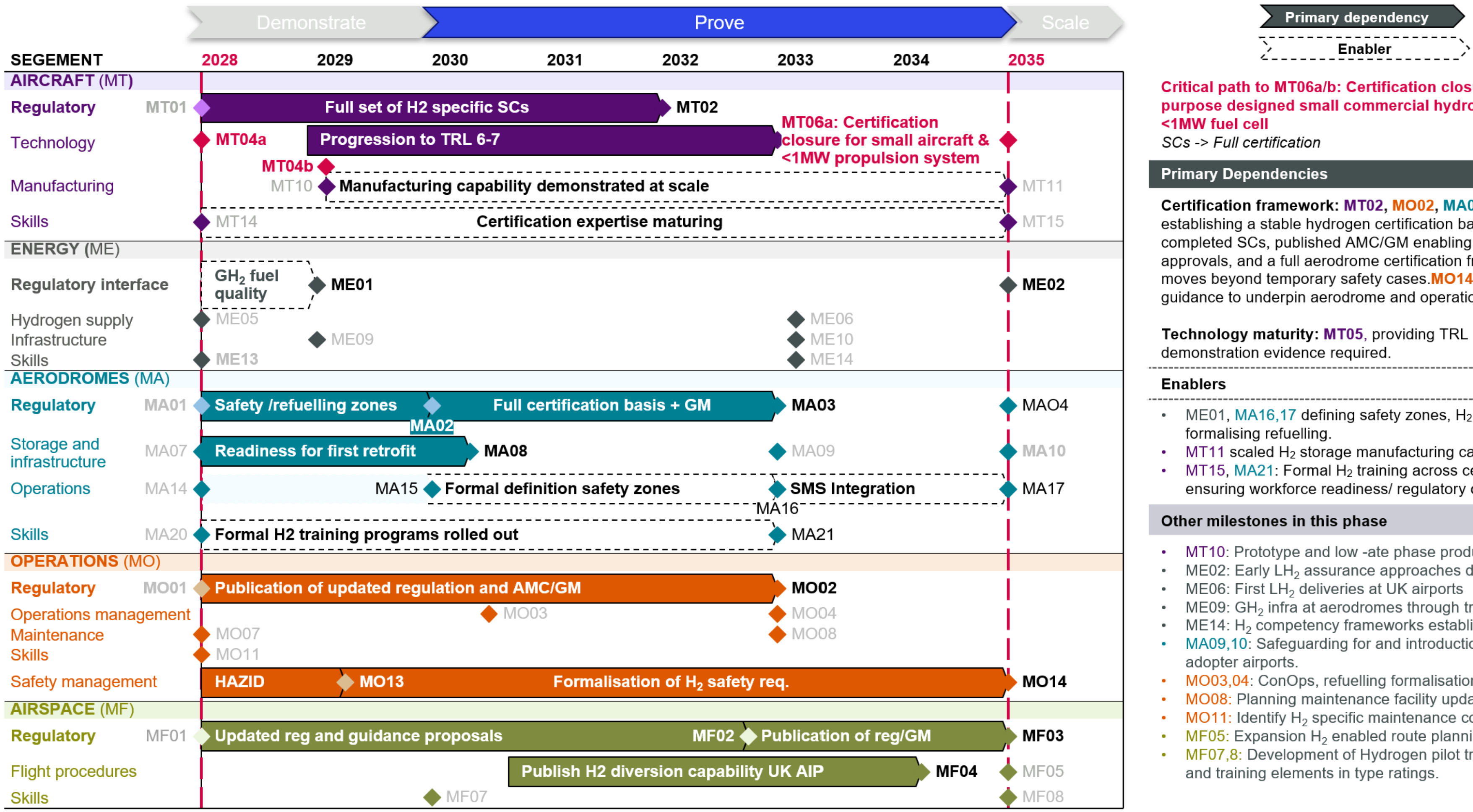

Critical path to MT06a/b: Certification closure for first purpose designed small commercial hydrogen aircraft and <1MW fuel cell

SCs -> Full certification

Primary Dependencies

Certification framework: MT02, MO02, MA03, MF03,04 establishing a stable hydrogen certification basis through completed SCs, published AMC/GM enabling repeatable approvals, and a full aerodrome certification framework that moves beyond temporary safety cases.**MO14:** coupling safety guidance to underpin aerodrome and operational approvals.

Technology maturity: MT05, providing TRL 6-7 system-level demonstration evidence required.

Enablers

- ME01, MA16,17 defining safety zones, H_2 quality and formalising refuelling.
- MT11 scaled H_2 storage manufacturing capability.
- MT15, MA21: Formal H_2 training across certification, ensuring workforce readiness/ regulatory confidence.

Other milestones in this phase

- MT10: Prototype and low -ate phase production
- ME02: Early LH_2 assurance approaches demonstrated
- ME06: First LH_2 deliveries at UK airports
- ME09: GH_2 infra at aerodromes through trials and safety ops
- ME14: H_2 competency frameworks established
- MA09,10: Safeguarding for and introduction of LH_2 at early adopter airports.
- MO03,04: ConOps, refuelling formalisation, safety guidelines
- MO08: Planning maintenance facility updates
- MO11: Identify H_2 specific maintenance competencies
- MF05: Expansion H_2 enabled route planning
- MF07,8: Development of Hydrogen pilot training competence and training elements in type ratings.

Figure 8: Prove period key milestones and dependencies

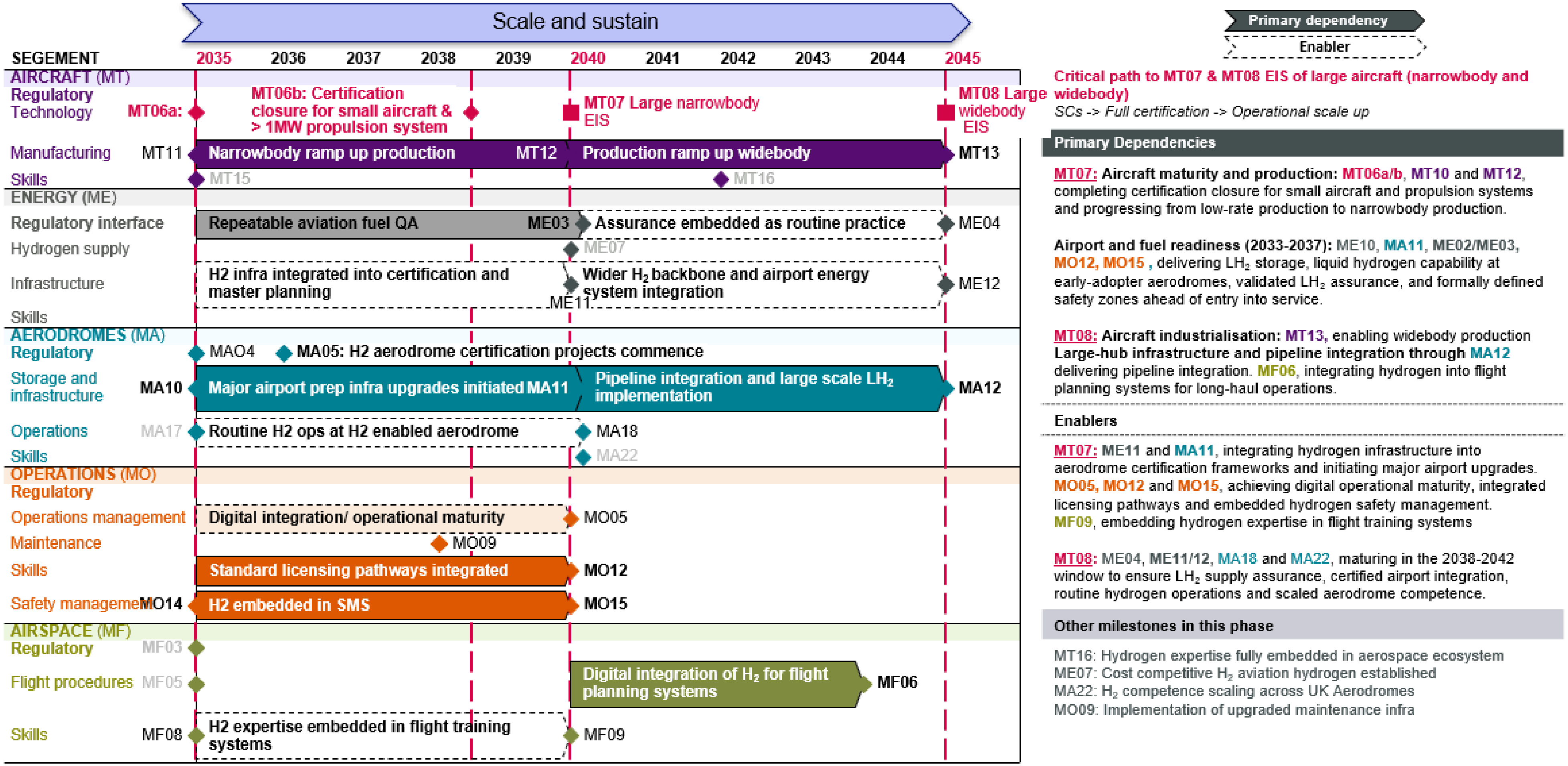

Figure 9: Scale and sustain period key milestones and dependencies

3.2 Detailed roadmap domains

This section summarises the five roadmap domains, outlining core activities for safe progression. Annex ***Section 6.1- 6.5*** contains further details and milestone code descriptions.

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3.2.1 Aircraft and Propulsion Systems

Aircraft and Propulsion Systems (MT)	**DEMONSTRATE** 2026-2030 **Establish evidence to regulation pipeline**	**PROVE** 2030-2035 **Formalise and apply repeatable certification material**	**SCALE AND SUSTAIN** 2035 onwards **Embed hydrogen into routine certification and oversight**
Regulatory, certification and guidance readiness	• Regulatory gap and impact assessments (EU 748/2012, EU 2015/640) • Certification basis planning for early hydrogen programmes • Trial-informed development of hydrogen-specific SCs • Applicability assessment of existing AMC/GM • Structured regulator-industry engagement to mature safety cases	• Consult and publish hydrogen-specific SCs for repeatable use • Introduce initial hydrogen MoC for priority safety topics • Publish AMC/GM updates reflecting hydrogen hazards • Mature organisational capability and oversight for hydrogen scope • International engagement supporting ICAO compatibility and harmonisation	• Routine use of hydrogen-specific SCs, MoC and AMC/GM • Hydrogen embedded in certification and oversight activities • Mature organisational capability across hydrogen scope • Ongoing international alignment and targeted harmonisation
Technology readiness	Fuel-cell systems <1MW TRL 4-5; hydrogen turbines TRL 2-4; ground and early flight trials	Fuel cell system >1MW TRL 4-5; system-level demonstrations progress technologies to TRL 6-7; first small/regional aircraft readiness	Full operational maturity (TRL 8-9); large narrowbody EIS and scaled deployment
Manufacturing, supply chain and industrialisation	Low-rate, prototype-led production; immature hydrogen supply chains	Transition to industrialisation; expanded production scope and resilient supply chains	Embedded hydrogen manufacturing with scalable, mature supply chains
Personnel skills, knowledge, qualification	Foundational hydrogen competence across industry and regulator	Mature hydrogen certification and design expertise	Hydrogen skills embedded in standard aerospace and regulatory frameworks
Key dependencies	Availability of trial and safety data, early demonstrator projects, regulator capacity, safety data available	Sufficient certification evidence, stable MoC and international coordination	Operational experience, stable safety performance and sustained regulatory resources

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3.2.2 Energy

Energy (ME)	**DEMONSTRATE** 2026-2030	**PROVE** 2030-2035	**SCALE AND SUSTAIN** 2035 onwards
	Define early aviation-grade interfaces using evidence	**Mature repeatable fuel QA and refuelling assurance for early adopters**	**Embed aviation hydrogen assurance as routine practice**
Regulatory, certification and guidance readiness	• Define early aviation hydrogen quality and assurance expectations for GH_2-based trials. • Use relevant standards as inputs to aviation assurance discussions (ISO 14687/ISO 19880) Translate trial learning into certification and operational safety material.	• Strengthen fuel quality assurance and contamination control aligned to aerodrome safety cases. • Extend assurance to LH_2, including cryogenic handling and refueling competence.	• Embed fuel QA, refuelling assurance and competence as routine practice at hydrogen-capable aerodromes. • Maintain ICAO compatibility and targeted international harmonisation where aligned with UK interests.
Supply of hydrogen for aviation	Road delivered GH_2. UK low production hydrogen remains limited, early ops supported by targeted procurement	Availability increases as national production sales. LH_2 capability develops in UK to support early cryogenic deliveries.	Integration more fully into mature logistics networks supporting more routine operations
Airport and backbone infrastructure integration	Early GH2 trials infra trials, safety cased based ops and early ConOps into airport planning cycles	Early LH2 at select aerodromes, publish hydrogen specific aerodrome guidance and MoC supporting repeatable storage, QA	Integrate hydrogen infra into Aerodrome certification frameworks and routine master planning
Personnel skills, knowledge, qualification	Early learning from other sectors developed among CAA inspectors, accessors and safety specialists	Competency frameworks mature for storage, handling, refuelling, safety cases, QA and contamination control	Competence embedded in standard regulatory and aerodrome training regimes Recertification for cryogenic handling.
Key dependencies	National hydrogen production logistics, evidence that supports stable refuelling and QA models	Aerodrome investment cycles, national hydrogen production volumes, liquefaction capability	Maturation of safety cases and operational data, both UK and international

UK Civil Aviation Authority

3.2.3 Aerodromes

Aerodromes (MA)	DEMONSTRATE 2026-2030	PROVE 2030-2035	SCALE AND SUSTAIN 2035 onwards
	Complete gap/impact assessments and trial-informed early guidance	**Publish and apply repeatable aerodrome hydrogen requirements**	**Embed hydrogen aerodrome frameworks into routine certification and oversight**
Regulatory, certification and guidance readiness	• Gap and impact assessments using Regulation EU 139/2014, ANO and CS-ADR-DSN • Assess impact and update needs across CAP 168/738/699/642/1168 • Address cross regime interfaces related to infrastructure and ops (DESAR/DSEA COMAH, ATEX, PSSR, COSHH) • Develop early guidance for safety zones, refueling and emergency response using early trials data	• Publish repeatable hydrogen aerodrome certification bases and GM/MoC covering hydrogen specific updates in CS-ADR-DSN • Formalise safety zones, hazardous area classification and fuel QA frameworks • Align guidance with ICAO material and emerging standards ICO Annex 14/19, ICAO documents 9157/9137/ 9774 • Progress standardisation activities for refuelling, defueling, e.g. as part of SAE AE5	• Publish repeatable hydrogen aerodrome certification bases and guidance • Formalise safety zones, hazardous area classification and fuel QA frameworks • Align guidance with ICAO material and emerging standards.
Energy storage	Deploy small-scale GH_2 storage to support early and retrofit aircraft, aligned to aerodrome planning and aircraft EIS timelines	Introduce LH_2 storage and early liquefaction capability at selected aerodromes, with safeguarding for large-scale energy upgrades	Deliver large-scale hydrogen storage, pipeline integration and energy system upgrades to support narrowbody and later widebody operations
Operations management	Establish early hydrogen ConOps, QA processes and provisional safety zones to support GH_2 ops at selected aerodromes	Formalise refuelling protocols, safety zones and QA processes, integrating hydrogen procedures into aerodrome SMS frameworks	Formalise refuelling protocols, safety zones, QA processes, integrating procedures into SMS frameworks
Personnel skills, knowledge, qualification	Build foundational hydrogen competence across CAA, aerodrome operators and RFFS through trials and early operations	Formalise hydrogen competency frameworks and expand training for refuelling, QA and emergency response	Embed competence into standard aerodrome training and qualification regimes with routine recurrent training
Key dependencies	Safety data availability, deployable technologies, international regulatory process	Operational evidence, stable refuelling models, international coordination	Operational experience, mature standards, sustained regulatory capacity

UK Civil Aviation Authority

3.2.4 Operations and Safety Management

Operations and Safety Management (MO)	**DEMONSTRATE** 2026-2030	**PROVE** 2030-2035	**SCALE AND SUSTAIN** 2035 onwards
	Complete gap/impact assessments for continuing airworthiness and operational material	**Publish and apply updated operational / continuing airworthiness material**	**Embed hydrogen operational assurance as routine practice**
Regulatory, certification and guidance readiness	• Reg (EU) 1321/2014, focusing on Annex I Part-M, Annex II Part-145, Annex III Part-66, Annex V Part-CAO), alongside AMC/GM • Assess CAP 700 for hydrogen related competence implications. Impacts on maintenance approvals, certifying privileges for hydrogen specific task facilities	• Publish and apply updated operational / continuing airworthiness material; • formalise refueling/coupling safety guidance and operational controls where needed	• Embed mature continuing airworthiness and operational oversight as routine practice, maintaining ICAO compatibility and targeted harmonisation
Operations management	Enable first GH_2 operations through leakage detection/mitigation, early venting procedures, coupling development, and preliminary safety distance concepts	Formalise coupling safety guidelines and harmonised refueling protocols; validate venting; safety distances mature influencing apron layout and automation	Embed leakage/venting/safety distance management in digital operational systems, with mature procedures supporting large aircraft operations through the 2040s
Maintenance management	Assess hydrogen-specific maintenance risks, tooling and equipment needs for propulsion, tanks and refueling interfaces	Plan facility upgrades (ventilation, detection/alarm systems) and develop cryogenic handling capability for LH_2	Implement upgraded maintenance infrastructure; standardise and embed hydrogen maintenance procedures
Safety management	Identify hydrogen hazards (fire/explosion, etc.), review RFFS procedures, and initiate capability upgrades (e.g. detection approaches and cryogenic PPE preparation where relevant	Expand hazard databases into defined requirements and SMS integration; standardise hydrogen emergency response and make drills/exercises routine	Fully embed hydrogen safety management and emergency response into daily operations and oversight
Personnel skills, knowledge, qualification	Identify hydrogen-specific maintenance competencies; build knowledge across CAA and industry; scope training modules and any certifying staff privilege implications	Expand training and begin formal hydrogen maintenance endorsements; training reflects new equipment, safety distances, venting and leakage procedures	Establish standard licensing pathways and recurrent training; hydrogen expertise becomes a routine part of aviation skill frameworks.
Key dependencies	First mover projects and experts; aerodrome infrastructure readiness, availably of safety data	Upgraded airport/maintenance facilities	Serviceable certified aircraft and market demand for scaled operations

UK Civil Aviation Authority

3.2.5 Airspace and Flight Procedures

Airspace and Flight Procedures (MA)	DEMONSTRATE 2026-2030	PROVE 2030-2035	SCALE AND SUSTAIN 2035 onwards
	Gap/impact assessments for flight operations material	**Develop and apply updated regulatory/guidance proposals**	**Embed hydrogen operations into routine operational oversight**
Regulatory, certification and guidance readiness	• Regulation (EU) 965/2012 and the Air Navigation Order, as referenced in the draft, focusing on diversion/alternate planning, operational limitations and any hydrogen-specific safety interfaces • Assess AMC/GM to Regulation (EU) 965/2012 and CAP 1074 (as referenced) to identify guidance updates needed for safe introduction and consistent operator practice	• Develop and apply proportionate regulatory and guidance updates aligned with operational evidence and aerodrome hydrogen capability without disproportional operational burden	• Embed updated regulatory and GM within routine operator oversight and operational practice where hydrogen operations occur • Maintain ICAO compatibility and foster harmonisation where aligned to UK safety and operational interests
Flight procedures and route definition	Identify and publish hydrogen-capable diversion aerodromes and develop early route planning concepts reflecting limited refueling availability	Formalise AIP publication of hydrogen diversion capability, including infrastructure and RFFS compatibility	Integrate hydrogen-specific route planning, alternates and fuel strategies into digital flight planning systems
Personnel, skills, knowledge qualification	Define pilot and aircrew hydrogen training concepts covering propulsion characteristics, risks and operational constraints	Introduce hydrogen training elements into type ratings and recurrent training, including diversion and limitation awareness.	Fully embed hydrogen knowledge into routine flight training, recurrent training and operational practice.
Key dependencies	Progress in aircraft certification and other regulatory streams for and aerodrome hydrogen readiness	The availability of serviceable aircrafts proven throughout extensive testing and certified	• Market demand for the use and scaled deployment of hydrogen-powered aircraft • Expansion of hydrogen-capable aerodrome infrastructure, including compatible refuelling systems and RFFS readiness

4 Factors influencing the roadmap

Section 4.1 addresses uncertainty in the pace and form of hydrogen aviation adoption, the roadmap uses three plausible scenarios, High Ambition, Central (baseline) and Low Ambition. These scenarios reflect different combinations of policy support, technological progress, infrastructure development and industry uptake, and provide a structured way to explore how adoption pathways and readiness requirements could vary over time.

Section 4.2 assesses key risks and opportunities, including the identification of “push” factors that could delay hydrogen adoption and “pull” factors that could accelerate progress, together with the stakeholders best placed to influence these drivers.

4.1 Scenario analysis: Adoption pathways

The three scenarios represent alternative adoption pathways for hydrogen aviation in the UK and are used to stress-test roadmap sequencing, identify critical sensitivities and inform periodic review. They are not forecasts, but structured narratives that support evidence-led planning under uncertainty.

Scenario design is grounded in the Jet Zero analytical assumptions[8] regarding the timing and scale of zero emission- flight. Hydrogen aviation is treated as a long-term enabling abatement lever, complementing SAF and efficiency improvements rather than acting as a sole route to net zero- aviation emissions by 2050.

The scenarios imply materially different adoption timelines and system coordination requirements. In the High Ambition scenario, small hydrogen aircraft enter service around 2030, compared with approximately 2035 in the Central scenario and 2040 in the Low Ambition scenario. Large narrowbody hydrogen aircraft follow in the late 2030s, around 2040, and post-2045, respectively. Infrastructure readiness evolves accordingly, with LH_2 capability established earlier in High Ambition, broadly aligned with aircraft entry into service in Central, and lagging materially in Low Ambition.

These differences reinforce the importance of early evidence generation, repeatable regulatory material and investable aerodrome design bases during the Demonstrate (2026-2030) and Prove (2030-2035) phases, to avoid mis-sequencing aircraft development, infrastructure investment and regulatory readiness.

A summary table compares the scenarios across aircraft EIS timing, infrastructure readiness, regulatory and certification progress, market acceptance and emissions impacts.

[8] Jet Zero illustrative scenarios and sensitivities

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Table 3: Scenario analysis[9]

Scenario	EIS timing	Infrastructure readiness	Regulatory progress	Certification and airworthiness	Aerodrome regulation and infrastructure	Operational and airspace regulation	Public / industry acceptance	Hydrogen CO_2 savings (2050)	Cumulative impact (avoided carbon cost 2025-2050)
High Ambition	Small aircraft by ~2030; large narrowbody by late 2030s	Ahead of demand; LH_2 infra by mid-2030s	Proactive; standards in place by early 2030s	MoC finalised by 2030; type certification by 2032-2035	Hydrogen-specific updates to CAPs by 2030; early LH_2 infra standards	Hydrogen-capable aerodromes in AIP by 2032; updated ANO and EU 965/2012 by 2035	Strong support; early orders	3.8 $MtCO_2$	£5.4bn
Central (Baseline)	Small aircraft by ~2035; large narrowbody by ~2040	On time with aircraft EIS	Steady progress; aligned with Jet Zero	Certification frameworks mature by 2035; MoC or AMC/GM aligned with development	Regulatory updates phased with infra rollout; LH_2 standards by 2035-2040	Flight planning and diversion updates by 2035-2040; hydrogen in type ratings	Moderate support	2.8 $MtCO_2$	£3.5bn
Low Ambition	Small aircraft by ~2040; large narrowbody post-2045	Lagging; limited airport readiness	Delayed; fragmented standards	Certification basis not finalised until late 2030s or 2040s	Limited updates; hydrogen infrastructure treated as exceptional	Minimal updates; hydrogen not integrated until post-2045	Low confidence	2.2 $MtCO_2$	£2.9bn

[9] Detailed analysis and assumptions found in the annex – ***Section 6.6***

Across all scenarios, hydrogen aviation delivers a modest but material contribution to in-sector emissions abatement by 2050, consistent with UK policy evidence and analytical assumptions.

In the Central scenario, emissions abatement of around 2.8 $MtCO_2$ in 2050 is of a similar order of magnitude to the ~2 $MtCO_2$ contribution from zero-emission flight cited in the Jet Zero analytical annex, which treats hydrogen aircraft as a complementary, late-scaling abatement lever rather than a dominant mitigation route.

While annual emissions impacts in 2050 are relatively limited, the cumulative contribution of hydrogen aviation over time is more significant. Avoided carbon costs in 2050 are estimated at approximately £0.5-0.7 bn per year, while cumulative avoided carbon costs over 2025–2050 are in the range of £3-5 bn across scenarios, reflecting hydrogen's role as a long-duration transition option rather than a near-term cost-optimisation measure.

Consistent with Jet Zero and Climate Change Committee (CCC) pathways, total in-sector aviation emissions do not fall to zero by 2050 in any scenario. Residual emissions are assumed to be balanced through greenhouse gas removals elsewhere in the economy, reinforcing the need to coordinate hydrogen aviation deployment with SAF scale-up, efficiency improvements and wider net-zero system planning.

These scenarios are not static and should be revisited through periodic roadmap review to ensure that sequencing, regulatory priorities and investment signals remain aligned with observed progress, emerging constraints and evolving evidence, including future updates from the CCC, DfT and international initiatives such as the Alliance for Zero Emission Aviation (AZEA) and the International Air Transport Association (IATA).

4.2 Risks and opportunities

Several external factors may delay or accelerate the safe introduction and or scaling of hydrogen aviation in the UK. This section summarises those factors as:

- **Pull factors:** conditions that can enable or accelerate readiness and deployment
- **Push factors**: conditions that could hinder progress or introduce delay/complexity

A structured PESTLE method is used to group factors across Political, Economic, Social, Technological, Legal and Environmental domains. PESTLE is the organising tool; the focus here is on the practical risks and opportunities that influence timing, sequencing, safety assurance and investment decisions. Tables 4 and 5 provide a concise summary of pull and push factors, with responsible stakeholders indicated. The subsections that follow provide further explanation of how these factors could affect hydrogen aviation readiness.

Table 4: PESTLE Pull factors

Category	Pull Factor	Impact on Hydrogen Aviation Entry into Service	Key Responsible Parties and Stakeholders
Political	Government commitment, climate targets, elevated geopolitical risk	Strong policy support and clear targets accelerate development.	UK Government European Commission, ICAO

Economic	Public/private investment; carbon pricing; jet fuel price shocks	Investment in research and development (R&D), infrastructure, and fuel production enables earlier deployment.	UK Government, investors, ATI, airlines, OEMs
Social	Public demand for greener travel	Positive sentiment and early adoption by airlines build market confidence.	Airlines, NGOs, media, CAA
Technology	R&D breakthroughs; successful demonstrations	Accelerates certification and commercial readiness of hydrogen aircraft.	ATI, OEMs, academia, CAA
Legal	Proactive certification and sandboxing	Early regulatory clarity supports safe and timely EIS.	CAA, EASA, ICAO, SAE, EUROCAE, UK Government
Environmental	Net-zero targets; climate urgency	Strengthens the case for hydrogen as a long-term decarbonisation solution.	CCC, UK Government, ICAO

Table 5: PESTLE Push factors

PESTLE Category	Push Factor	Impact on Hydrogen Aviation Entry into Service	Key Responsible Parties and Stakeholders
Political	Policy gaps and global competition	Lack of consistent policy or international alignment delays investment and rollout.	UK Government
Economic	High upfront costs; uncertain ROI	Limits private sector investment and slows infrastructure and aircraft development.	Airlines, OEMs, investors, UK Government
Social	Safety concerns; low public awareness	Public hesitation may delay acceptance and certification of new technologies.	CAA, HSE, airlines, media, NGOs
Technology	Fuel cell and storage challenges	Technical hurdles in propulsion and infrastructure delay certification and rollout.	OEMs, ATI, academia
Legal	Slow rulemaking; fragmented standards	Regulatory uncertainty hinders planning and cross-border operations.	CAA, HSE, EASA, ICAO, Government
Environmental	Green hydrogen supply constraints	Limited availability of low-carbon hydrogen restricts early deployment.	Hydrogen producers, CCC, Government

4.2.1 Political

Pull factors

Strong policy support and clear targets accelerate development. The Jet Zero Strategy, published in 2022, set a target of net zero UK aviation by 2050.[10] Such political will, backed by cross-departmental initiatives (e.g. Jet Zero Taskforce , the UK Hydrogen Strategy[11], and the Modern Industrial Strategy that commits to fund the ATI programme to 2035.[12]), provides funding, direction, and confidence to industry, pulling forward the timeline for hydrogen aircraft. Internationally, frameworks like the EU's Green Deal/Clean Aviation Joint Undertaking[13] and ICAO's 2050 net-zero pledge[14] create additional momentum and coordination for zero-carbon aviation, reinforcing UK efforts.

Geopolitical risk. The escalation of the US-Israel conflict with Iran has highlighted the aviation sector's exposure to geopolitical risk, with disruption to Middle Eastern supply routes underlining the importance of jet fuel security. Continued reliance on oil-derived jet fuel leaves airlines and governments vulnerable to price spikes and physical supply risks during times of conflict. While near-term responses focus on supply diversification and demand management, repeated shocks strengthen the long-term case for reducing structural dependence on fossil fuels. In this context, hydrogen aviation offers not only a decarbonisation pathway but an energy-security benefit, acting as a pull factor for accelerated investment over the long term.

Key players: DfT; Department of Energy Security and Net Zero (DESNZ); Jet Zero Taskforce; UK government (climate legislation); European Commission (Fit for 55, Clean Aviation Joint Undertaking); ICAO's long-term global aspirational goal (LTAG) for international aviation of net-zero carbon emissions by 2050.

Push factors

Insufficient or inconsistent policy support can delay progress. A lack of a detailed long-term industrial strategy for hydrogen aviation or wavering political priorities could slow private investment. The UK risks falling behind if it doesn't keep pace with other governments' initiatives.

Policy or funding uncertainty (e.g. due to changing governments or economic pressures) creates business risk that can defer industry timelines. UK policymakers are more likely to maintain support beyond 2035 if the industry continues to bring forward hydrogen aviation projects and maturing the technology. The Government is less likely to force the technology.

Key players: HMT and Cabinet Office, for sustained funding and policy continuity; DfT and DESNZ (to develop consistent long-term policy, avoid focus shifting solely to other solutions); International governments and regulators (e.g. EU and US setting competitive benchmarks); Global bodies and forums (ICAO, IATA, G7, G20 shaping clean aviation commitments).

[10] https://www.gov.uk/government/news/skys-the-limit-as-uk-sets-out-strategy-to-reach-net-zero-aviation-and-deliver-guilt-free-flying
[11] https://www.gov.uk/government/collections/uk-hydrogen-strategy
[12] https://www.gov.uk/government/collections/the-uks-modern-industrial-strategy-2025
[13] https://www.clean-aviation.eu/about-us/who-we-are
[14] https://www.icao.int/environmental-protection/LTAG

4.2.2 Economic

Pull factors

Investment and market opportunity Public/private investment and economic opportunity accelerate timelines. The promise of new markets and jobs from hydrogen aviation is driving significant funding. The UK has committed large R&D investments – e.g. the Aerospace Technology Institute (ATI) programme will provide £685 million (with industry match funding) from 2022-2025 and an additional £975 million to 2030 to develop zero-emission aircraft technology.[15] Major aviation players (Airbus, Rolls-Royce, Boeing), fuel cell manufacturer Intelligent Energy and startups, like ZeroAvia, are also investing in hydrogen propulsion research.[16]

These investments are spurred by forecasts of economic gains: the UK government and industry studies project tens of thousands of new jobs by 2050 and substantial GDP growth if the UK leads in hydrogen aircraft manufacturing and supply chains.[17] Expected long-term savings from avoiding carbon costs (with carbon pricing rising via UK ETS and CORSIA) and first-mover export advantages further incentivise airlines and manufacturers to pursue hydrogen planes sooner rather than later.

Price shocks. The US-Israel conflict with Iran highlights the aviation sector's reliance on geopolitically sensitive jet fuel supply chains. Rising fuel costs increase operating risk for governments and airlines and feed through to higher fares and reduced connectivity. Repeated shocks strengthen the economic case for hydrogen aviation as a long-term hedge against fossil fuel price and supply volatility, despite high upfront investment costs.

Key players: UK government (HM Treasury funding, ATI grants; UK Research and Innovation (UKRI)); Private investors and aerospace industry (Airbus ZEROe program, Rolls-Royce, easyJet and other airlines partnering on hydrogen R&D); Energy companies (for H_2 production investment); EU Clean Aviation Joint Undertaking and Hydrogen Europe (R&D funding in EU); IATA and airlines (anticipating future operating cost benefits and carbon cost savings).

Push factors

High costs and uncertain ROI High upfront costs and unclear near-term returns can deter or delay deployment. Developing hydrogen-powered aircraft and the required new infrastructure (fuel production, liquefaction, storage and airport refuelling facilities) will require extensive investment across the aviation system, posing a financial challenge. Aircraft manufacturers face expensive design overhauls (new airframes, engines, and systems) without guarantee of immediate airline orders. Airlines operate on thin margins and may be reluctant to invest in unproven hydrogen aircraft or retrofit airports for hydrogen without strong business cases or subsidies. In the absence of robust government incentives (e.g. purchase guarantees, fuel price support) or regulations mandating zero-emission aircraft, the risk-adjusted return on investment remains uncertain, causing industry to hesitate. Cheaper or nearer-term alternatives can also

[15] https://www.ati.org.uk/news-events/news/a-new-5-year-funding-settlement-for-the-aerospace-technology-institute/
[16] https://www.intelligent-energy.com/news/hydrogen-lift-off-intelligent-energy-secures-17m-to-power-zero-emission-flight/
[17] https://www.ati.org.uk/wp-content/uploads/2022/04/ATI-Tech-Strategy-2022-Destination-Zero.pdf

divert funds, for example, airlines currently meet emissions goals via SAF blending (with the 10% SAF mandate by 2030 in the UK), which uses existing aircraft. If hydrogen's costs don't fall, or if policy doesn't bridge the gap, commercial scale up could be pushed back until the late 2030s or beyond.

Key players: Aircraft manufacturers and engine makers (weighing R&D and capital costs); Airlines and leasing companies (responsible for fleet purchase decisions and airport investments); UK government (e.g. DfT/Transport funding for H_2 infrastructure, incentives like contracts-for-difference for green fuels); Technology and innovation hubs (ATI, UKRI); International policymakers (e.g. EU's ReFuelEU mandates, carbon pricing) shaping the market economics.

4.2.3 Social

Pull factors

Public demand for green aviation Societal and consumer pressure for sustainable travel is an accelerator. The flying public and broader society are increasingly concerned about aviation's climate impact, creating demand for "guilt-free" air travel. Surveys indicate strong willingness to embrace new technology: for instance, 81% of UK consumers believe hydrogen is the best option to decarbonise aviation, and 71% say they are "excited to fly on a hydrogen plane" when available.[18] This positive public sentiment acts as a pull factor, encouraging airlines and manufacturers to invest in hydrogen aircraft as a future market differentiator. It also helps build political will as policymakers get backing from environmentally conscious voters and NGOs (e.g. climate advocacy groups) to set ambitious targets and funding for zero-emission flight. In short, social license and consumer interest in clean aviation smooth the path for hydrogen planes by ensuring there will be acceptance and demand once they are certified.

Key players: Air travellers (consumers) and corporate travel buyers (demanding low-carbon options); Environmental NGOs, industry groups (e.g. Sustainable Aviation) and public opinion leaders (e.g. Extinction Rebellion) raising awareness; Airlines' marketing and sustainability teams (responding to "flight shame" and offering greener alternatives); Government and regulators (influenced by public climate concerns to act on aviation emissions).

Push factors

Safety perceptions and awareness gap Concerns and unfamiliarity could slow adoption if not addressed. Hydrogen fuel evokes safety anxieties for some, partly due to historical events (e.g. the Hindenburg) and a general lack of public knowledge about modern hydrogen technology. Studies show that awareness of hydrogen in the UK population remains low, and many people have "incomplete understanding" – leading to concerns around using hydrogen as aircraft fuel, perceived explosion risks, and overall safety. Such fears or misconceptions might make passengers hesitant to fly in hydrogen-powered aircraft initially, putting pressure on airlines and regulators to prove the technology's safety. Extensive testing, transparent communication, and successful demo flights will be required to build public trust. If high-profile safety certifications or early commercial trials were delayed by mishaps or poor communication, public opposition could push the first

[18] https://www.airbus.com/en/newsroom/press-releases/2023-09-uk-hydrogen-alliance-established-to-accelerate-zero-carbon-aviation

hydrogen airliners further into the future.

Key players: National Aviation Authorities (CAA, EASA, FAA: ensuring rigorous safety standards to reassure the public); the Health and Safety Executive (HSE); Aircraft manufacturers and airlines (responsible for public demonstrations, education, and incident prevention); Media and industry communicators (shaping public perception); Passenger advocacy groups and local communities (who must accept hydrogen infrastructure at airports).

4.2.4 Technology

Pull factors

R&D progress and early demonstrations Rapid technological advancements are bringing hydrogen flight closer. The past few years have seen breakthroughs that strongly indicate feasibility: Rolls-Royce in 2022 successfully ground-tested a modern jet engine running on hydrogen.[19] Meanwhile, smaller innovators have achieved real milestones – e.g. ZeroAvia have flown hydrogen fuel-cell aircraft demonstrators (up to 19-seaters)[20] and are working toward certifying their first commercial hydrogen-electric commuter planes within a few years. These cutting-edge projects, supported by initiatives like the ATI's FlyZero study and international collaboration, act as a pull factor by proving the concept and solving technical puzzles (e.g. high-power fuel cells, cryogenic tanks) one by one. Early successes also attract further investment and talent into the field. In summary, strong momentum in aerospace R&D and successful flight demos accelerate the timeline for hydrogen aircraft entering UK service, likely first on short regional routes by the early 2030s.

Key players: Aerospace manufacturers (Airbus, Boeing: setting tech goals and prototypes); Aviation innovators (Rolls-Royce, GKN Aerospace, ZeroAvia: developing engines, fuel cells, tank systems); Research institutions (ATI, universities like Cranfield); Government-funded R&D programs (ATI, EU Clean Aviation partnership) enabling technology breakthroughs.

Push factors

Technical hurdles and timeline risk Significant engineering challenges could delay readiness. Hydrogen propulsion for airliners is still in prototype phase, and several critical issues remain unresolved: Hydrogen has a low energy density by volume, requiring large, cryogenic fuel tanks that add weight and require more aircraft space. Developing fuel cells or combustors that can deliver enough power for medium/long-haul aircraft is complex, as is optimizing aerodynamics for novel designs (e.g. potential blended-wing bodies). These hurdles have already forced timetable adjustments, for example, Airbus recently narrowed its hydrogen concept to a fuel-cell single-aisle and indicated its initial 2035 service date may slip to the "late 2030s" due to technology maturation delays.[21]

Furthermore, scaling up hydrogen production and airport refuelling infrastructure (liquefaction plants, fuel trucks, on-site storage) is a significant undertaking concurrent with aircraft development. If any of these technology or infrastructure pieces progress

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[19] https://www.rolls-royce.com/media/press-releases/2022/28-11-2022-rr-and-easyjet-set-new-aviation-world-first-with-successful-hydrogen-engine-run
[20] https://zeroavia.com/do228-first-flight/
[21] https://www.ft.com/content/12490140-dd6d-4191-9495-a0dadb68874c

slower than expected or if companies encounter unforeseen technical snags (e.g. materials issues, reliability problems, insufficient test data) the certification and service entry of hydrogen aircraft will be pushed back.

Key players: Aircraft manufacturers and engine developers (Airbus, Boeing, CFM International, Rolls-Royce: solving design and engineering issues); Energy and fuel companies (developing high-volume green hydrogen production, transport and storage technologies); Airport operators and aerospace suppliers (building refuelling infrastructure, new ground equipment); Government research agencies (ensuring testing facilities and engineering research support, e.g. UK Defence Science and Technology Laboratory, NASA and ESA for aeronautics R&D).

4.2.5 Legal

Pull factors

Proactive regulation and standards Adaptive regulators can speed up entry by smoothing the path to certification. The novel challenges of hydrogen fuel require new safety standards, certification rules, and infrastructure regulations – and UK and international authorities are already moving on this. The CAA has launched a “Hydrogen Challenge” regulatory sandbox in collaboration with industry (including projects with ZeroAvia and a major airport) to identify safety risks and update regulations for hydrogen-fuelled aircraft and airport operations. In December 2024, EASA (with FAA and CAA participation) held its first international workshop on hydrogen aircraft certification, aiming for a harmonised global approach to approving H_2-powered planes. Early regulator involvement and coordination ensure that by the time manufacturers are ready to launch a hydrogen airliner, the necessary rules (airworthiness standards, refuelling safety codes, maintenance and training requirements) will be in place. This supportive legal environment is a key pull factor – reducing uncertainty and preventing certification bottlenecks, thus keeping the 2030s timeline achievable.

Key players: CAA (updating national aviation regulations, staffing hydrogen expertise); EASA and FAA (developing international certification standards jointly); UK government (DfT and CAA, ensuring regulators have resources and mandates to innovate); International bodies (ICAO, standard-setting organizations like SAE and EUROCAE for fuel and components standards).

Push factors

Certification and regulatory delays Gaps in the regulatory framework can postpone service entry. Hydrogen aviation involves many regulatory firsts – new fuelling methods, new types of powerplants, new safety considerations – but the governing rules and certifications are still in development. Regulators will need to develop and adapt frameworks in sync with aircraft manufacturers and engine developers, even a ready-to-fly hydrogen airliner cannot enter commercial service without approval. As of 2025, there is no comprehensive regulatory framework yet for hydrogen use in aviation: for example, standards for crash safety of H_2 tanks, protocols for liquid hydrogen refuelling or defueling, and airport hydrogen storage regulations are all in progress. Any delay in resolving these will directly delay aircraft certification. Likewise, lack of international regulatory alignment could hamper global operations (e.g. a plane approved in the UK might face hurdles flying to jurisdictions without hydrogen standards). In short, if the regulatory groundwork lags technological progress, it will act as a drag, a push factor, on the timeline for hydrogen aircraft introduction.

Key players: National Aviation Authorities (CAA, EASA, FAA: responsible for aircraft certification and operational rules); Standards bodies (ISO, SAE, etc., developing technical standards for hydrogen handling and materials); Government safety regulators (HSE for fuel storage and transport rules); Policymakers (ensuring timely updates to aviation and environmental laws to accommodate H_2).

4.2.6 Environment

Pull factors

Climate change imperative and emissions targets Climate policy demands are a prime mover accelerating hydrogen flight. Aviation's large carbon footprint has put it in the spotlight of climate action. The UK's framework for achieving net-zero greenhouse emissions by 2050 is legally binding, now explicitly including international aviation emissions in its Carbon Budgets.[22] This and the global aviation goal (agreed through ICAO in 2022 to reach net-zero carbon by 2050) create intense pressure on industry to find truly zero-emission solutions for air travel.[23] Hydrogen fuel (when produced from renewables) can eliminate in-flight CO_2 emissions entirely, a clear advantage over today's fossil jet fuel. Thus, to hit long-term climate targets and the UK's interim milestones (like cutting aviation emissions in half by 2035), government and industry are strongly motivated to bring hydrogen aircraft into service as soon as they are viable. Environmental urgency justifies public spending on hydrogen R&D and pushes airlines to support demonstration projects, acting as a critical pull factor.

Key players: UK government and parliament (enforcing Climate Change Act targets, Carbon Budgets that include aviation); International bodies (ICAO: CORSIA scheme, long-term goal; UNFCCC/Paris Agreement influencing national policies); Environmental NGOs and scientific bodies (e.g. CCC advising UK on aviation emissions pathways); General public and consumers (choosing low-carbon travel as part of climate action).

Push factors

Sustainability and climatic uncertainties Environmental challenges could temper hydrogen's rollout if not addressed. First, to deliver true climate benefits, hydrogen fuel must be produced sustainably (green hydrogen via renewable electricity). The UK's plan for 10 GW of low-carbon hydrogen by 2030 includes 5 GW of "blue" hydrogen (from natural gas with carbon capture).[24] If green hydrogen production and renewable energy expansion lag aviation's needs, early hydrogen aircraft might rely on carbon-intensive hydrogen – undermining their climate value and potentially failing to meet future sustainability criteria. This could reduce political and public support, stalling adoption. Second, non-CO_2 emission effects from hydrogen-fuelled flight are not yet fully understood. Hydrogen combustion produces water vapor which can form contrails, and high-temperature combustion can generate some NO_x; the climate impacts of these remain uncertain. Ongoing research (UK Jet Zero funding for non-CO_2 impacts, and projects like Germany's Blue Condor contrail study) is needed to ensure hydrogen aircraft

[22] https://www.theccc.org.uk/publication/the-seventh-carbon-budget/
[23] https://www.icao.int/environmental-protection/LTAG
[24] https://www.gov.uk/government/collections/uk-hydrogen-strategy

truly minimize global warming.[25] Should unexpected environmental drawbacks emerge (e.g. more persistent contrails), extra mitigation measures or redesigns might be required, potentially delaying EIS.

Key players: Energy sector and renewables industry (scaling up green hydrogen production, grid decarbonisation); DESNZ (overseeing hydrogen strategy and sustainability standards for H_2 fuel); Environmental regulators and researchers (studying contrail/NO_x impacts e.g. Natural Environment Research Council (NERC) and academic institutions under Jet Zero research programs); International climate bodies (ensuring life-cycle emissions accounting for alternative fuels, e.g. EU taxonomy, ICAO CAEP).

5 Conclusion

This roadmap sets out a coherent sequence for the safe integration of hydrogen into UK aviation across aircraft, energy, aerodromes, operations and airspace. It prioritises evidence-led safety assurance and dependency management so enabling activities progress coherently and bottlenecks are avoided. Through the three maturity-based time periods: Demonstrate (2026 - 2030), Prove (2030 - 2035), Scale and sustain (2035 onwards), the roadmap supports structured progress while recognising uncertainty and the need for periodic review. International engagement is framed around ICAO compatibility and targeted harmonisation where it serves UK interests.

5.1 Next steps

Following publication, the immediate focus is on mobilisation and delivery management, rather than binding implementation commitments. The priority is therefore to establish the conditions for effective delivery, including coordination, evidence capture and alignment across programmes and stakeholders. Sustained investment and programme continuity during the Demonstrate period are critical to maintaining momentum and translating early activity into enduring capability.

The actions below set out near-term priorities for coordination and sequencing, recognising that detailed delivery decisions remain the responsibility of relevant parties.

Key near-term priorities include:

1) **Establish governance:** Establishing and maintaining an appropriate governance and coordination structure that supports cross-domain alignment, dependency management and periodic review of the roadmap.
2) **Regulatory capability and capacity:** Strengthen the CAA's capability, capacity and funding to support hydrogen and other zero-emission certification programmes, fuel assurance processes and infrastructure, consistent with the Jet Zero taskforce recommendations[26] [27]
3) **Confirm critical-path priorities:** Identify and agree the most system critical priorities across the five domains, including evidence capture, regulatory gap and impact assessments, safety zone principles, fuel quality interfaces, refuelling protocols and competence frameworks to provide clarity on

[25] https://www.dlr.de/en/latest/news/2025/world-first-in-flight-measurements-of-contrails-from-hydrogen-propulsion
[26] Jet Zero Taskforce Hydrogen Task and Finish Group Report
[27] Jet Zero Taskforce 2025 annual report

sequencing and ensure that effort and resources and focused where they matter most.

4) **Continued engagement:** Continue engagement with stakeholders involved in trials, demonstrations and early deployments, ensuring that learnings and evidence are captured systematically and translated into regulatory and operational understanding.
5) **Align key Demonstrate period activity:** Ensure early activity is aligned with the objectives of the Demonstrate (2026-2030) period, prioritising evidence-led progression over scale and maintaining alignment across regulatory, operational and infrastructure readiness.
6) **Periodic review preparation:** Establish arrangements for periodic review and refresh, aligned where appropriate with wider policy cycles, so that assumptions, sequencing and priorities can be updated as evidence, technology maturity and system readiness evolve.

These next steps provide the foundation for coordinated progression through the Demonstrate and Prove periods. They support safe and proportionate development while retaining flexibility to adapt to emerging evidence, programme outcomes and external conditions, and help ensure demonstrator activity translates into enduring regulatory and operational capability.

6 Annex

Section 6.1-6.5 sets out the core roadmap across the five domains. Each domain includes a 2050 end-state description, key dependencies, and the enabling activities that support safe progression through the three periods. Milestone codes appear as such:

- MT = Aircraft and Propulsion Systems
- ME = Energy
- MA = Aerodromes
- MO = Operations and Safety Management
- MF = Airspace and Flight Procedures

Section 6.6 Includes the modelling assumptions for the scenario analysis.

6.1 Aircraft and Propulsion Systems

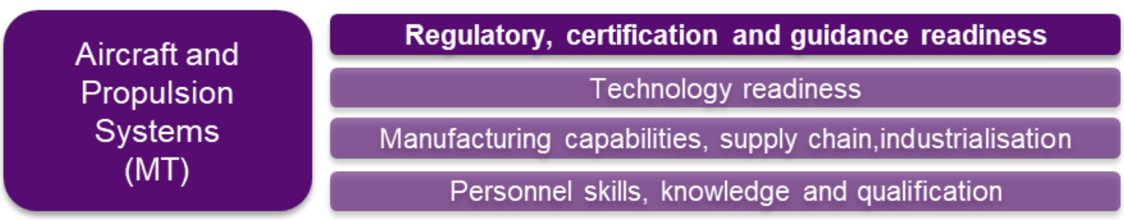
2050 end state for Aircraft and Propulsion Systems
By 2050, hydrogen-powered aircraft using fuel cell-electric propulsion and/or hydrogen combustion are integrated into UK civil aviation for suitable applications. Safety assurance is supported by mature certification and continuing airworthiness arrangements informed by evidence and operational experience, providing confidence equivalent to conventional aviation.

Purpose of the domain
This domain sets out the regulatory and system steps that enable safe progression from early hydrogen aircraft trials to routine certification and oversight. It reflects the roadmap's overarching intent to establish a UK-centric roadmap with a regulatory overlay and gap analysis, focused on identifying where new hydrogen-specific rules, SC and supporting material are required.

Structure of the domain
This domain is organised across four interdependent subdomains:

1) **Regulatory, certification and guidance readiness (core regulatory pathway)**
2) Technology readiness; (evidence generation and maturity)
3) Manufacturing, supply chain and industrialisation; and
4) Personnel skills, knowledge and qualification readiness.

For each subdomain, the roadmap sets out enabling activities and indicative milestones aligned to the three standard periods used throughout this report: (2026–2030) Demonstrate; (2030–2035) Prove; (2035 onwards) Scale and sustain.



6.1.1 Regulatory, certification and guidance readiness (core regulatory pathway)

UK Civil Aviation Authority

This subdomain describes how evidence from trials and early projects is translated into formal regulatory outputs that support repeatable certification and oversight. It focuses on:
(i) defining and updating certification bases;
(ii) developing hydrogen-specific SC;
(iii) creating MoC and updating Alterative Means of Compliance (AMC) or GM; and
(iv) ensuring continuing airworthiness and organisational capability can support hydrogen programmes.

(2026–2030) Demonstrate: establish the evidence-to-regulation pipeline. Activities focus on preparation, structured assessment and evidence capture:

- Gap and impact assessments across the core airworthiness and certification framework, including Regulation (EU) 748/2012 and Regulation (EU) 2015/640, and across relevant Certification Specifications. Existing assessments already referenced in the roadmap (e.g. work covering CS-23, CS-25 and CS-E) provide an input to broader assessment scope, including CS-22, CS-27, CS-29 and SC-VTOL.
- Certification basis planning for early hydrogen programmes, using established aviation approaches while identifying where hydrogen introduces novel features requiring additional conditions or interpretative material.
- Development of hydrogen-specific SC informed by trial evidence and gap findings, targeting the areas explicitly highlighted in the roadmap text (e.g. hydrogen leakage, flammability, fire protection, storage integrity, system integration and testing).
- Review of existing AMC/GM to assess applicability to hydrogen technologies and organisational arrangements, identifying where updates or new guidance is required.
- Use of structured engagement mechanisms (including sandbox-style engagement referenced in the roadmap) to collect evidence in real time and clarify safety cases for early projects, supporting the translation of learning into formal material

Outputs from this period are framed as enabling products, not delivery commitments: a clearer evidence plan for hydrogen safety topics, a prioritised register of regulatory gaps, early drafts of hydrogen-specific SC topics, and an AMC/GM update pipeline aligned to evidence availability.

(2030-2035) Prove: formalise and apply repeatable certification material. Activities focus on consolidating and applying formal regulatory material to support repeatable approvals:

- Hydrogen-specific SC are consulted and published in a form that supports repeatable use across applicants and aircraft categories where appropriate.
- Initial hydrogen MoC are introduced for priority safety topics, supporting consistent compliance demonstration and reducing the need for ad-hoc approaches where evidence supports standardisation.
- AMC/GM updates are developed, consulted and published where required, ensuring guidance reflects hydrogen-specific hazards and compliance methods without reducing safety assurance.
- Organisational and oversight readiness matures alongside certification activity, including capability to manage hydrogen scope within design approvals and certification projects (aligned to the roadmap's emphasis on building competence).
- International engagement: Engagement supports compatibility with ICAO commitments and fosters harmonisation where this aligns with UK safety and operational interests. The domain references coordination with other authorities

and standards activity (e.g. standardisation working groups such as SAE AE-7F and EUROCAE WG-80) as inputs to interoperability and assurance development, recognising that different authorities may adopt different approaches within the broader safety continuum.

(2035 onwards) Scale and sustain: embed hydrogen into routine certification and oversight. Activities focus on embedding and maintaining the mature regulatory framework as deployments expand:

- Hydrogen certification and oversight become routine within the CAA's certification and continuing airworthiness activity, as programmes mature and the evidence base supports stable compliance approaches.
- DOA and certification projects increasingly include hydrogen scope such as hydrogen aircraft and propulsion systems and more TC or STC are issued, supported by established SC/MoC/AMC/GM material and accumulated operational experience.
- Regulatory material is maintained through periodic review, reflecting new evidence, evolving technologies and interoperability needs, anchored on ICAO compatibility and targeted harmonisation where in the UK's interest.

Key dependencies for the regulatory pathway: availability of safety data from trials, and availability of data and technically feasible limitations to support the definition of safety and certification requirements; maturity of hydrogen propulsion and storage technologies; alignment between certification material and aerodrome/energy readiness; and standards evolution relevant to hydrogen fuel and system interfaces.

6.1.2 Technology readiness

This subdomain describes the evidence base that underpins certification and oversight readiness.

(2026-2030) Demonstrate: It is expected that hydrogen aircraft technology remains at an early stage of maturity, with propulsion systems and aircraft integration typically assessed at TRL 4- 5 for hydrogen fuel cell and TRL 2-4 for hydrogen turbines.

- Activities include the further progress of integration of hydrogen systems into aviation systems or their development in line with aviation safety approaches. In addition, feasibility will be tested through laboratory test or ground demonstration campaigns as well as early flight trials. Hydrogen fuel cell-electric propulsion systems are expected to dominate early applications, particularly for smaller aircraft and retrofit programs.
- Demonstrator aircraft play a critical role in this phase. Flight trials of modified existing airframes, such as commuter turboprops converted to hydrogen propulsion, or small-to-medium scale new products, are expected to continue, supporting safety case development and informing regulatory developments. The CAA's Hydrogen Innovation Sandbox[28] (launched 2023) has been supporting first trials, allowing manufacturers to work with regulators on safety cases in real time.
- By 2025 - 2028, we expect the first small passenger hydrogen aircraft (under ~20 seats) to attain initial certification with a propulsion system. These will likely be retrofits of existing airframes (e.g. turboprops converted to hydrogen fuel cell-electric propulsion).
- Testing will be required to demonstrate compliance with environmental, structural,

[28] Hydrogen Sandbox - Civil Aviation Authority - Citizen Space

structural and crashworthiness standards, including high-voltage systems, hydrogen storage integrity, and fire safety performance.

(2030–2035) Prove: Hydrogen propulsion and aircraft integration technologies are expected to progress to TRL 6 and 7, supported by more representative system-level demonstrations. Purpose-designed hydrogen aircraft architectures are expected to emerge, moving beyond retrofit solutions and enabling improved performance, payload and range. During this period, potential first small or possibly regional hydrogen aircraft may close certification projects. This is likely to employ a low-powered fuel cell <1 MW in size. Further development efforts will focus on the improvement of fuel cell power, storage systems for liquid hydrogen or the improvement of thermal management systems.

(2035 onwards) Scale and sustain: Hydrogen aircraft technologies are expected to reach full operational maturity, corresponding to TRL 8 and 9. For small or regional hydrogen aircraft employing high-powered fuel cell technology >1 MW in size may close certification by 2040. Hydrogen propulsion options for narrowbody aircraft are anticipated to enter into service more towards the early 2040s, which widebody application following later. It is expected that, by 2050, hydrogen aircraft technologies are mature, proven and deployed at scale, supported by established design, test and validation practices.

Key dependencies: The definition and agreement of a certification basis, SC and MoC and Aerodrome infrastructure and operational readiness

6.1.3 Manufacturing, supply chain and industrialisation

Production and industrialisation activities heavily depend on certification and technology readiness domains and progress made in these.

(2026 – 2030) Demonstrate: Manufacturing activities are characterised by low-rate production, prototype production and integration of systems into existing airframes. It is expected that the supply chain for hydrogen-specific components, such as storage systems, fuel cells and control systems, remain relatively immature and fragmented. Industrial activities focus on supporting demonstrator programmes, retrofit installations and experimental flights and certificates.

(2030 – 2035) Prove: Manufacturing and supply chains are expected to begin to transition towards industrialisation. Approved production organisations will start to expand their scope to include hydrogen-specific systems and assemblies. The supply chain becomes more resilient. It is expected that production volumes remain modest but start to increase. In addition, hydrogen storage manufacturing capabilities must be established by key suppliers or aircraft manufacturers.

(2035 onwards) Scale and sustain: Hydrogen aircraft manufacturing will be fully embedded in the aerospace industry. Supply chains are mature and start to scale. In the 2040s, scaling and ramp-up of production for hydrogen-specific systems or aircraft is expected supporting the growing demand for commercial hydrogen flights.

Key dependencies on the manufacturing domain exist for

- The availability of certified aircraft

6.1.4 Personnel skills, knowledge and qualification readiness

(2026 - 2030) Demonstrate: Skills development will focus on building foundational hydrogen competence within both industry and the CAA beyond specific individuals. This includes the development of hydrogen-specific knowledge for CAA personnel involved in certification and Design Organisation review and approval projects. It also includes knowledge generation and on-the-job training for Compliance Verification Engineers (CVE). Early learnings may be derived from non-aviation hydrogen industries being combined with established aviation and certification skills.

(2030 - 2025) Prove: Certification competences related to hydrogen aircraft design and propulsion systems will become more mature as expert pools and projects continue to grow and achieve the first certificates.

(2035 onwards) Scale and sustain: Hydrogen expertise is fully embedded within standard aerospace and regulatory skill frameworks. Hydrogen systems, safety and certification are treated as established disciplines, supported by mature training, qualification and knowledge-sharing mechanism across academia, industry and regulators.

Key dependencies on the qualification subdomain for the aircraft domain exist for

- The availability of first-mover projects and experts involved
- Academic and educational program availability

Key milestones for the Aircraft and Propulsion Systems domain are:

- **For the regulatory, certification and guidance subdomain:**
  - **MT01: Completion of regulatory gap and impact assessments by 2028**
  - **MT02: Preparation of full set of hydrogen-specific SC completed by 2032 for small aircraft class**
- **For the technology readiness subdomain:**
  - MT03: Completion of early demonstration flight trials by 2027
  - MT04a: Experimental certification of first small hydrogen aircraft by 2028 (small propulsion system <1MW)
  - MT04b: Experimental certification of first small hydrogen aircraft by 2028 (large propulsion system >1MW)
  - MT05: Progression to TRL 6-7 through system-level demonstrations by 2033-2035
  - **MT06a: Certification closure for first purpose-designed small GA commercial hydrogen aircraft by 2035 (<1 MW low-powered fuel cell)**
  - **MT06b[29]: Certification closure for first purpose-designed small GA commercial hydrogen aircraft by 2040 (>1 MW high-powered fuel cell)**
  - **MT07: EIS of hydrogen narrowbody aircraft by 2040**
  - **MT08: EIS of hydrogen widebody aircraft by 2045**
  - MT09: Full technology maturity and scaled deployment by 2050
- **For the manufacturing subdomain:**
  - MT10: Prototype and low-rate production phase by 2030
  - MT11: Hydrogen storage manufacturing capability established at scale by 2035

[29] All dependencies and enablers for MT06b will be the same as MT06a, however the technology, specifically the fuel cell TRL development for high-powered systems >1MW will be at a later stage.

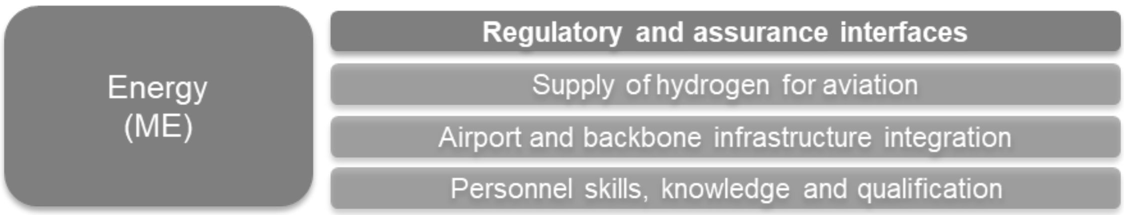
  - MT12: Production ramp up for narrowbody aircraft by 2040
  - MT13: Production ramp up for widebody aircraft by 2045
- **For the qualification subdomain:**
  - MT14: Foundational hydrogen competence established by 2028
  - MT15: Certification expertise matures by 2035
  - MT16: Hydrogen expertise fully embedded in aerospace ecosystem by 2042

6.2 Energy

2050 end state for Energy
By 2050, the UK aviation energy system supports hydrogen operations safely and reliably at scale (GH_2 and LH_2 where applicable), with mature supply chains, resilient logistics and aviation-grade fuel quality and handling interfaces integrated into aerodrome operations and safety management.

Purpose of this domain
This domain sets out the regulatory and assurance interfaces that enable safe provision, handling and use of hydrogen as an aviation fuel, recognising that many delivery decisions sit outside the CAA's remit while aviation safety interfaces (fuel quality, refuelling and operational constraints) must be sufficiently defined to support safe trials and repeatable operations.

Structure of this domain
The Energy domain is organised around four interdependent subdomains:
1. Regulatory and assurance interfaces
2. Hydrogen supply for aviation
3. Airport and backbone integration
4. Personnel skills, knowledge and competence



6.2.1 Regulatory and assurance interfaces (core aviation safety touchpoints)

(2026-2030) Demonstrate: define early aviation-grade interfaces using evidence.
Activities focus on establishing aviation-relevant fuel interfaces for trials and early operations:
- Clarify aviation-grade purity expectations and early assurance practices for hydrogen provided to aerodromes, recognising that early demand is limited and supported via delivered GH_2 arrangements. External analysis, including the Hydrogen Task & Finish Group[30], identifies the establishment of a clear, agreed and scalable aviation hydrogen fuel assurance process as a critical enabler for early operations and subsequent scale-up, and an area where CAA leadership is required in collaboration with other stakeholders.

[30] Jet Zero Taskforce Hydrogen Task and Finish Group Report

- Use early references to relevant standards as inputs to aviation assurance discussions (including ISO 14687 for hydrogen fuel quality and ISO 19880 for fuelling systems, alongside emerging aviation-relevant standardisation activity referenced in the draft).
- Translate trial learning into safety considerations within certification and operational material where relevant (e.g., storage, leakage and flammability interfaces that influence aircraft-fuel coupling and refuelling approaches).

(2030–2035) Prove: **mature repeatable fuel QA and refuelling assurance for early adopters.** Activities focus on moving from trial arrangements to repeatable assurance models:

- Strengthen fuel quality assurance and contamination control practices used in early deployments, aligning with aerodrome operational models and safety cases.
- Expand assurance approaches to cover LH_2 where relevant to early adopter infrastructure and aircraft pathways, including cryogenic handling interfaces that influence aerodrome procedures and competence.

(2035 onwards) Scale and sustain: **embed aviation hydrogen assurance as routine practice.** Activities focus on embedding mature assurance and interoperability:

- Embed fuel QA, refuelling assurance and competence within routine operations at hydrogen-capable aerodromes, aligned to the wider system's readiness and deployment scale.
- Maintain ICAO compatibility and harmonisation where it supports UK safety and operational interests, recognising that different authorities may adopt different approaches across the broader safety continuum.

Key dependencies: National hydrogen production and logistics readiness; aerodrome investment cycles; and evidence that supports stable refuelling and quality assurance models.

6.2.2 **Supply of Hydrogen for aviation** (readiness assumptions that drive aviation planning)

2026-2030 Demonstrate:.UK low-carbon hydrogen production remains limited; aviation demand is small and met via road-delivered GH_2 from industrial suppliers. Green hydrogen costs remain a constraint, with early operations supported by targeted procurement and commercial agreements.

(2031-2035) Prove: hydrogen availability increases as national production scales; LH_2 capability develops in the UK/Europe to support early cryogenic deliveries where relevant.

(2035 onwards) Sustain and scale: hydrogen supply integrates more fully into mature logistics networks supporting routine operations at scale

Key dependencies for the hydrogen supply domain include national hydrogen production volumes and cost curves; DESNZ hydrogen business models and market mechanisms; ICAO/EASA hydrogen fuel standards; Industrial build-out of electrolyser and liquefaction capacity.

6.2.3 **Airport and backbone infrastructure integration** (energy-aerodrome interface)

(2026–2030) Demonstrate: support early GH_2 infrastructure trials and safety-case-based operations; develop provisional safety zones and integrate early concepts into aerodrome planning cycles.

(2030–2035) Prove: implement early LH_2 storage at selected aerodromes where relevant; publish hydrogen-specific aerodrome guidance and MoC that support repeatable storage, leakage, refuelling protocols and QA.

(2035 onwards) Scale and sustain: integrate hydrogen infrastructure into aerodrome certification frameworks and routine airport master planning where deployed.

Key dependencies include DESNZ and industry delivery of backbone transport infrastructure, liquefaction capability and grid reinforcement and land use planning for large energy footprints.

6.2.4 Personnel skills, knowledge and qualification readiness

(2026-2030) Demonstrate: Foundational hydrogen competence developed among CAA inspectors, aerodrome assessors and safety specialists. Minimum competency expectations established for aerodrome operators, refuelling entities and utilities partners. Early learning transferred from industrial hydrogen sectors.

(2030- 2035) Prove: Hydrogen-specific competency frameworks developed for: H_2 storage and handling; Refuelling operations; Safety case preparation; Quality assurance and contamination control. Joint training with RFFS, utilities and emergency services expanded.

(2036 - 2050) Scale and sustain: Hydrogen competence embedded in standard regulatory and aerodrome training regimes. Recertification and recurrent training for cryogenic handling, leak response, and hydrogen firefighting made routine.

Key dependencies Availability of early hydrogen demonstration projects, Academic and vocational training programme development, Maturation of safety cases and operational data.

Key milestones for the Energy domain:

Regulatory and assurance interface
- **ME01: Aviation-relevant GH_2 fuel quality and assurance interfaces defined to support trials and early operations by 2029-2030**
- **ME02: Early LH_2 assurance approaches demonstrated for aviation use at selected locations in 2033-2035**
- **ME03: Repeatable aviation fuel QA and refuelling assurance established for early adopters by 2040**
- **ME04: Aviation hydrogen assurance embedded as routine practice, aligned with ICAO compatibility by 2045**

Hydrogen supply for aviation
- ME05: Initial aviation GH_2 supply secured by 2028
- ME06: First LH_2 deliveries to UK airports by 2033
- ME07: Cost-competitive aviation hydrogen established in late 2030s
- ME08: Fully scaled, low-carbon aviation hydrogen supply by 2050

Airport and backbone infrastructure integration

- ME09: GH_2 infrastructure arrangements demonstrated at aerodromes through trials and safety-case-based operation in 2029-2030
- ME10: LH_2 storage capability commissioned at selected early-adopter aerodromes by 2033-2035
- ME11: Hydrogen infrastructure integrated into aerodrome certification frameworks and routine master planning by 2040
- ME12: Wider hydrogen backbone and airport energy system integration established where deployed in the 2040s
- ME13: National aviation LH_2 logistics infrastructure mature, and full airport hydrogen infrastructure integration complete by 2050

Skills and qualification

- **ME13: Foundational hydrogen competence established across CAA and aerodrome functions by 2028**
- ME14: Hydrogen operational competency frameworks formalised for storage, refuelling QA, safety case activity by (2033
- ME15: National-scale hydrogen competence embedded with routine regulatory and aerodrome training and recurrent assurance by 2050

Hydrogen supply and airport energy infrastructure must be available 3 to 7 years ahead of aircraft EIS milestones to avoid bottlenecks.

6.3 Aerodromes

2050 end state for Aerodromes:
By 2050, a network of hydrogen-enabled UK aerodromes supports routine operations, with proportionate GH_2 capability at suitable sites and LH_2 capability at strategically designed hubs where relevant with liquefaction and hydrant distribution systems capable of supporting narrowbody and widebody hydrogen aircraft. Hydrogen infrastructure and procedures are integrated into aerodrome SMS, emergency response, fuel QA and operational systems, supported by mature safety zones and hazardous area classification approaches.

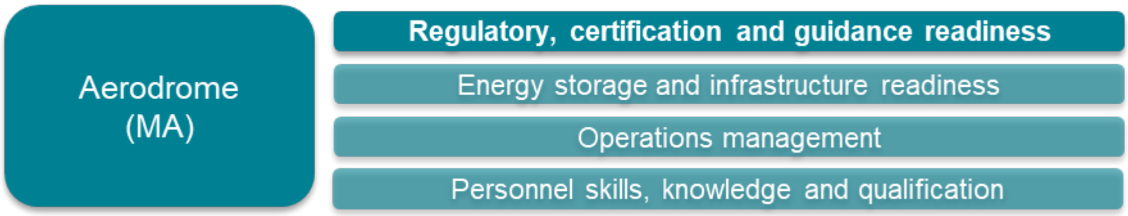
Purpose of this domain
This domain sets out how aerodrome regulatory frameworks, guidance and assurance practices evolve to support safe hydrogen infrastructure and operations, ensuring that early trial learning is translated into repeatable requirements that aerodromes can apply for investable design and safe operations. Infrastructure is scaled proportionately to aircraft entry-into-service milestones, ensuring that energy supply, storage and refuelling capability are available in advance of operational demand. The transition from early operations in the late 2020s focussing on smaller aerodromes using delivered gaseous hydrogen to major airport pipeline supply and on-site liquefaction requires early infrastructure planning and system-wide coordination across the major domains.

Structure of this domain
The Aerodromes domain is organised across four interdependent subdomains:

1. **Regulatory, certification and guidance readiness (core regulatory pathway)**
2. Aerodrome operations management (procedures, safety zones, QA and SMS integration)
3. Energy storage and infrastructure readiness (GH_2/LH_2 storage and refuelling

capability)

4. Personnel skills, knowledge and qualification readiness (including RFFS competence)



6.3.1 Regulatory, certification and guidance readiness (core regulatory pathway)

(2026-2030) Demonstrate: complete regulatory gap/impact assessments and trial-informed early guidance. Activities focus on structured assessment and evidence capture to define hydrogen aerodrome requirements:

- Conduct gap and impact assessments across the aerodrome regulatory landscape referenced in the draft, including Regulation (EU) 139/2014, the Air Navigation Order (ANO), draft ground handling requirements as well as certification specifications CS-ADR-DSN (where relevant to aerodrome design requirements).
- Assess impacts and update needs across relevant CAP guidance referenced in the draft: CAP 168 (Licensing of Aerodromes), CAP 738 (Safeguarding of Aerodromes), CAP 699 (RFFS competence), CAP 642 (Airside Safety Management) and CAP 1168 (GM for Organisations/Operations/Design for Aerodromes).
- Address cross-regime interfaces relevant to hydrogen infrastructure and operations (DESAR/DSEAR, COMAH, ATEX, PSSR, COSHH as referenced) so aerodrome guidance aligns with wider hazardous substances and major accident hazard expectations.
- Use evidence from early aerodrome trials and safety cases to develop provisional approaches for safety zones/keep-out areas, refuelling protocols, and emergency response considerations.

(2030 - 2035) Prove: publish and apply repeatable aerodrome hydrogen requirements Activities focus on formalising and applying repeatable aerodrome frameworks:

- Publish updated aerodrome certification bases and GM for hydrogen-enabled infrastructure and operations. The activities include the update and publication of certification basis for hydrogen-enabled aerodrome infrastructure, the development and publication of updated GM as well as the development of required MoC to cover hydrogen-specific updates in CS-ADR-DSN.
- Formalise hydrogen safety zones and hazardous area classification approaches using accumulated evidence and operational experience from early deployments.
- Develop and formalise hydrogen quality assurance and sampling approaches aligned to repeatable refuelling models and SMS integration.
- In addition, the hydrogen quality assurance framework is developed and formalised and international alignment will be supported on ICAO level, especially related to ICO Annex 14 (Aerodromes), Annex 19 (Safety Management) and ICAO documents 9157 (Aerodrome Design Manual), 9137 (Airport Services Manual) and 9774 (Manual on Certification of Aerodromes). Standardisation activities for

refuelling and defueling, e.g. as part of SAE AE5 will progress and inform harmonised implementation. First airport certification or re-certification starts.

(**2035 onwards) Scale and sustain: embed hydrogen aerodrome frameworks into routine certification and oversight**. Activities focus on fully establishing the new hydrogen aerodrome certification requirements and manage certification and implementation projects as they arise.

- Activities include the publication of additional or new hydrogen-specific aerodrome requirements and the implementation of hydrogen in aerodromes across the UK.
- Maintain hydrogen aerodrome frameworks through periodic review, keeping ICAO compatibility and targeted harmonisation where in the UK's interest. Internationally harmonised requirements are published, and mature standards exist and are used by aerodromes and aerodrome users.

Key dependencies on the regulatory readiness subdomain for the aerodrome domain exist for

- The availability of ready-to-deploy technologies to be proven in implementation and certification processes,
- The availability of safety data to support regulatory definition of hydrogen quality checks, safety zones and refuelling standards,
- The contribution and progress made by other aviation authorities and bodies, such as EASA, FAA and ICAO to ensure international harmonisation and alignment.

6.3.2 Energy storage

Hydrogen energy readiness at aerodromes must evolve in line with aircraft scale and hydrogen form (gaseous versus liquid), recognising the significant differences in storage density, infrastructure footprint and energy requirements.

(2026 – 2030) Demonstrate: aerodrome energy and hydrogen storage activities focus on enabling initial EIS and small regional, retrofitted aircraft expected from the late 2020s. Key activities hereby include deployment of small-scale gaseous hydrogen storage solutions, supported by tanker delivery or mobile dispensing systems as well as the integration of hydrogen infrastructure into aerodrome infrastructure planning cycles.

At this stage hydrogen volumes remain modest but the alignment with aircraft development roadmaps is essential. Energy storage capability must be available in advance of demonstrator aircraft and initial certified retrofit aircraft operations. The early identification of potential sites for future liquefaction facilities should begin during this phase.

(2031 – 2035) Prove: purpose-design regional hydrogen aircraft approach EIS and aerodromes must transition towards the introduction of liquid hydrogen storage capabilities, the identification and initial build of liquefaction facilities, and the expansion of on-site storage and distribution systems. Infrastructure planning must account for at least 10-year lead time before implementation requiring planning and safeguarding for large-scale hydrogen storage and energy system upgrades during this period.

(2035 onwards) Sustain and scale: major airports expected to support large narrowbody hydrogen aircraft must initiate preparatory infrastructure upgrades. During the 2040s, a growing number of narrowbody and widebody aircraft operations is expected requiring large-scale storage facilities, potential on-site liquefaction plants, integration with hydrogen pipeline networks and upgrades to the aerodrome energy systems and electrical infrastructure to be done.

6.3.3 Aerodrome operations management

(2026 - 2030) Demonstrate: operational aerodrome activities focus on enabling a safe introduction of gaseous hydrogen at selected aerodromes. The focus will be on establishing requirements for hydrogen quality checks and sampling processes and by this the development of an initial hydrogen quality assurance process. In addition, the drafting of detailed operational concepts for on-site hydrogen management, storage, distribution and refuelling will influence and shape the detailed implementation of the next phases. A focus will also be on safety zones and keep-out areas, which must be defined, although full formalisation may follow aircraft certification MoC development by a few years. Refuelling requirements and operational protocols will similarly evolve further.

(2031 - 2035) **Prove**: aerodrome operations management frameworks mature and formalise. The activities will include harmonised refuelling requirements and protocols based on established certification frameworks but also the formal definition and implementation of hydrogen safety zones and hazardous area classifications. The implementation of hydrogen quality assurance processes will start to scale and the integration hydrogen operational procedures into the aerodrome Safety Management Systems is ongoing.

(2035 onwards) Sustain and scale: hydrogen operations become routine components for aerodromes with fully harmonised refuelling protocols, integrated storage and distribution management systems and aerodromes support narrowbody and widebody hydrogen aircraft operations under mature, internationally aligned procedures and standards.

Key dependencies on the operations management subdomain for the aerodrome domain exist for

- The availability and entry-into-service timelines for retrofit aircraft, regional aircraft and later narrowbody and widebody aircraft
- The use of new aircraft types by commercial operators and airlines
- The national hydrogen production, transport and liquefaction capabilities.

6.3.4 Personnel Skills, Knowledge and Qualification Readiness

(2026 - 2030) Demonstrate: skills development will focus on building foundational hydrogen competence within both industry and the CAA beyond specific individuals, this also applies to the aerodrome domain. This includes the development of hydrogen-specific knowledge for CAA personnel involved in certification and aerodrome review and approval projects. In addition, RFFS competence development for hydrogen-specific hazards will be a key focus area to ensure safety from the first trial operations before scaled implementation. The SMS and the key personnel referenced in it will gain knowledge for addressing differences between kerosene and hydrogen operations.

(2031 – 2035) Prove: training programs are developed further and applied to more aerodromes across the UK. Competence frameworks for RFSS response capabilities mature and ground handling and fuel quality personnel certification for hydrogen operations starts to be established.

(2036 – 2040) Sustain and scale: ground handling and fuel quality personnel will mature and scale across UK aerodromes. During the 2040s, hydrogen competence becomes embedded within standard aerodrome operational training frameworks and RFFS, SMS managers and operational personnel treat hydrogen systems as established operational elements, supported by mature training pathways and recurring qualification processes.

Key dependencies on the qualification subdomain for the aerodrome domain exist for

- The availability of first-mover projects and experts involved
- Academic and educational program availability

Key milestones for the Aerodrome domain are:

- **For the regulatory, certification and guidance subdomain:**
  - **MA01: Completion of Regulatory gap and impact assessments by 2028**
  - **MA02: Hydrogen safety zone and refuelling requirements frameworks defined by 2030**
  - **MA03: Publication of full set of updated certification basis and GM by 2033**
  - MA04: Hydrogen quality assurance framework formalised by 2035
  - **MA05: Hydrogen aerodrome certification projects commence by 2036**
  - MA06: Fully mature and internationally harmonised hydrogen aerodrome framework by 2050
- **For the energy storage subdomain:**
  - MA07: Initial GH2 infrastructure deployment at selected aerodromes by 2028
  - **MA08: Energy storage readiness for first retrofit or small regional aircraft EIS by 2030**
  - MA09: Introduction of liquid hydrogen capabilities at early-adopter aerodromes by 2033
  - MA10: Infrastructure safeguarding for large-scale hydrogen operations by 2035
  - **MA11: Major airport preparatory infrastructure upgrades initiated by 2040**
  - MA12: Pipeline integration and large-scale LH2 storage implementation by 2045
  - MA13: Full-scale hydrogen energy integration at UK aerodromes
- **For the aerodrome operations subdomain:**
  - MA14: Initial hydrogen operational concepts and QA frameworks established by 2028
  - MA15: Provisional safety zones and refuelling protocols defined by 2030
  - MA16: Formal definition of hydrogen safety zones by 2033
  - MA17: Integration of hydrogen procedures into aerodrome SMS by 2035
  - MA18: Routine hydrogen operations at hydrogen-enabled aerodromes by

2040
    - MA19: hydrogen operations mature and internationally harmonised by 2050
- **For the qualification subdomain:**
    - MA20: Foundational hydrogen competence established by 2028
    - MA21: Formal hydrogen training programmes rolled out by 2033
    - MA22: Hydrogen competence scaling across UK aerodromes achieved by 2040
    - MA23: Hydrogen competence fully embedded by 2050

6.4 Operations and Safety Management

2050 end state for Operations and Safety Management
By 2050, hydrogen aircraft operations, maintenance and safety assurance are embedded within routine UK aviation operational and oversight frameworks. Operational procedures, continuing airworthiness arrangements, training and emergency response practices maintain safety levels equivalent to conventional kerosene operations.

Purpose of this domain
This domain sets out how operational concepts, continuing airworthiness and safety management arrangements evolve so that hydrogen-specific hazards (leakage, fire/explosion risk, cryogenic handling where relevant) are addressed systematically, and so that early learning from trials is translated into repeatable operational and maintenance practices.

Structure of this domain
The Operations and Safety Management domain is organised across five interdependent subdomains:
1. **Regulatory, certification and guidance readiness (core regulatory pathway)**
2. Operations management (turnaround/refuelling/leakage/venting operational concepts)
3. Maintenance management (tooling, facilities, procedures and approvals)
4. Safety management (hazard identification, emergency response, SMS integration)
5. Personnel skills, knowledge and qualification readiness

6.4.1 Regulatory, certification and guidance readiness (core regulatory pathway)

(2026-2030) Demonstrate: complete gap/impact assessments for continuing airworthiness and operational material. Activities focus on structured assessment to identify hydrogen-specific updates:
- Conduct gap and impact assessments for continuing airworthiness requirements in

Regulation (EU) 1321/2014, focusing on the parts referenced in the draft (Annex I Part-M, Annex II Part-145, Annex III Part-66, Annex V Part-CAO), alongside associated AMC/GM.

- Assess CAP 700 (Operational Safety Competences, Training and Proficiency Checks) for hydrogen-related competence implications, aligned to early operational concepts and hazards.
- The early assessments are not only laying the groundwork for future updates and harmonisation of safe hydrogen system maintenance activities, but also determine impacts on maintenance organisation approvals, certifying staff privileges or competence requirements to be updated to reflect hydrogen systems, where hydrogen introduces novel tasks, tooling and facility requirements (e.g., ventilation and detection needs, cryogenic PPE where relevant).

(2030–2035) Prove: publish and apply updated operational / continuing airworthiness material where required. Activities focus on translating assessment outputs into repeatable guidance and oversight:

- Publish updates to relevant regulation and AMC/GM where required, aligned to evidence and early deployment experience, supporting repeatable maintenance procedures, approvals, equipment requirements and competence frameworks.
- Formalise refuelling/coupling safety guidance and operational controls where these sit within operational assurance expectations, aligning with aerodrome safety zone approaches and refuelling protocols.

(**2035 onwards) Scale and sustain: embed hydrogen operational assurance as routine practice.** Activities focus on embedding mature requirements as hydrogen operations scale:

- Apply mature continuing airworthiness and operational oversight practices routinely across hydrogen operations where deployed.
- Maintain ICAO compatibility and foster harmonisation/international alignment where aligned to UK safety and operational interests.

Key dependencies on the regulatory readiness subdomain for the operations and safety management domain exist for

- The availability of serviceable aircrafts proven throughout extensive testing and certified
- Market demand for the use and scaled deployment of hydrogen-powered aircraft
- The availability of upgraded and new airport infrastructures and availability of maintenance facilities

6.4.2 Operations management

Hydrogen aircraft operations introduce new operational considerations across turnaround management, refuelling, ground handling and contingency procedures.

(2026 - 2030) Demonstrate: the initial focus is on enabling safe introduction of first, gaseous, hydrogen aircraft flights. To achieve this, the focus is on leakage management and control as well as on how to embed the detection, monitoring and mitigation of hydrogen leaks in operational procedures. Furthermore, operational concepts or scenarios are developed to prevent hydrogen accumulation in enclosed compartments which may lead to alteration of turnaround procedures. In addition, the technical development of coupling systems for truck and pipeline refuelling systems as well as the research and assessment of potential safety distances for refuelling and ground handling activities is ongoing. Early venting procedures are defined.

(2031 – 2035) Prove: safety guidelines for the newly developed coupling systems are in place and provisional safety distances turned into specific requirements influencing apron layout and may trigger increase automation in the next years. Venting procedures defined earlier are validated and proven. In addition, refuelling requirements and protocols become harmonised and formalised and operational procedures are updated. Automation solutions start to reach technical maturity level and start to be deployed.

(2035 onwards) automation will support the proven procedures on mature level. Leakage detection, venting and safety distance management are embedded in digital operational systems and operational scenarios for narrowbody and widebody hydrogen aircraft are becoming mature throughout the 2040s.

Key dependencies on the operations management subdomain for the operations and safety management domain exist for

- The availability of serviceable aircrafts proven throughout extensive testing and certified
- Market demand for the use and scaled deployment of hydrogen-powered aircraft

6.4.3 Maintenance management

(2026 - 2030) Demonstrate: Initial maintenance management activities focus on new maintenance equipment required for hydrogen propulsion systems, storage tanks and refuelling interfaces. Hydrogen-specific maintenance risks and tooling requirements are assessed.

(2031 – 2035) Prove: the planning of facility upgrades begins and is becoming a focus area. Ventilation upgrades for hangars and enclosed maintenance areas as well as new hydrogen gas detection and alarm systems will be considered. The planning of cryogenic handling capability where liquid hydrogen systems are introduced is progressing.

(2035 – 2040) Scale and sustain: new and upgraded maintenance facilities will be build, including new alarm and detection systems as well as maintenance equipment and procedures. Towards the mid-2040s, with the first entry-into-service of narrowbody and widebody hydrogen-powered aircraft, maintenance procedures will become standardised and proven and are part of routine operations in 2050.

Key dependencies on the maintenance management subdomain for the operations and safety management domain exist for:

- The availability of serviceable aircrafts proven throughout extensive testing and certified
- Market demand for the use and scaled deployment of hydrogen-powered aircraft
- The availability of upgraded and new airport infrastructures and availability of maintenance facilities

6.4.4 Personnel skills, knowledge and qualification

(2026 – 2030) Demonstrate: the activities of skills and qualification readiness focus on the identification of hydrogen-specific maintenance skills and knowledge building within the CAA and the industry related to hydrogen-specific maintenance tasks. Special training modules will start to be conceptually developed, and initial assessments of certifying staff privileges adjustments are identified.

(2031 – 2035) Prove: training programs will start to expand supporting formal hydrogen maintenance endorsements. Operational training will reflect handling of new hydrogen-specific equipment and safety distances to be considered as well as first venting and leakage management procedures.

(2036 – 2040) Scale and sustain: and the early 2040s, standard maintenance licensing pathways are identified, and recurrent operational training is established. Hydrogen expertise becomes a routine component of aviation skillset.

Key dependencies on the qualification subdomain for the operations and safety management domain exist for

- The availability of first-mover projects and experts involved
- Academic and educational program availability

6.4.5 Safety management

Hydrogen and its hazards must be addressed systematically across aircraft and operational domains, and the safety management contributors touch on multiple domains and domains, ensuring a holistic and overarching approach to safety and ensure just culture is implemented for hydrogen-powered aircraft.

(2026 – 2030) Demonstrate: the key activities include the identification of hydrogen-specific hazards, particularly related to fire and explosion risks to inform the development of hydrogen airworthiness standards and certification requirements that account for these hazards. Rescue and firefighting procedures are reviewed to prepare the adaptation. Airports and operators start to plan the use of thermal imaging cameras to support the detection of hydrogen flames. The initial procurement of cryogenic personal protective equipment for liquid hydrogen handling preparation starts.

(2031 – 2035) Prove: safety hazard databases expand leading to defined certification requirements, safety distances and are incorporated into SMS documentation. Rescue and firefighting procedures are standardised for hydrogen incidents and emergency response exercises and hydrogen-specific drills become routine.

(2035 onwards) Scale and sustain: hydrogen safety management and emergency response management becomes fully embedded within processes and daily operations.

Key dependencies on the safety management subdomain for the operations and safety management domain exist for

- The aerodrome infrastructure readiness
- The availability of safety data to inform emergency response procedures.

Key milestones for the Operations and Safety Management domain are:

- For the regulatory, certification and guidance subdomain:

  - **MO01: Completion of continuing airworthiness gap assessments by 2028**
  - **MO02: Publication of updated regulation and AMC/GM by 2033**
- For the operation management subdomain:
  - MO03: Definition of initial operational concepts, leakage detection and control and venting procedures by 2030
  - MO04: Formalisation of refuelling and coupling safety guidelines by 2033
  - MO05: Digital integration and operational maturity achieved by 2040
  - MO06: Routine hydrogen operations for narrowbody and widebody aircraft by 2050
- For the maintenance management subdomain:
  - **MO07: Assessment of hydrogen-specific maintenance requirements done by 2028**
  - MO08: Planning of maintenance facility updates closed by 2033
  - MO09: Implementation of upgraded maintenance infrastructure by 2038
  - MO10: Standardisation of hydrogen maintenance for large aircraft fully implemented by 2050
- For the qualification subdomain:
  - MO11: Identification of hydrogen-specific maintenance competencies by 2028
  - MO12: Integration of standard licensing pathways by 2040
- For the safety management subdomain:
  - **MO13: Identification of hydrogen-specific hazards by 2029**
  - **MO14: Formalisation of hydrogen safety requirements by 2035**
  - MO15: Embedding hydrogen widely in safety management systems by 2040

6.5 Airspace and Flight Procedures

2050 end-state for Airspace and Flight Procedures
By 2050, hydrogen aircraft operate within a UK airspace system supported by mature flight procedures and route planning frameworks. Diversion planning, alternate aerodrome selection and publication (AIP) reflect hydrogen operational characteristics while maintaining safety levels equivalent to conventional operations.

Purpose of this domain
This domain sets out how flight procedures, publication, training, regulatory and GM adapt so hydrogen operations integrate safely into the UK airspace system, particularly where limited hydrogen-capable aerodromes and refuelling capability affect diversion/alternate planning and operational constraints.

Structure of this domain
The Airspace and Flight Procedures domain is organised across three interdependent subdomains:

1. **Regulatory, certification and guidance readiness (core regulatory pathway)**
2. Flight procedures and route definition (UK AIP publication, diversion/alternate planning concepts)
3. Personnel skills, knowledge and qualification readiness (pilot/aircrew training concepts)

Airspace and Flight Procedures (MF)

Regulatory, certification and guidance readiness

Flight procedures and route definition

Personnel skills, knowledge and qualification

6.5.1 Regulatory, certification and guidance readiness (core regulatory pathway)

Although the existing regulatory framework under the Regulation (EU) 965/2012 and the Air Navigation Order provides a robust foundation for flight operations, hydrogen implementation may trigger targeted adaptations.

(2026-2030) Demonstrate: gap/impact assessments for flight operations material
Activities focus on identifying where hydrogen introduces operational considerations:

- Conduct gap and impact assessments for Regulation (EU) 965/2012 and the Air Navigation Order, as referenced in the draft, focusing on diversion/alternate planning, operational limitations and any hydrogen-specific safety interfaces.
- Assess AMC/GM to Regulation (EU) 965/2012 and CAP 1074 (as referenced) to identify guidance updates needed for safe introduction and consistent operator practice.

(**2030-2035) Prove: develop and apply updated regulatory/guidance proposals where required.** Activities focus on maturing and applying guidance proportionately:

- Develop and apply updated regulatory and guidance proposals where required, ensuring hydrogen operations achieve equivalent safety levels without disproportionate operational burden.
- Align guidance development with aerodrome hydrogen capability publication and operational experience to ensure procedures reflect real constraints and interoperability needs.

(2035 onwards) Scale and sustain: embed hydrogen operations into routine operational oversight. Activities focus on routine integration as deployments scale:

- Embed updated regulatory and GM within routine operator oversight and operational practice where hydrogen operations occur.
- Maintain ICAO compatibility and foster harmonisation where aligned to UK safety and operational interests.

Key dependencies on the regulatory subdomain exist for

- The progress on other regulatory streams for airport requirements and aircraft certification pathways.

6.5.2 Flight procedures and route definition

Although it is expected that broader airspace integration is not too much affected by the introduction of hydrogen, it introduces new considerations into route definition, diversion planning, flight procedure management and crew training.

(2026 - 2030) Demonstrate: the focus is on enabling safe introduction of first hydrogen aircraft flights within existing airspace structures. Key activities include the identification and publication of hydrogen-capable diversion aerodromes within the UK AIP, the evaluation of compatible refuelling equipment, refuelling control procedures, the development of route planning strategies accounting for limited hydrogen availability in departures and arrival aerodromes as well as early concepts for updated network operations.

(2031- 2035) Prove: initial activities further progress and include formal reflection of hydrogen-capable diversion aerodromes in the AIP, including infrastructure status and RFFS compatibility.

(2035 onwards) Scale and sustain: the development of refined route planning strategies addressing hydrogen endurance, alternate aerodrome suitability and fuel reserve strategies progressed, and hydrogen is integrated into digital flight planning systems and operator route planning tools.

Key dependencies on the flight procedure and route subdomain exist for

- The availability of serviceable aircrafts proven throughout extensive testing and certified
- Market demand for the use and scaled deployment of hydrogen-powered aircraft
- Expansion of hydrogen-capable aerodrome infrastructure, including compatible refuelling systems and RFFS readiness.

6.5.3 Personnel skills, knowledge and qualification

(**2026 – 2030) Demonstrate:** a structured concept for pilot and aircrew training related to hydrogen operations is developed which includes the identification of hydrogen-specific knowledge areas, such as propulsion system functionality, hydrogen fuel characteristics and risks. Training modules are conceptually developed.

(2031 – 2035) Prove: Training organisations begin with the implementation of hydrogen-related training elements, including the integration of propulsion system functionalities into type rating and recurrent training programmes as well as the inclusion of risk awareness, alternate aerodrome planning considerations and operational limitations.

(2036 – 2040) Scale and sustain: and throughout the 2040s, hydrogen-related knowledge is fully integrated into flight trainings. Recurrent training incorporates hydrogen-specific route planning, diversion management and emergency considerations.

Key dependencies on the qualifications subdomain exist for

- The availability of serviceable aircrafts proven throughout extensive testing and certified
- Market demand for the use and scaled deployment of hydrogen-powered aircraft

Key milestones for the Airspace and Flight Procedures domain are:

- **For the regulatory subdomain:**
    - **MF01: Completion of regulatory gap and impact assessments by 2028**
    - **MF02: Development of updated regulatory and guidance proposals by**

2033
  - **MF03: Publication of updated regulation and GM by 2035**
- **For the flight procedures and route definition subdomain:**
  - **MF04: Initial publication of hydrogen diversion capability in UK AIP by 2034**
  - MF05: Expansion of hydrogen-enabled route planning network by 2035
  - MF06: Digital integration of hydrogen into flight planning systems by 2045
- **For the qualification subdomain:**
  - MF07: Development of hydrogen pilot training concept by 2030
  - MF08: Implementation of hydrogen training elements in type ratings by 2035
  - MF09: Hydrogen expertise fully embedded in flight training systems and courses by 2040

6.6 Scenario modelling

6.6.1 Purpose and scope

This annex documents the modelling approach used to estimate the potential emissions impact and avoided carbon cost associated with hydrogen aviation adoption under the scenarios presented in ***Section 4***. The analysis is designed to support roadmap development and sequencing, rather than to provide a full economic appraisal or market forecast.

The model quantifies:
- In-sector aviation CO_2 emissions under different adoption pathways.
- Incremental emissions savings attributable to hydrogen (zero-emission aircraft, ZEA); and
- Indicative avoided carbon compliance costs, based on an exogenous carbon price trajectory.

The modelling explicitly does not estimate:
- capital or operating costs of hydrogen aircraft;
- hydrogen fuel production or supply costs;
- aerodrome or system infrastructure investment requirements; or
- net economic benefits or welfare impacts.

Accordingly, the outputs should be interpreted as abatement potential and carbon-liability exposure, not as a business case for hydrogen aviation.

6.6.2 System boundary and definition of net zero

The model covers in-sector CO_2 emissions from aviation only. Emissions are calculated from:
- fossil jet fuel combustion;
- residual lifecycle emissions from SAF; and
- zero tailpipe CO_2 emissions from hydrogen aircraft.

Consistent with the UK Jet Zero Strategy and CCC pathways, aviation does not reach zero in-sector emissions by 2050 in any scenario. Instead, residual emissions remain and are assumed to be balanced through greenhouse gas removals elsewhere in the economy.

As a result:

- the modelled "Total emissions" trajectory does not fall to zero by 2050; and
- the roadmap does not assume that hydrogen aviation alone delivers net-zero aviation outcomes.

This treatment aligns with Jet Zero analytical assumptions, which identify zero-emission flight as a complementary abatement wedge alongside SAF, efficiency improvements and demand-side measures.

A3) Hydrogen eligibility and fuel displacement assumptions

Hydrogen aviation is applied only to a defined eligible share of aviation energy demand, reflecting realistic aircraft and route constraints.

In the Central (baseline) scenario:

- Hydrogen is assumed to apply to ~30% of total aviation fuel demand, broadly corresponding to domestic and short-haul operations.
- Hydrogen penetration is expressed as a share of energy within the eligible domain, not of total aviation fuel.
- This structure ensures that hydrogen abatement is bounded by operational feasibility and does not implicitly assume long-haul or wide-body hydrogen adoption.

This treatment is deliberately conservative and is consistent with Jet Zero central assumptions, under which zero-emission flight contributes on the order of ~2 $MtCO_2$ of in-sector abatement by 2050.

Higher or lower eligible shares are explored qualitatively through the High and Low Ambition scenarios and represent key sensitivities in the roadmap.

A4) Emissions accounting and hydrogen abatement

For each year and scenario:

1. Total aviation fuel demand is allocated between hydrogen and hydrocarbon fuels based on the eligible fuel share and hydrogen penetration.
2. Remaining hydrocarbon fuel is split between SAF and fossil jet fuel.
3. CO_2 emissions are calculated using standard jet fuel emission factors, with SAF emissions adjusted for lifecycle savings.
4. A counterfactual "no-hydrogen" emissions pathway is calculated using identical assumptions but with zero hydrogen penetration.
5. Hydrogen emissions savings are calculated as the difference between emissions with and without hydrogen.

This approach ensures that:

- hydrogen abatement is calculated incrementally;
- no double-counting occurs between SAF and hydrogen; and
- hydrogen impacts are transparent and auditable.

A5) Carbon price and avoided cost metric

The avoided carbon cost is calculated as:

Annual hydrogen CO_2 savings × carbon price (£/tCO_2)

This metric represents avoided carbon compliance liability, not cash savings or net benefit.

Key characteristics:

- The carbon price is exogenous to the aviation system.
- Avoided carbon costs scale linearly with the assumed carbon price.
- The metric does not reflect who captures the benefit (airlines, government, society), nor how costs are redistributed.

The avoided carbon cost is therefore best interpreted as a policy-relevant valuation signal, useful for comparing abatement levers on a consistent basis, rather than as an investment justification.

A6) Annual vs cumulative impacts

Hydrogen aviation delivers a late-onset but persistent abatement effect. As a result, annual impacts in 2050 materially understate its overall contribution.

In the Central scenario:

- Annual avoided carbon cost in 2050 is approximately £0.5 bn per year.
- Cumulative avoided carbon cost over 2025-2050 is approximately £3.5 bn.

Across scenarios, cumulative avoided carbon costs range from ~£3-5 bn, reflecting differences in adoption timing, eligible fuel share and hydrogen penetration. Cumulative metrics are therefore the preferred basis for assessing hydrogen aviation's contribution to the net-zero transition, particularly for infrastructure and regulatory planning.

A7) Key sensitivities and uncertainties

The modelling results are most sensitive to the following parameters:

1. **Carbon price trajectory**: Avoided carbon costs scale directly with the assumed carbon price and do not reflect endogenous market responses.
2. **Eligible fuel share**: The proportion of aviation energy to which hydrogen can be applied is the dominant technology-side driver of impact.
3. **Hydrogen penetration within the eligible domain**: Adoption rates materially affect both annual and cumulative abatement outcomes.

Secondary sensitivities include total fuel demand growth and efficiency assumptions. SAF lifecycle savings assumptions have limited influence on hydrogen-specific results but affect overall emissions levels.

A8) Interpretation and policy alignment

The modelling confirms that hydrogen aviation:

- delivers modest but material in-sector abatement by 2050;

- has a much larger cumulative impact over time;
- does not eliminate residual aviation emissions; and
- requires coordination with SAF, efficiency measures and GGRs to achieve net-zero outcomes.

These findings are consistent with:
- Jet Zero and CCC pathways, which identify zero-emission flight as a necessary but insufficient contributor to net-zero aviation; and
- international evidence (e.g. AZEA, IATA), which similarly emphasises long-term, system-level integration rather than near-term cost optimisation.

A9) Limitations

Key limitations of the analysis include:
- exclusion of capital, operating and infrastructure costs;
- exclusion of upstream hydrogen lifecycle emissions;
- simplified treatment of route structure and fleet heterogeneity; and
- reliance on scenario-based rather than probabilistic assumptions.

These limitations are appropriate for a roadmap and sequencing exercise but would need to be addressed in any full economic appraisal or investment case.

6.7 Glossary

Table A1: Glossary

Term	Definition
Aerodrome Safety Management System (SMS)	A systematic approach to managing safety at an aerodrome, including organisational structures, accountabilities, policies and procedures used to identify hazards, manage risks and assure safety performance. In the context of hydrogen operations, SMS integrates hydrogen-specific hazards, procedures and emergency response arrangements.
Aeronautical Information Publication (AIP)	An official, regularly updated, and legally binding document issued by a state's aviation authority containing essential information for air navigation, such as regulations, procedures, airport data, and, in some cases, aeronautical charts.
Air Navigation Order (ANO)	The UK statutory instrument that sets out the legal framework for civil aviation, including aircraft operations, airworthiness and aerodrome requirements.
Alternative Means of Compliance (AMC)	Non-binding material published by aviation authorities that describes acceptable methods for demonstrating compliance with regulatory requirements.
Certification Basis	The set of applicable airworthiness requirements, including regulations, Certification Specifications and Special Conditions, against which an aircraft, engine or system is approved.
Certification Readiness Levels (CRL)	CRL is a nine-level scale used to evaluate the maturity of a regulatory system for the certification and operational readiness of aeronautical products

Design Organisation Approval (DOA)	An approval granted to an organisation allowing it to design aircraft and aeronautical products and to demonstrate compliance with applicable airworthiness requirements.
Fuel Quality Assurance (QA)	Processes and controls used to ensure aviation fuel meets defined quality, purity and contamination standards, including verification of interfaces between fuel supply, storage, refuelling and aircraft systems.
Gaseous Hydrogen (GH2)	Hydrogen stored and supplied in gaseous form, expected to support trials and early operations at selected aerodromes.
General Aviation (GA)	Covers all civil aircraft operations other than commercial air transport (scheduled flights) or commercial aerial work.
Guidance Material (GM)	Non-binding explanatory material that supports the application of regulatory requirements and Acceptable Means of Compliance.
Hydrogen Safety Zones	Defined areas around hydrogen storage, refuelling and operational activities at aerodromes where specific controls apply to manage hydrogen-related hazards.
International Civil Aviation Organization (ICAO) Compatibility	Alignment with ICAO Standards and Recommended Practices to support international interoperability and aviation safety.
Liquid Hydrogen (LH2)	Hydrogen stored at cryogenic temperatures in liquid form, offering higher energy density by volume than gaseous hydrogen.
Means of Compliance (MoC)	Approved methods used to demonstrate compliance with airworthiness or operational requirements.
Rescue and Fire Fighting Services (RFFS)	Aerodrome-based emergency response services responsible for aircraft rescue and firefighting.
Sustainable Aviation Fuels (SAF)	Is a cleaner, drop-in alternative to conventional jet fuel, made from waste oils, agricultural residues, or synthetic sources, which can reduce aviation emissions.
Technical Readiness Levels (TRL)	TRL is a nine-point, NASA-developed, standardized system used to assess the maturity of technologies.
Zero-Emission Aircraft (ZEA)	Aircraft that produce no CO2 emissions at the point of operation, including hydrogen-powered aircraft.

6.8 Definitions and concepts

Table A2: Definitions

Term	Definition
Hydrogen Aviation	The use of hydrogen as an aviation energy source, including fuel cell-electric propulsion and hydrogen combustion, together with the associated aircraft, fuel supply, aerodrome infrastructure, operations and regulatory frameworks required to maintain aviation safety.
Demonstrate (2026-2030)	The roadmap period focused on trials, demonstrations and evidence generation to identify hydrogen-specific hazards, regulatory gaps and operational considerations.
Prove	The roadmap period focused on developing repeatable,

UK Civil Aviation Authority

(2030-2035)	certifiable solutions and applying hydrogen-specific regulatory material to early commercial deployments.
Scale and Sustain (2035 onwards)	The roadmap period focused on embedding hydrogen aviation as routine practice through mature regulatory frameworks, infrastructure and operational oversight.
Hydrogen-Specific Special Conditions (SC)	Additional airworthiness requirements developed where existing certification specifications do not adequately address novel features introduced by hydrogen propulsion, storage or systems.
Jet Zero Strategy	The UK government's policy framework for achieving net-zero aviation emissions by 2050, which this roadmap supports through safety-led enabling actions rather than delivery commitments.

Technical Readiness Levels (TRL) and Certification Readiness Levels (CRL)

Table A3: CRL levels as per CONCERTO[31]

CRL	Short label	Definition
CRL 1	Regulator familiarisation	Safety authority familiarised with the technology and Concept of Operations (CONOPS)
CRL 2	CONOPS & safety objectives	CONOPS assumptions and high-level safety objectives confirmed with stakeholders
CRL 3	Regulatory gap analysis	Identification of affected regulations and priority gaps requiring amendment or development
CRL 4	Certification principles	Main principles for technical standards defined and roadmap established for rulemaking and standardisation
CRL 5	Aviation framework readiness	Roadmap defined for wider aviation framework readiness (airworthiness, operations, ATM, licensing, continuing airworthiness, etc.)
CRL 6	Draft regulatory material	Necessary technical knowledge confirmed and first drafts of regulatory or rulemaking material available (e.g. via IPC, PAC, TAC)
CRL 7	Generic certification basis	Mature draft generic certification basis elements available (e.g. published Generic SC, Interpretative Material, or MoC)
CRL 8	Product certified	Product integrating the technology is certified (including organisational approvals where applicable)
CRL 9	Operationally proven	Certified system proven through operational service and routine oversight

[31] CONCERTO | Clean Aviation

Table A4: TRL levels as per NASA[32]

TRL	Short label	Definition
TRL 1	Basic principles	Basic principles observed and reported
TRL 2	Technology concept	Technology concept and/or application formulated
TRL 3	Proof of concept	Analytical and experimental proof of concept demonstrated
TRL 4	Lab validation	Component and/or breadboard validation in laboratory environment
TRL 5	Relevant environment validation	Component validation in a relevant environment
TRL 6	Subsystem demonstration	Subsystem or system model or prototype demonstrated in a relevant environment
TRL 7	System prototype demonstration	System prototype demonstrated in an operational environment
TRL 8	Flight qualified	Actual system completed and flight qualified through test and demonstration
TRL 9	Flight proven	Actual system proven through successful operations across the full flight envelope

The below figure shows the alignment between TRL, Manufacturing Readiness Levels (MRL) and CRL.

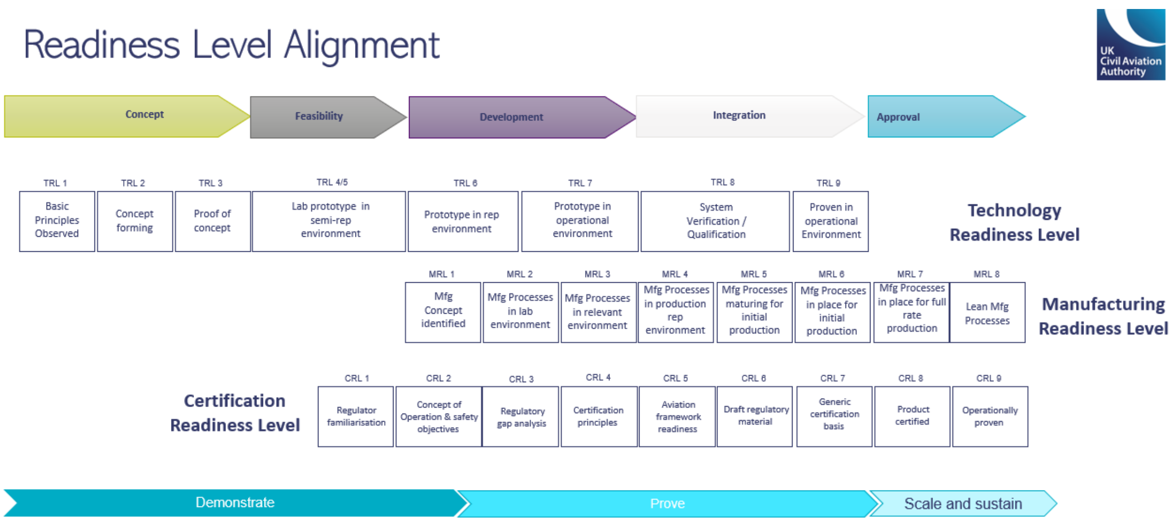


Figure A1: TRL, MRL and CRL alignment

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[32] [Technology Readiness Levels - NASA](#)