TECHNOLOGY ROADMAPS

Technology Pathways to Enable Zero-Carbon Emission Flight

FLY ZERO

AEROSPACE TECHNOLOGY INSTITUTE

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ABOUT FLYZERO

Led by the Aerospace Technology Institute and backed by the UK government, FlyZero began in early 2021 as an intensive research project investigating zero-carbon emission commercial flight. This independent study has brought together experts from across the UK to assess the design challenges, manufacturing demands, operational requirements and market opportunity of potential zero-carbon emission aircraft concepts.

FlyZero has concluded that green liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft utilising fuel cell, gas turbine and hybrid systems. This has guided the focus, conclusions and recommendations of the project.

This report forms part of a suite of FlyZero outputs which will help shape the future of global aviation with the intention of gearing up the UK to stand at the forefront of sustainable flight in design, manufacture, technology and skills for years to come.

To discover more and download the FlyZero reports, visit **ati.org.uk**

ACKNOWLEDGEMENTS

Lead Authors

Lauren Hadnum
FlyZero Industrial Strategy Manager

Co-Authors

Mark Pacey
Katy Milne

FlyZero contributing companies: *Airbus, Belcan, Capgemini, easyJet, Eaton, GE Aviation, GKN Aerospace, High Value Manufacturing Catapult (MTC), Mott MacDonald, NATS, Reaction Engines, Rolls-Royce, Spirit AeroSystems.*

These roadmaps have been developed with a view to accelerate zero-carbon technology development and maximise the potential future value for the UK. They are unconstrained by the availability of funding.

Department for
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EXECUTIVE SUMMARY

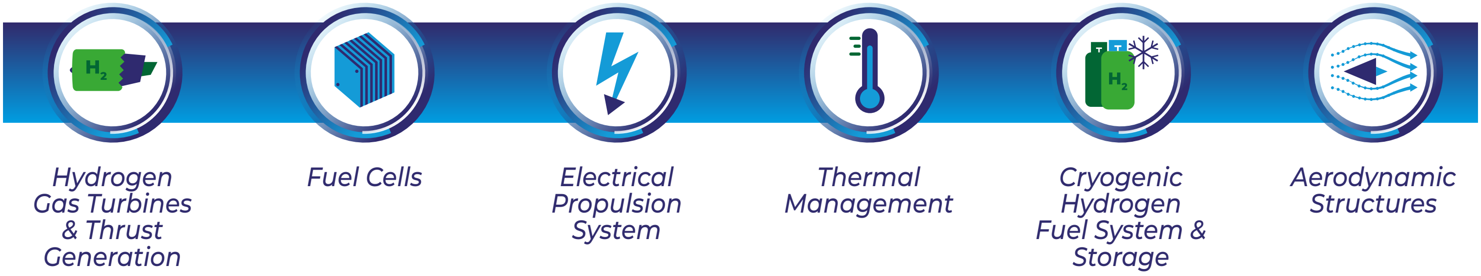
The Aerospace Technology Institute (ATI) FlyZero project has found that liquid hydrogen aviation is feasible and capable of operational ranges up to 5,250 nautical miles (nmi). This range could enable all worldwide flight paths with one stop.

FlyZero has identified two propulsion architectures which could deliver large scale zero-carbon flight:

- A liquid hydrogen fuel cell electric aircraft, capable of scaling to regional aircraft
- A liquid hydrogen gas turbine aircraft, capable of scaling to midsize aircraft

The FlyZero technology roadmaps outline developments which could be aligned to one or both architectures. Collectively they detail a route to transforming the aviation industry to utilise hydrogen as its primary fuel and potentially completely decarbonise aviation. The ATI FlyZero project team has identified 13 technology 'bricks' that are required to enable hydrogen flight. Six hydrogen aircraft bricks are revolutionary aerospace technologies fundamental to realising liquid hydrogen fuelled aircraft. Seven cross-cutting bricks are critical to ensuring that hydrogen aircraft are commercially and operationally enabled and deliver tangible sustainability improvements. A technology roadmap has been generated for each technology brick, and major findings for each brick as well as integration steps are outlined in this report.

Hydrogen Aircraft Technology Bricks



Cross Cutting Technology Bricks

Figure 1 – FlyZero technology bricks

The technology roadmaps have been created to enable technology readiness level (TRL) 6 of the first generation of hydrogen technology by 2025. When and how a hydrogen fleet may come to market is still uncertain. However, hydrogen aircraft are expected to reach market in the early to mid-2030s, scaling up to the narrowbody market by mid-2040s. The FlyZero technology roadmaps demonstrate the importance of significantly ramping up technology development in support of this introduction.

The UK has world leading capability in several of the roadmap technologies including gas turbines, fuel systems, aerodynamic structures, thermal management and electrical systems. With its deep understanding of the certification challenges associated with these systems, UK aerospace can provide the technical leadership required to compress the development cycle and accelerate the delivery of hydrogen powered aircraft to market.

This report details major tests, challenges and opportunities on the pathway to demonstrating and certifying a hydrogen powered aircraft. This includes the tests which are required to demonstrate performance of a hydrogen aircraft propulsion architecture, fuel system, dry wing, airport refuelling approach, environmental impact and which culminate in integrated flight test. Creating the infrastructure and test programmes outlined in this report, either in the UK or in collaboration internationally, is a vital step in delivering hydrogen aircraft to market. These tests will be on the critical path for hydrogen technology development and, depending on industry ambition laid out in this report, flying demonstrators of regional or larger scale aircraft will be required from 2026 onward.

While developing the technology roadmaps and concepts [1], FlyZero has identified the top five key technical risks and long lead items for the development of hydrogen aircraft.

Climate science

Significant research is required in the short term to develop an understanding of the effects that CO_2 and non-CO_2 emissions have on our climate. This will drive market decisions.

Fundamental liquid hydrogen behaviour

Due to the low TRL nature of these technologies, there are limited skills and testing capabilities in the UK to understand the behaviour of liquid hydrogen.

Material properties

Limited data exists for aerospace grade materials for use with liquid hydrogen. Data from adjacent industries, such as the space industry, is expected to have gaps for aerospace applications.

Hydrogen combustion systems

System design, manufacture and rig testing to accommodate the different combustion behaviour of hydrogen will be a significant challenge as an area of high novelty.

Cryogenic hydrogen fuel system and storage

Cryogenic fuel system understanding and technology are relatively immature. Components and integration will bring significant challenges to meet performance and life requirements.

To address these major challenges and bring hydrogen technologies to market the FlyZero project has identified four key recommendations. These actions would require UK R&D investment in the order of £270m per year.

Key recommendations

- **Deliver the research and development technologies identified in the FlyZero technology roadmaps**

  The technologies identified in the FlyZero technology roadmaps lay the pathway for a credible route to realising hydrogen aviation. Investment and collaboration building to deliver these technologies is required without delay. At this period of high disruption, it is acknowledged that technology development is high risk, most of the novel technologies for hydrogen are low TRL (1-3). An approach to this development which embraces early testing and simulation to manage uncertainty and data gaps will be required to deliver these technology roadmaps on time. Delivery of this action can only be achieved via a coordinated approach by UK industry, the academic and research network, the ATI and government.

- **Deliver underpinning infrastructure.**

  Early development of test infrastructure, identified in this report, is an enabler for delivery of these technologies. It is also a mechanism for upskilling the aerospace and aviation industry, which has not managed cryogenic hydrogen. A comprehensive testing programme will be required, including unit, sub-system and system testing to de-risk and validate zero-carbon commercial aerospace. Again, delivery of this action can only be achieved via a coordinated approach by UK industry, the academic and research network, the ATI and government.

- **Deliver manufacturing developments alongside product developments.**

  The introduction of hydrogen aviation to achieve the 2050 net zero targets will be a product challenge but also a significant manufacturing challenge. Airbus A320s are to be delivered at a rate of 64 per month by mid-2023. By 2050, each major OEM is anticipated to supply narrowbody aircraft at a rate of over 100 per month. Development to achieve rate enables an earlier fleet to market, which maximises decarbonisation. Delivery of these technologies will support the world-leading research and development work carried out in the UK to translate into manufacturing jobs, securing 40 plus years of aerospace production.

- **Support skills development and cross-sector collaboration.**

  Delivering the technology roadmaps in the timescales set out in this report will require significant new skills and/or upskilling in support of the above actions. In the short term, when experience in the use of liquid hydrogen is at a low level, cross-sector collaboration, and potentially a cross-sector approach to shared infrastructure, could concentrate skills in the UK and facilitate shared learning on standards and safe handling practices.

ATI FlyZero 'The Case for the UK to Accelerate Zero-Carbon Emission air travel' [2] outlines the economic and regulatory context which would be required, in addition to the above actions, to support the delivery of hydrogen aircraft.

In summary, the FlyZero study has indicated that liquid hydrogen powered aviation is feasible. While the focus of FlyZero has been large aircraft, to maximise potential carbon impact, the full ATI Technology Strategy captures all pathways to net zero flight. This includes technology developments to support battery electric architectures for sub-regional flight and ultra-efficient aircraft powered by drop-in alternatives to kerosene (referred to as sustainable aviation fuels (SAF)). To achieve the government's 2050 net zero vision the recommendations on hydrogen, above, should be progressed in parallel with development and deployment of SAF. The technology roadmaps detail a route to transforming the aviation industry to utilise hydrogen as its primary fuel and potentially completely decarbonise aviation. Delivery of these recommendations will develop product technology, UK skills and expertise in a growing market, and establish the UK as a key location for developing hydrogen technologies.

01. INTRODUCTION

FlyZero has concluded that green liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft [3]. This report and the supporting technology roadmaps detail the pathway for technology development to deliver liquid hydrogen aviation. The supporting technology roadmaps are listed in **Appendix B – Technology Roadmaps**.

Liquid hydrogen's high energy density means reduced fuel mass, which is particularly advantageous for longer range aircraft. A family of hydrogen powered aircraft that could achieve operational ranges up to 5,250 nautical miles (nmi) would address 92% of tailpipe carbon emissions. If a single stop was introduced for all air transport routes above 5,250 nmi, then tailpipe carbon emissions could be fully eliminated. In 2050, this could enable a £200bn per year zero-carbon aircraft market and a 45% reduction in CO_2 emitted by aviation.

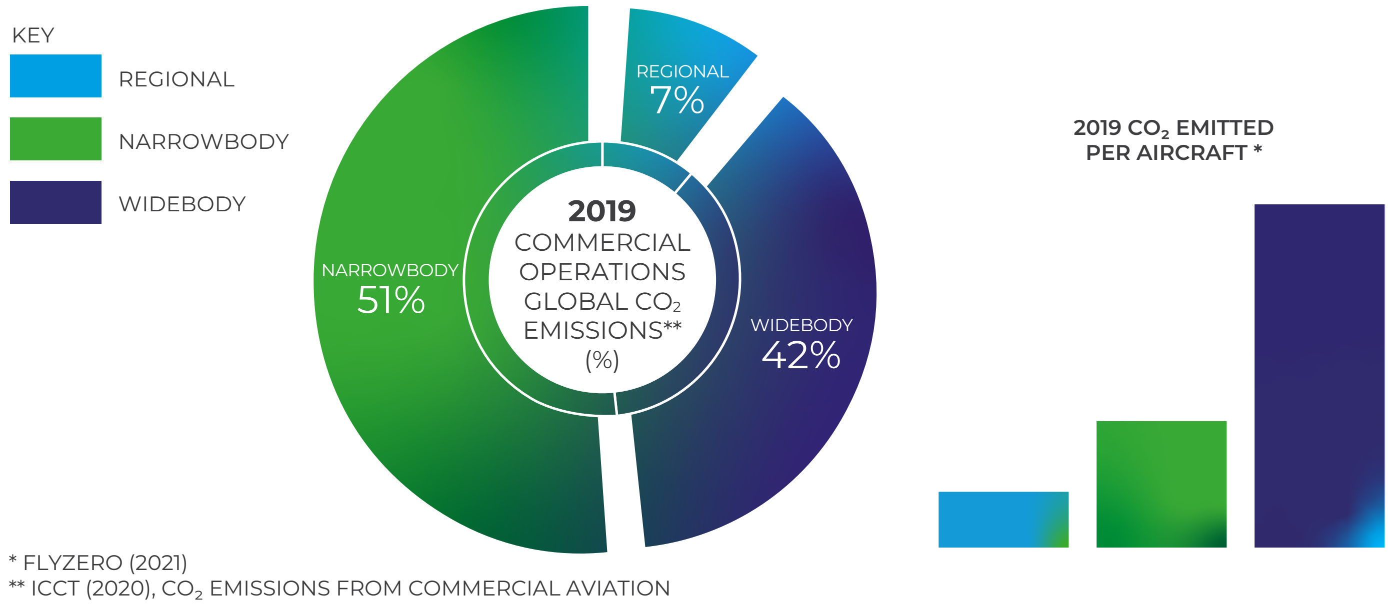


Figure 2 – Fleet and CO_2 impact.

Larger (regional, narrowbody and widebody) aircraft are currently responsible for the majority of CO_2 emissions (**Figure 2**). Two zero-carbon architectures have the potential to operate at ranges in these market segments.

Liquid hydrogen fuel cell electric propulsion, combined with near term thrust generation technologies and architectures, have potential to power regional aircraft. Liquid hydrogen gas turbines have the potential to power aircraft up to midsize with 5,250 nmi operational range [3]. **Figure 3** summarises the applicability of propulsion systems to aircraft type, as well as showing the scope of the FlyZero project.

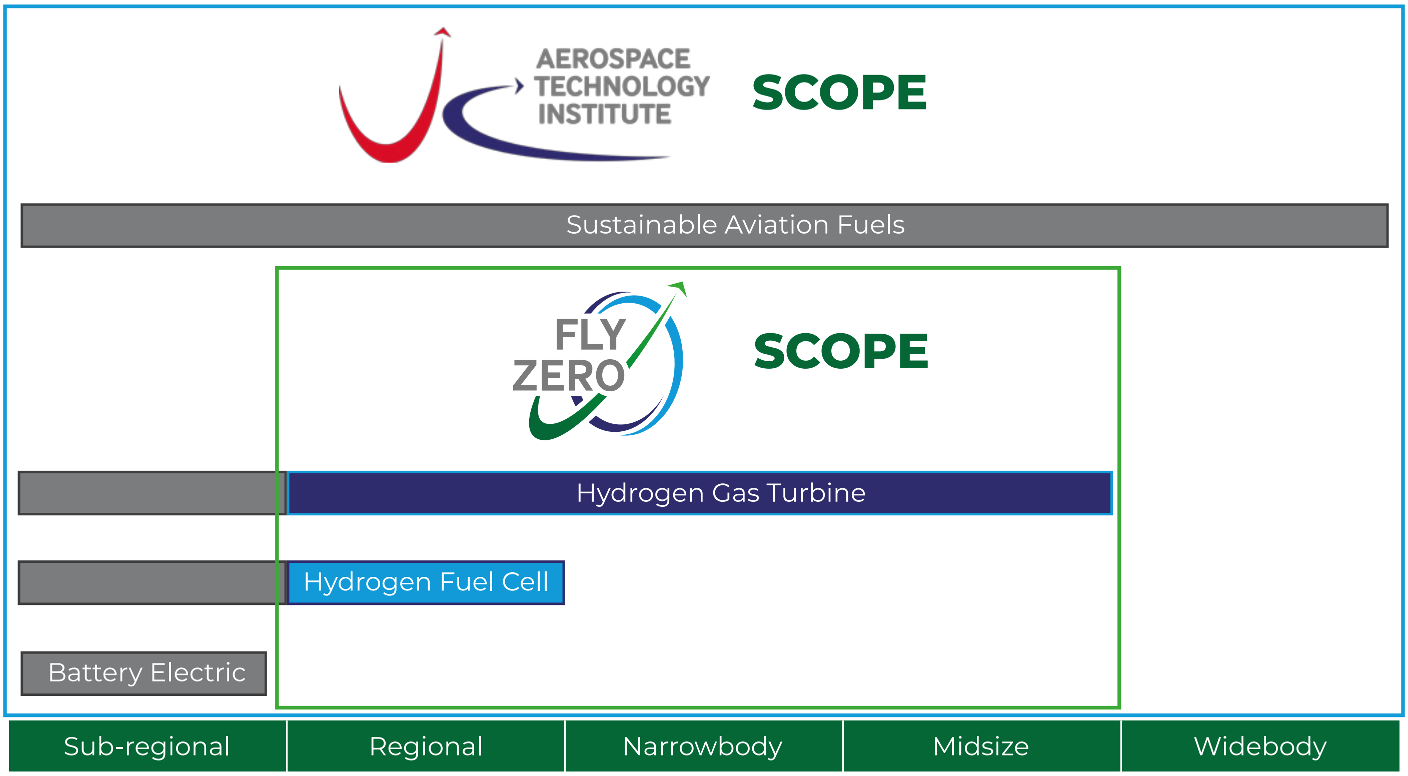


Figure 3 – Applicability of propulsion systems to market and scope of the FlyZero project.

While the Aerospace Technology Institute's (ATI) Technology Strategy covers technology pathways to net zero flight for all market segments from sub-regional to widebody, the ATI FlyZero project has limited its scope to aircraft between regional and midsize (see Figure 3).

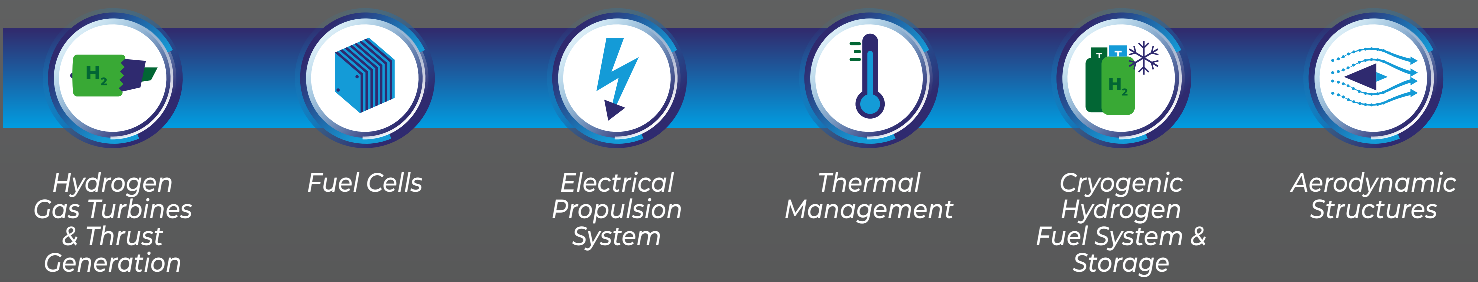
FlyZero has not considered sub-regional flight since it has minimal CO_2 impact, approximately 1% of global aviation CO_2 emissions **[4]**. Battery electric solutions are a good potential candidate for primary propulsion for the sub-regional market and numerous battery electric aircraft development programmes are underway. FlyZero has also not considered widebody aircraft with operational ranges >5,250 nmi. These aircraft are most likely to be powered by drop-in alternatives to kerosene, referred to as sustainable aviation fuels (SAF) rather than hydrogen. This report focuses on the hydrogen technologies which have potential to scale to address the CO_2 impact of aviation. However, to achieve maximum decarbonisation by 2050 it is recognised that development of sub-regional and particularly SAF technologies alongside hydrogen is of critical importance.

This report lays out the technology pathway to hydrogen powered flight for regional to midsize aircraft and signposts to the FlyZero technology roadmaps, **Appendix B – Technology Roadmaps**. **Section 2** identifies thirteen technology bricks. **Section 3** lays out the approach that FlyZero used to generate technology roadmaps for each technology brick, including development timescale assumptions. **Section 4** details the technology demonstration pathway, considering major tests required for two aircraft architectures: hydrogen fuel cell electric and hydrogen gas turbine. **Section 5** summarises the key developments required for each technology brick. **Section 6** provides an overview of UK capability and opportunity, followed by conclusions and recommendations in **Section 7**.

02. FLYZERO TECHNOLOGY BRICKS AND ROADMAP APPROACH

The ATI FlyZero project team has identified thirteen technology bricks which are required to enable hydrogen powered flight for regional to midsize aircraft. Six hydrogen aircraft technology bricks are revolutionary aerospace technologies fundamental to realising liquid hydrogen fuelled aircraft. Seven cross-cutting technology bricks are critical to ensuring that hydrogen aircraft are commercially and operationally enabled and deliver tangible sustainability improvements. A technology roadmap has been generated for each technology brick.

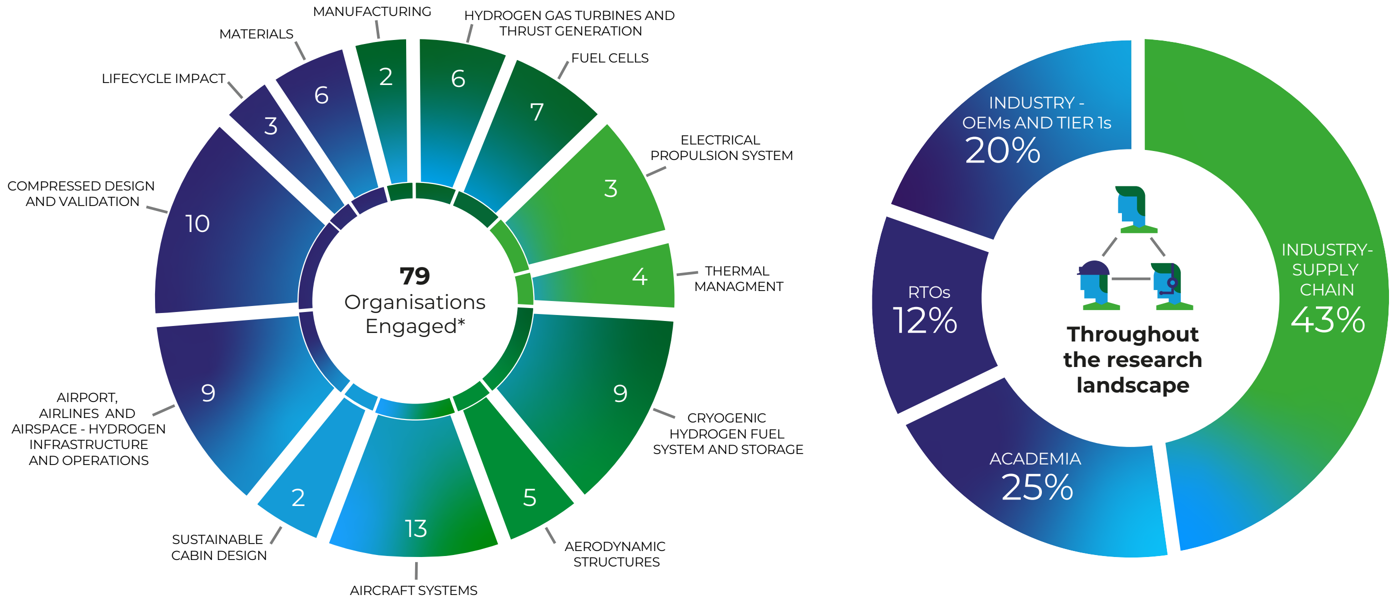
Hydrogen Aircraft Technology Bricks



Cross Cutting Technology Bricks

Figure 4 – FlyZero Technology Bricks.

During the project, FlyZero developed three concept aircraft, with the aim of understanding the technology challenges and developments needed. Technology assessment was carried out both by the 100 strong FlyZero team and by the 50 industrial and academic organisations that FlyZero partnered with in delivery. Although these concepts aided the roadmap development, the technologies in the roadmaps could be applied to any zero-emission regional, narrowbody or midsize aircraft, not just the FlyZero concepts. FlyZero also sought input and peer review from UK industry and the research community. A summary of the technology roadmap engagements can be seen in **Figure 5**.



**Individuals from different departments in large organisations counted separately*

Figure 5 – FlyZero engagement on technology roadmaps.

The FlyZero technology roadmaps capture development typically to TRL6 unless otherwise indicated, using the NASA TRL scale as a basis for the assessments (**Figure 6**).

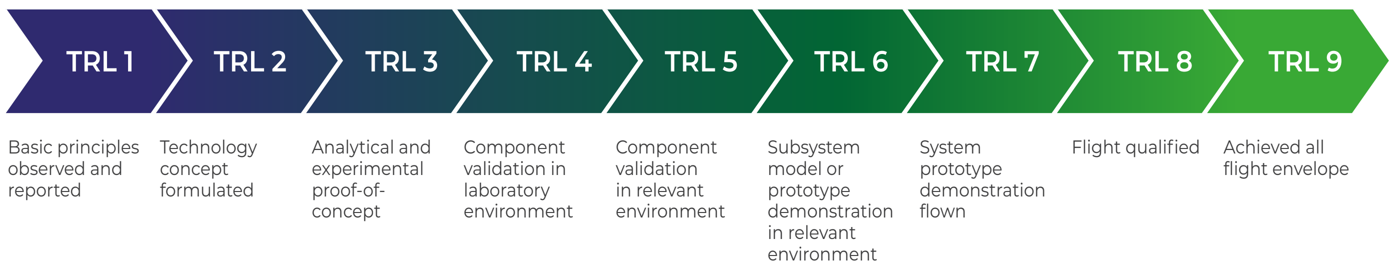


Figure 6 – NASA TRL scale used by FlyZero in its assessments.

The roadmaps detail essential and competitive technology developments. Essential developments are those required to bring a hydrogen product to market. Competitive technology developments are those which deliver subsequent performance improvements. Competitive technology developments may therefore include developments of second generation technologies, which could eventually replace the first generation technologies.

The technology roadmaps also include technology indicator tables, which aim to show the expected industry development required to stay at the forefront of technology development for each technology brick. The metrics aim to be ambitious but achievable in the timescales set out in the technology roadmaps.

03. PRODUCT DEVELOPMENT TIMELINES

There is still high uncertainty about how and when hydrogen aircraft could come to market.

Two scenarios for entry into service (EIS) of hydrogen aircraft are shown in **Figure 7** below. These timelines relate to generic aircraft types as opposed to specific aircraft.

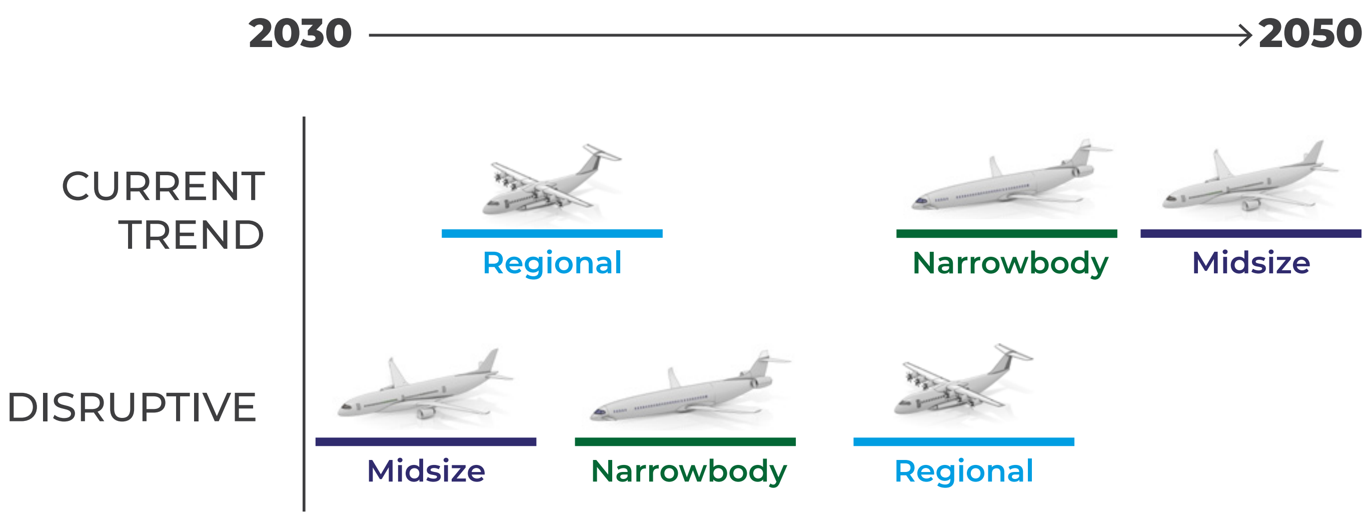


Figure 7 – FlyZero scenarios for entry into service of hydrogen powered aircraft.

- **Current trend:** In this scenario, the development rate of hydrogen technology means industry delivers the first hydrogen regional aircraft to market in 2035. This slower market adoption, coupled with the increasing need for lower carbon impact, will mean an ultra-efficient, hydrocarbon fuelled narrowbody product enters service before a hydrogen fuelled narrowbody. The need to secure return on investment for the hydrocarbon fuelled aircraft delays the scaling of hydrogen to larger aircraft. Hydrogen narrowbody and midsize aircraft might only reach the market in the late 2040s to early 2050s.

- **Disruptive – Midsize 1st:** In this scenario, high investment and early demonstration of hydrogen technology enables a hydrogen powered midsize aircraft to come to market in the early to mid-2030s. This decarbonises a market segment which currently has higher annual emissions per aircraft than regional or narrowbody (**Figure 2**). Successful demonstration of hydrogen enables a narrowbody aircraft to follow quickly. Of the many scenarios that FlyZero considered, this scenario has the largest carbon reduction and UK market opportunity by 2050.

These two scenarios represent bookends between which there are several other potential scenarios and exploitation routes. In both scenarios, hydrogen aircraft enter service in the early to mid-2030s and are scaled for the lucrative narrowbody market by the mid-2040s. These timescales reinforce the importance of significantly ramping up technology development in support of hydrogen aircraft.

The FlyZero technology roadmaps show technology developments needed to achieve TRL6 for the first generation of hydrogen technology by 2025. This timescale is selected to align with either scenario above.

The current aircraft fleet reflects over 50 years of development. Hydrogen aerospace technologies will continue to be developed to 2050 and beyond. Further progress on generic technologies such as light weighting will also be critical for hydrogen, to help reduce fuel burn and increase range.

04. TECHNOLOGY PATHWAY

The technologies in the FlyZero technology roadmaps could be applicable to:

- A hydrogen fuel cell electric propulsion aircraft
- A hydrogen gas turbine propulsion aircraft
- Both

This section details the major integration challenges and major testing and demonstration required for both aircraft architectures (hydrogen fuel cell electric and hydrogen gas turbine) covering:

- Propulsion
- Fuel system
- Dry wing
- Airport refuelling
- Environmental impact
- Integrated flight testing

Further detail on major tests and demonstrations is included in ATI FlyZero 'Zero-Carbon Aerospace Technology Validation Strategy' [5]. The FlyZero technology roadmaps give further information on the detail testing required at the level of each technology brick sub-system.

Creating the infrastructure and test programmes outlined in this report, either in the UK or in collaboration internationally, is a vital step in delivering hydrogen aircraft to market. These tests will be on the critical path for hydrogen technology development and, depending on industry ambition laid out in this report, flying demonstrators of regional or larger scale aircraft will be required from 2026 onward.

04.1
HYDROGEN FUEL CELL ARCHITECTURES

Major integration findings

FlyZero identified the following major integration findings for fuel cell architectures:

- Electrical propulsion systems lend to distributed propulsion. The fuel cell and motor are sized for peak take-off power demand, adding propulsors was seen to improve the weight efficiency of the system.
- In the future, a fuel cell powering an open rotor may be an opportunity to enable longer range, faster cruise applications.
- There is a potential optimisation of system layout to utilise plug and play storage and propulsion units (pods). This may allow shorter range applications to reduce mass and complexity from the airframe and enable replaceable tanks for modular maintenance.
- Fuselage diameter is a challenge for all configurations due to the higher volume of storage required for hydrogen, but particularly for regional applications where the fuel cell is appropriate. A larger diameter, more spherical hydrogen tank aids gravimetric efficiency, but increasing the fuselage size to allow for this increases the drag of the airframe.
- Thermal management will be a key challenge for fuel cells. The placement of this system has a drag impact, and the weight of the system reduces the overall power density of the fuel cell solution.
- High voltage electrical systems and cables will be required. To transmit power, 1 kV to 3 kV voltage levels were deemed essential for acceptable resistive losses and cable masses.
- Aircraft on-board systems, such as air conditioning and entertainment systems, could be powered by a gas turbine, fuel cell or internal combustion auxiliary power unit (APU). More work is required to determine the most appropriate selection for each aircraft, but integration of multiple systems would each bring different integration challenges.

Fuel cell propulsion specific testing

The electrical propulsion system must show it is capable of withstanding flight operating conditions including vibration, reduced temperature and pressure. Vibration testing can be performed on individual components in the system (battery, fuel cell, power electronics, motor). However, full environmental testing at reduced temperature and air pressures requires an environmental chamber. No current operational facility has this full capability although electrical and altitude test facilities do exist in the UK. Further work is needed to confirm if an existing facility could be adapted given the challenges of hydrogen supply and storage. Given the novelty of fuel cell electrical propulsion to aviation, these tests must be carried out to demonstrate an acceptable level of safety prior to flight.

Major tests

Fuel cell architectures are applicable to the regional market segment.

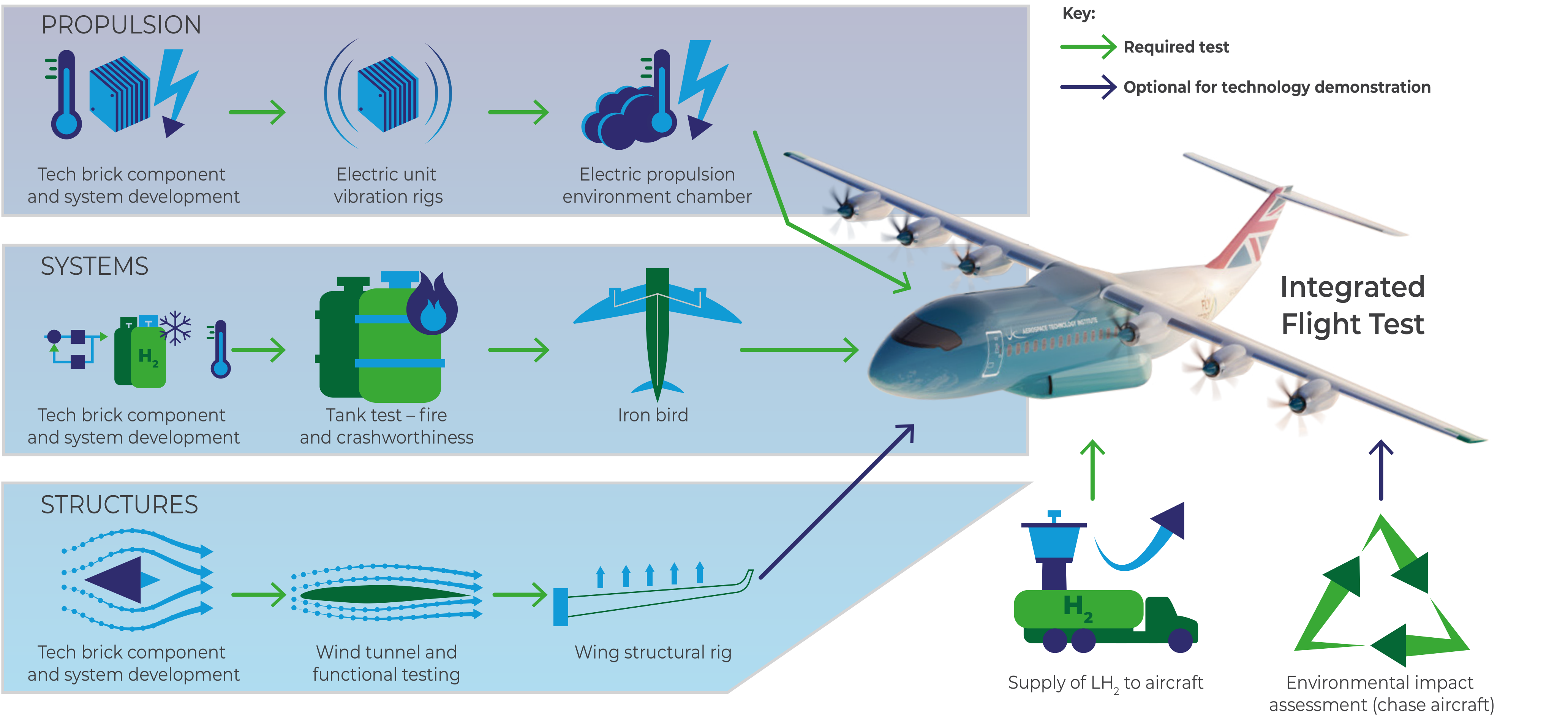


Figure 8 – Hydrogen fuel cell aircraft architecture – major tests.

04.2 HYDROGEN GAS TURBINE ARCHITECTURES

Major integration findings

FlyZero identified the following major integration findings for gas turbine architectures:

- A hydrogen gas turbine propulsion system can scale to larger applications than a fuel cell architecture. More complex and integrated structures may be possible than in smaller applications. For example, for narrowbody and midsize aircraft, tanks could be integrated into the fuselage structure thus improving airframe structural performance.
- For midsize architectures, centre of gravity management requires delta tanks toward the front of the aircraft to ensure weight and balance stay within reasonable limits. These tanks may be smaller and therefore would typically have a poorer gravimetric efficiency, reducing aircraft performance.
- There are various opportunities associated with dry wing for gas turbine architectures, including locating flap mechanisms within the wing structure rather than requiring external fairings.
- Thermal management will also be a key challenge for gas turbine architectures. It will be necessary to modify the heat management system to heat liquid hydrogen before it is injected into the combustion chamber.
- Aircraft on-board systems, such as air conditioning and entertainment systems, could be powered by a gas turbine, fuel cell or internal combustion auxiliary power unit (APU). More work is required to determine the most appropriate selection for each aircraft, but integration of multiple systems would each bring different integration challenges.

Propulsion specific testing

Most gas turbine technologies could be read across from kerosene products. Testing will focus on the major sub-systems which have been modified to enable the burning of hydrogen. Predominantly, these are the combustion, control and thermal management systems.

An engine test provides fully representative conditions for the combustor and is also an opportunity to confirm the impact of hydrogen combustion on emissions including NO_x and noise. A representative aircraft fuel system would be needed for engine testing since the condition of the hydrogen will affect how it burns. No gas turbine engine test beds currently exist with liquid hydrogen fuel supply installed, although Rolls-Royce have indoor engine test beds in both Bristol and Derby which, if repurposed, could be a route to demonstration for Rolls-Royce and its supply chain. However, there are safety considerations when testing with liquid hydrogen that may drive testing to a purpose-built outdoor facility.

The ability of the engine to relight at altitude is a certification requirement. It is expected this would be conducted on ground in an altitude test facility (ATF), but there is no facility globally adapted for liquid hydrogen. A flying test bed is an alternative option. This would have limitations in terms of the range of conditions it would be able to demonstrate and would require kerosene burning engines (and supporting fuel systems) to ensure safety of flight, alongside the hydrogen engines.

Major tests

Hydrogen gas turbine architectures are applicable to all market segments considered in FlyZero: regional, narrowbody and midsize.

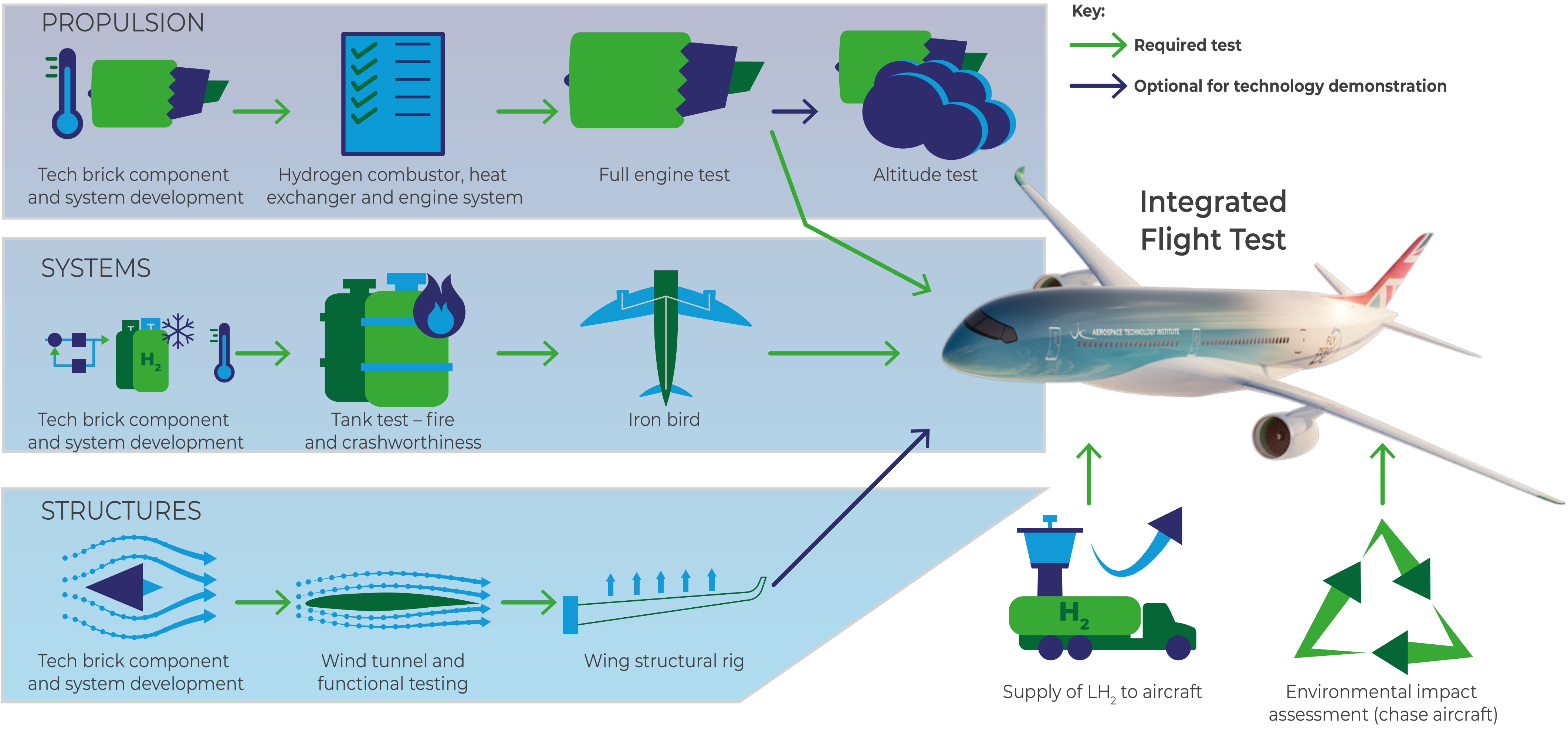
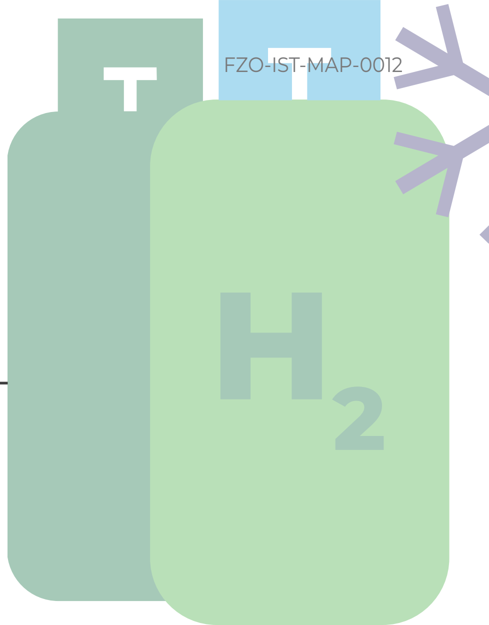


Figure 9 – Hydrogen gas turbine aircraft architecture - major tests.



04.3 TESTS APPLICABLE TO BOTH ARCHITECTURES

Fuel systems demonstrations

Large hydrogen aircraft will store hydrogen in tanks as a liquid. The full fuel system will contain hydrogen in multiple phases including liquid, supercritical liquid and gas.

Fuel tanks must be capable of withstanding crash loading without rupture. Demonstration will require a practical test of both the tank and any surrounding structures that could affect the test outcome. Testing will be a challenge due to hydrogen safety requirements and early testing could utilise water in tanks to achieve an early indication of tank performance. This test will need adequate space for exclusion zone in case of potential ignition or detonation. HSE has experience of conducting similar tests at their Buxton site.

The fuel system will be demonstrated first in an ‘iron bird’, where the system is laid out on the ground as close to the final configuration as possible, before moving to flight test. Iron bird facilities exist with Airbus in Filton and could be a route to demonstration for Airbus and its supply chain but repurposing for hydrogen applications would be a significant undertaking. Fuel system iron birds could be repurposed to satisfy both fuel cell and gas turbine configurations.

Dry wing demonstration

Fuel is stored in the wings in kerosene aircraft and hydrogen technologies will likely require a tank in the fuselage, allowing a dry wing. This is a major opportunity for disruptive wing structures, which will require test prior to flight. Fuel cell and gas turbine architectures will likely be significantly different. For example, a fuel cell aircraft is more likely to incorporate distributed propulsion.

Aerodynamic wind tunnel testing will be required for novel configurations and could be carried out in various UK facilities, probably at subscale. Some wing designs (e.g., a fully morphing wing) may drive the need for flight demonstration.

Structural (static and fatigue) testing of the full wing will be required. An adaptive wing may also drive specific test requirements around actuation and deflection. A wing test rig, like that required for the demonstration, is managed by Airbus at Filton and there are others in the UK which could be upgraded for novel airframe testing.

Supply of liquid hydrogen at airports

Turnaround of hydrogen aircraft will require refuelling to be carried out at the same time as loading of baggage and aircraft servicing. New technologies will be needed to refuel a hydrogen aircraft without placing personnel at risk. Demonstration will be required at system level first and then a full-scale demonstration of refuelling the aircraft at a gate. Liquid hydrogen could be installed at existing facilities for this test and could serve both hydrogen fuel cell and hydrogen gas turbine architectures.

Environmental impact assessment (chase aircraft)

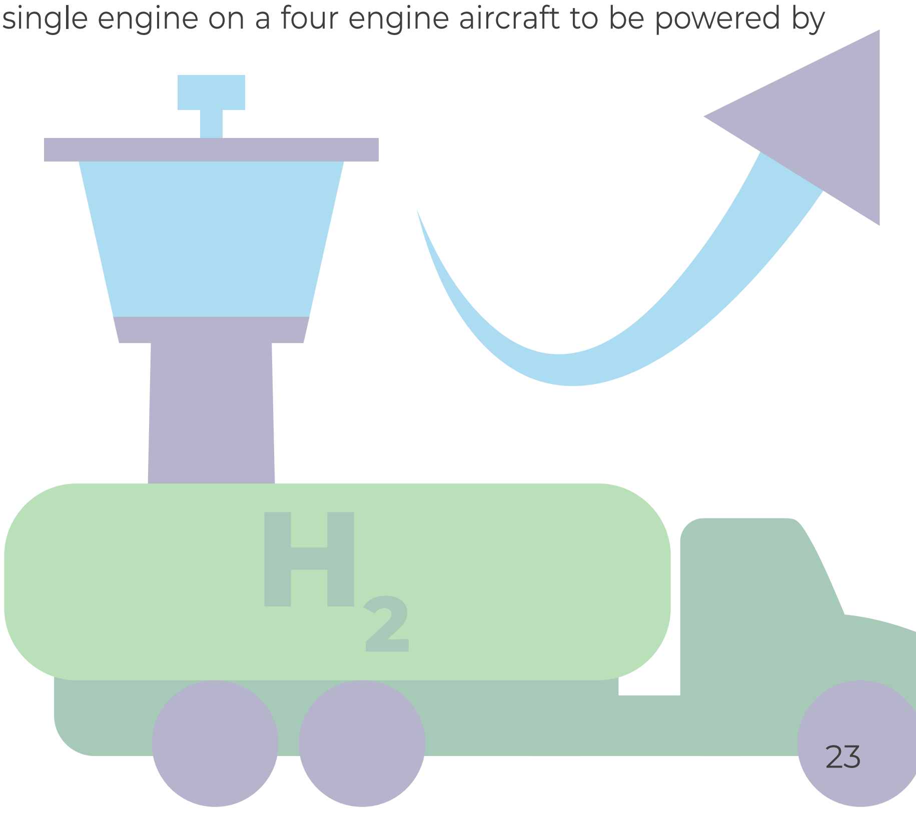
The environmental impact of contrails and water vapour is highly uncertain and significant scientific research is required to understand the climate impact of hydrogen aircraft **[6]**. Simulations will likely have to be validated by measurements from the trail of a hydrogen aircraft, taken with an instrumented chase plane capable of measuring the density of ice particles. This testing will be particularly critical for the gas turbine architecture which will emit water vapour and NO_x which may not be present in a fuel cell architecture.

Integrated flight test

The testing described in previous sections will fulfil most validation requirements. Nevertheless, flight test remains the ultimate representative environment for all aerospace components and systems and creates the most confidence in the technology.

Flight tests can take place in one of two configurations: on a flying test bed (FTB) or a flying demonstrator. A FTB is an existing certified aircraft converted to demonstrate technology, with novel sub-systems integrated in the aircraft but retaining sufficient conventional technology to assure safety of flight (e.g., converting a single engine on a four engine aircraft to be powered by hydrogen). A flying demonstrator is an experimental aircraft that is designed to showcase the new technology and is totally reliant on the technology for safety of flight.

Flight testing has the potential to accelerate entry into service of a hydrogen fleet. Flight drives maturity faster than any other test and could also help win public confidence in hydrogen aircraft ahead of delivery to market.



05. TECHNOLOGY BRICKS KEY FINDINGS

05.1 KEY CHALLENGES

While developing the technology roadmaps and concepts [1], FlyZero has identified the top five key technical risks and long lead items for the development of hydrogen aircraft.

Climate science

Significant research is required in the short term to develop an understanding of the effects that CO_2 and non-CO_2 emissions have on our climate. This work is critical to decisions by aerospace companies carrying out aircraft design, by airliners purchasing new aircraft and by government forming policy. This is a significant risk to be managed on the path to hydrogen fuelled aviation.

Fundamental liquid hydrogen behaviour

Due to the low TRL nature of these technologies, there are limited skills and testing capabilities in the UK to understand the behaviour of liquid hydrogen. Requirements for safe handling, standards, regulations and test specifications are required to serve multiple industrial applications.

Material properties

Limited data exists for aerospace grade materials for use with liquid hydrogen. Building the test infrastructure and certification plan to deliver qualified materials is expected to be a long lead time activity for the first generation of hydrogen technology.

Hydrogen combustion systems

System design, manufacture and rig test to accommodate the different combustion behaviour of hydrogen will be a significant challenge as an area of high novelty. New combustion designs, infrastructure and manufacturing processes are expected to be required and these developments are likely to drive the critical path for gas turbine development.

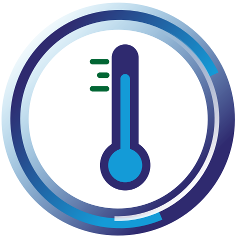
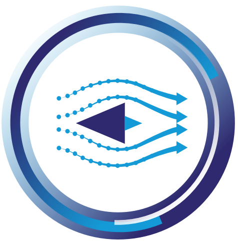
Cryogenic hydrogen fuel system and storage

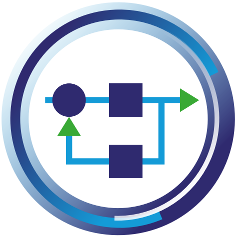
Cryogenic fuel system understanding and technology is relatively immature. Individual components, such as fluid pumps, and integrated components, such as tanks, will bring significant challenges including design, material selection and integration to meet performance and life requirements. Some understanding can be read across from the space sector but many of the fundamental requirements and the operating environment for aviation are very different.

05.2 SUMMARY OF FINDINGS BY TECHNOLOGY BRICK

The FlyZero technology roadmaps detail the developments needed to realise hydrogen flight. The key findings for each brick are summarised below and can be explored in more detail in documents listed in **Appendix B - Technology Roadmaps**.

Technology Roadmaps	*Key Findings*
Hydrogen Gas Turbines and Thrust Generation	*At the level of analysis carried out by FlyZero, there appear to be no fundamental technical barriers to developing gas turbines able to run on hydrogen fuel. There is potential to make a hydrogen gas turbine more efficient and to produce lower NO_x than a kerosene or SAF fuelled equivalent, although this will need practical validation.* *Hydrogen burning combustors will require significant development supported by new test capability at sector rig, annular rig and engine levels. Manufacturing processes for combustors may also be significantly different to those seen today.* *Engine supply chain capacity will need to grow significantly, to deliver rates an order of magnitude higher than the UK engine community supply at today.*
Fuel Cells	*Fuel cells can potentially have lower environmental impact than gas turbines as they do not produce NO_x and water vapour could potentially be repurposed during flight.* *Fuel cells have significant mass, unit cost and durability / life challenges compared to gas turbines and are immature in aviation applications. However, they have the potential to exceed the efficiency of a gas turbine running on liquid hydrogen.* *Significant development is needed in low temperature (LT) proton exchange membrane (PEM) fuel cell stacks and balance of plant. Thermal management challenges are significant and drive complex system design.* *There is a need to develop both current (LT PEM) and future (high temperature (HT), 160° plus, PEM) technologies. HT technologies could offer a step change in system performance.*
Electrical Propulsion System	*All key components on the electrical system require significant upgrade for them to meet the power requirements for aviation, but clear pathways are available for these upgrades.* *An advantage of an electrical propulsion system is the possibility of modularity and distributed propulsion.*

Technology Roadmaps	*Key Findings*
 *Thermal Management*	*Thermal management will be a significant challenge for low temperature PEM fuel cells. Moving to high temperature PEM technology would enable a smaller and simpler heat rejection system.* *Thermal management is also a key challenge for gas turbine architectures. A novel heat management system will be required to heat liquid hydrogen before it is injected into the combustion chamber.* *Hydrogen opens an opportunity for novel heat exchanger technology, but this will require new manufacturing approaches.*
 *Cryogenic Hydrogen Fuel System and Storage*	*One key driver of the design is the management of the pressure and the temperature of the liquid hydrogen inside the tank and fuel system. This is a key area of research, there is a trade between weight, reliability and complexity. Because of the low boiling point of hydrogen, insulation of the tanks and fuel system is a major challenge, and all known insulation and / or active cooling technologies have limitations.* *The size and shape of cryogenic fuel tanks are important factors in their gravimetric efficiency. The number of tanks in an aircraft should be minimised both for tank and system weight management. Tank geometries should be close to spherical or low aspect ratio cylinders for thermal and structural reasons. The gravimetric efficiency of the tank and system can be improved by new fuel system technologies.* *Currently available cryogenic temperature materials data refer to metals, mainly aluminium alloys. Composite materials offer a potential opportunity for the future to reduce weight but will require a significant development.* *The equipment for the fuel system does not currently exist and a lot of work between equipment suppliers and airframer is required to ensure robust installation, especially with regards to leaks and maintenance.*
 *Aerodynamic Structures*	*Aerostructures technologies are relevant to new fuel cell and hydrogen gas turbine architectures, but also to any new ultra-efficient kerosene burning aircraft.* *Dry wing is both a challenge and an opportunity; it causes the loss of wing bending relief but also opens the potential for morphing technologies and manufacturing improvements.* *Composites will be increasingly deployed in new wings. There is a significant opportunity to grow UK large primary composite manufacture with the transition to hydrogen. Manufacture and assembly development is required alongside part development to secure production rates.*

Technology Roadmaps	*Key Findings*
 *Aircraft Systems*	*Some systems that are present on conventional aircraft (e.g., pneumatics and water ballast), are not expected to feature on hydrogen aircraft.* *New technology will be required for other systems, including for the fire protection system and the auxiliary power unit (APU). There will be significant opportunities for the UK to grow its industrial footprint by providing sensing, halon replacement and propulsion technologies for APU applications.*
 *Sustainable Cabin Design*	*Cabin is one of the largest recycling challenges on the aircraft. Increasing focus on sustainability, technologies and business models which enable repair, reuse and recycling of cabin materials is going to be increasingly required of original equipment manufacturers (OEM) and operators.* *Light weighting is going to be a continued and increasingly important driver for cabin in the transition to hydrogen, to maximise range.*
 *Airports, Airlines and Airspace – Hydrogen Infrastructure and Operations*	*The ability to turn an aircraft around both safely and efficiently will be a critical enabler for adoption by the airlines. New refuelling technology is required to enable this for hydrogen.* *The supply infrastructure for generation and delivery of liquid hydrogen fuel will start with bowser tankers. For larger airports this will move rapidly to pipeline supply of hydrogen and on-airport liquefaction.* *To prepare for increasing traffic, air traffic management developments are critical and could be applied to the whole fleet - both hydrogen aircraft and ultra-efficient kerosene burning aircraft.*
 *Lifecycle Impact*	*Improving understanding of the climate impact of hydrogen aircraft in comparison to kerosene is critical. Focus is required on the impact of contrails, where uncertainty is large, and the potential for avoiding contrail formation by adapting flight paths.* *Developing design for sustainability and life cycle assessment good practice and toolsets to aid design will enable better informed decision making and more sustainable solutions.*

Technology Roadmaps	*Key Findings*
Compressed Design and Validation	*Technology and aircraft development could be accelerated by embracing early prototyping and testing; adopting agile development processes and tools; using digital technologies.* *Achieving certification takes time. The groundwork for hydrogen certification challenges should start now.* *The UK should develop new digital tools (simulation, digital twins) to address hydrogen aerospace challenges.*
Materials	*There is a shortage of UK facilities for material testing at cryogenic temperatures in a hydrogen environment. New facilities will be needed to requalify existing materials and coatings and qualify new ones.* *Greater research emphasis on the interaction of hydrogen with materials will be needed before advanced materials, specifically for use in hydrogen environments, can be developed.* *Embedding sustainability impact in the selection process for materials will be increasingly important. It is vital that the materials used in aerospace are responsibly sourced, limiting environmental impacts, minimising greenhouse gas emissions, respecting human rights and supporting local communities.*
Manufacturing	*Liquid hydrogen will drive new aircraft architectures and new system requirements, so driving a need for novel manufacturing solutions. Advances in advanced forming and joining processes, composite processing and cure, and additive technologies will all be required.* *While the UK supply chain has good capability, achieving narrowbody aircraft production rates for hydrogen aircraft will pose a significant challenge. The UK aeroengine supply chain particularly is largely supplying at lower widebody rates today. Concurrent design, design for manufacture and process development will be necessary.*

Table 1 – Technology brick summaries.

06. UK OPPORTUNITY

To ensure continued UK competitiveness during the transition to zero-carbon, key aerospace capabilities need development to retain and enhance them. The FlyZero technology roadmaps detail these developments for hydrogen. The UK has world leading capability in several of the roadmap technologies including gas turbines, fuel systems, aerodynamic structures, thermal management and electrical systems, Figure 10 below. With its deep understanding of the certification challenges associated with these systems, UK aerospace can provide the technical leadership required to compress the development cycle and accelerate the delivery of hydrogen to market.

Large technology disruption means the barriers to entering the aerospace supply chain are currently lower, creating potential for new market entrants. It will also create an opportunity for shared learning with established suppliers to other sectors (e.g., energy, automotive, space), many of which are ahead of aerospace in the journey to net-zero tailpipe CO_2 emissions, or already using hydrogen. This could expose the UK to a potential loss of market share in areas where it is traditionally strong. However, it could also offer an opportunity to grow market share by developing and implementing new technology.

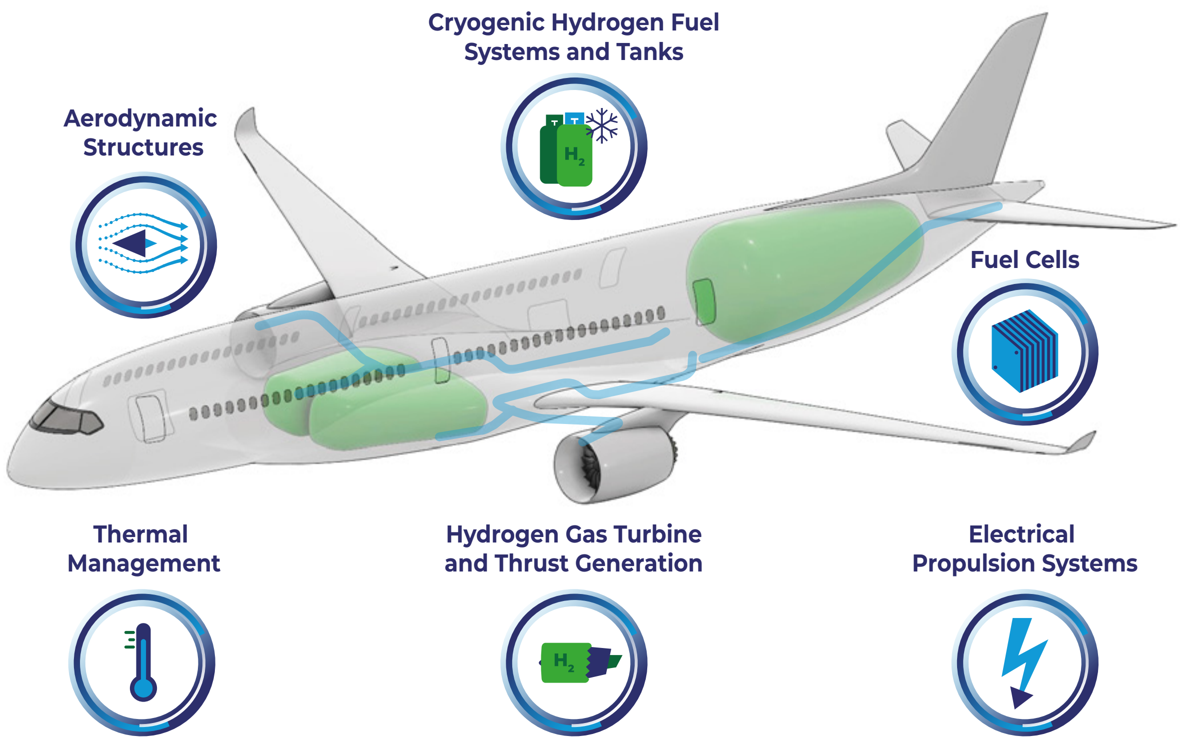


Figure 10 – Overview of UK capability for revolutionary technologies fundamental to realising liquid hydrogen fuelled aircraft.

Other nations are investing heavily now. The ATI FlyZero 'UK Capability in Zero-Carbon Aircraft Technologies' [7] report indicates annual spends of £0.5 billion per annum for leading European nations, the USA and Japan. If the UK fails to act in time, development is more likely to be secured abroad, and the UK will fall behind or find it more difficult to compete. FlyZero has assessed the global level of patent activity for hydrogen aviation technologies as shown in **Figure 11** below. The number of patents submitted can been used to indicatively quantify the relative level of technology activity in each country. This data suggests that the global leaders, for intellectual property generation at least, are Japan, the USA and South Korea. The UK has a similar level of patent activity to France, Italy and the Netherlands.

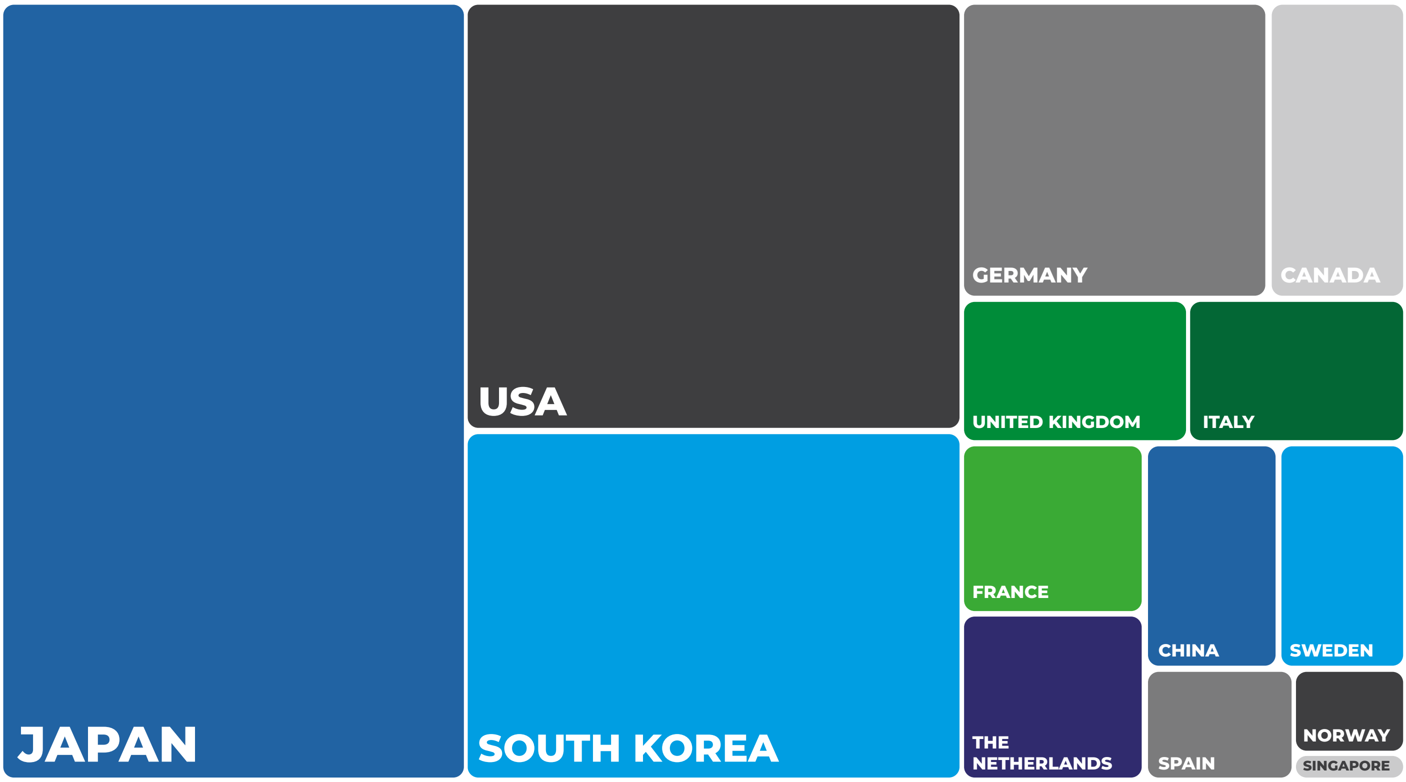


Figure 11 – Indication of relative level of patent activity by country in technology areas relevant to hydrogen aircraft.

To move incumbents forward, foster new entrants to aerospace and ensure it remains a leading aerospace player, the UK must rapidly ramp up efforts on hydrogen technology development.

As well as demonstrating technology performance, it will also be critical to demonstrate manufacturing rate capability. This will be of importance to OEMs when deciding on partners and investment in manufacturing. Rate demonstration will help to ensure the UK's world class research and development translates to manufacturing jobs. For new technology providers, support to deliver to the standards required to supply the aerospace industry will also translate to UK value.

Creating the know-how and infrastructure to deliver the hydrogen aerospace technologies laid out in this report in the UK will secure intellectual property (IP), understanding and critical skills and create a unique global capability. Due to the lifecycle of aerospace products, investing now has the potential to secure 40 plus years of aerospace production in the UK.

07. CONCLUSIONS AND RECOMMENDATIONS

FlyZero has identified liquid hydrogen as a fuel of the future for aviation.

The project has assessed the design challenges, manufacturing demands, operational requirements and market opportunity of hydrogen powered aircraft and has identified 13 technology bricks critical to realising large (regional, narrowbody and midsize) hydrogen aircraft by the mid-2030s. FlyZero forecasts that in 2050, this could enable a £200 billion per year zero-carbon market and a 45% reduction in CO_2 emitted by aviation.

Alongside the technology roadmaps and to understand the scale of activity needed to deliver this technology pathway, the FlyZero team performed a detailed costing of the technologies highlighted by each technology brick, as well as cost for major integration steps such as flight test. This work found that investment in the order of £270 million per year in UK R&D across industry and government is required to achieve the FlyZero current trend scenario, as seen in **Figure 7**. This costing is based on the major assumption that both hydrogen fuel cell and hydrogen gas turbine architectures are both pursued at pace, and both require a flight test vehicle. Costs could be reduced if this flight test was supported through international collaboration or a down selection of architectures was made. However, a flying test bed is fundamental for fully validating most of the technology bricks. Until the hydrogen implementation challenges, outlined in **Section 5.1**, are resolved, it is anticipated spend of this order will be required to maximise UK content and achieve entry into service timescales. This development activity is expected to run for at least the next five years and will require contribution from UK industry, the academic and research network, the ATI and government.

The process of developing the technology roadmaps has enabled us to identify four key recommendations for onward investment and development.

- **Deliver the research and development technologies identified in the FlyZero technology roadmaps.**

  The technologies identified in the FlyZero technology roadmaps lay the pathway for a credible route to realising hydrogen aviation. Investment and collaboration building to deliver these technologies is required without delay, to enable TRL6 by 2025. The UK has world leading capability in several of the roadmap technologies including gas turbines, fuel systems, aerodynamic structures, thermal management and electrical systems. UK aerospace can provide the technical leadership required to compress the development cycle and accelerate the delivery of hydrogen powered aircraft to market. Maximum decarbonisation can be achieved by acting rapidly. At this period of high disruption, it is acknowledged that technology development is high risk, most of the novel technologies for hydrogen are low TRL (1-3). An approach to this development which embraces early testing and simulation to manage uncertainty and data gaps will be required to deliver these technology roadmaps on time. Delivery of this action can only be achieved via a coordinated approach by UK industry, the academic and research network, the ATI and government.

Deliver underpinning infrastructure

Early development of test infrastructure is an enabler for delivery of these technologies. It is also a mechanism for upskilling the aerospace and aviation industry, which has no experience of working with cryogenic hydrogen. A comprehensive testing programme will be required, including unit, sub-system and system testing to de-risk and validate zero-carbon commercial aerospace. Section 4 and the ATI FlyZero 'Zero-Carbon Aerospace Technology Validation Strategy' [5] report detail the major infrastructure required to support this. Engaging with the UK network, such as the Research and Technology Organisations (RTOs) and Health and Safety Executive (HSE), to gather test specifications and early readiness of infrastructure will secure UK learning, potentially for cross-sector applications. Again, delivery of this action can only be achieved via a coordinated approach by UK industry, the academic and research network, the ATI and government.

Deliver manufacturing developments alongside product developments

The introduction of hydrogen aviation to achieve the 2050 net zero targets will be a product challenge but also a significant manufacturing challenge. Airbus A320s are to be delivered at a rate of 64 per month by mid-2023. By 2050, each major OEM is anticipated to supply narrowbody aircraft at a rate of over 100 per month. Development to achieve rate enables an earlier fleet to market, which maximises decarbonisation. This manufacturing development will be supported by the UK Catapult and RTO network as well as industry. Delivery of these technologies will support the world-leading research and development work carried out in the UK to translate into manufacturing jobs, securing 40 plus years of aerospace production.

Support skills development and cross-sector collaboration

Delivering the technology roadmaps in the timescales set out in this report will require significant new skills and / or upskilling in support of actions 1 to 3. The ATI FlyZero 'Workforce to Deliver Liquid Hydrogen Powered Aircraft' [8] report highlights key gaps in the UK. In the short term, when experience in the use of liquid hydrogen is at a low level, cross-sector collaboration, and potentially a cross-sector approach to shared infrastructure, could concentrate skills in the UK and facilitate shared learning on standards and safe handling practices.

ATI FlyZero 'The Case for the UK to Accelerate Zero-Carbon Emission air travel' [2] outlines the economic and regulatory context which would be required, in addition to the above actions, to support the delivery of hydrogen aircraft.

In summary, the FlyZero study has indicated that liquid hydrogen powered aviation is feasible. To achieve the government's 2050 net zero vision the recommendations on hydrogen above should be progressed in parallel with development and deployment of sustainable aviation fuels (SAF). The technology roadmaps detail a route to transforming the aviation industry to utilise hydrogen as its primary fuel and potentially completely decarbonise aviation. Delivery of these recommendations will develop product technology, UK skills and expertise in a growing market, and establish the UK as a key location for developing hydrogen technologies.

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08.1 APPENDIX A – LIST OF ABBREVIATIONS

APU	Auxiliary Power Unit
ATF	Altitude Test Facility
ATI	Aerospace Technology Institute
EIS	Entry Into Service
FTB	Flying Test Bed
HSE	Health and Safety Executive
HT	High Temperature
HVM	High Value Manufacturing
IP	Intellectual Property
LT	Low Temperature
NASA	National Aeronautics and Space Administration
OEM	Original Equipment Manufacturers
PEM	Proton Exchange Membrane
RTO	Research and Technology Organisations
SAF	Sustainable Aviation Fuels
TRL	Technology Readiness Level

08.2
APPENDIX B – TECHNOLOGY ROADMAPS

All technology roadmaps available at **ati.org.uk**

Hydrogen Aircraft	*Roadmap Ref.*	*Roadmap Report Ref.*	*Capability Report Ref.*
Aerodynamic Structures	*FZO-AIR-MAP-0015*	*FZO-AIR-COM-0016*	*FZO-AIR-CAP-0066*
Thermal Management	*FZO-PPN-MAP-0018*	*FZO-PPN-COM-0019*	*FZO-PPN-CAP-0067*
Hydrogen Gas Turbines & Thrust Generation	*FZO-PPN-MAP-0022*	*FZO-PPN-COM-0023*	*FZO-PPN-CAP-0068*
Cryogenic Hydrogen Fuel System and Storage	*FZO-PPN-MAP-0026*	*FZO-PPN-COM-0027*	*FZO-PPN-CAP-0069*
Electrical Propulsion System	*FZO-PPN-MAP-0029*	*FZO-PPN-COM-0030*	*FZO-PPN-CAP-0070*
Fuel Cells	*FZO-PPN-MAP-0032*	*FZO-PPN-COM-0033*	*FZO-PPN-CAP-0071*

Cross-cutting	*Roadmap Ref.*
Aircraft Systems	*FZO-AIR-POS-0013*
Lifecycle Impact	*FZO-STY-POS-0034*
Hydrogen Infrastructure and Operations – Airports, Airlines, Airspace	*FZO-CST-POS-0035*
Advanced Materials	*FZO-IST-POS-0036*
Advanced Manufactoring	*FZO-IST-POS-0037*
Compressed Design and Validation – Culture and Digital Tools	*FZO-IST-POS-0038*
Sustainable Cabin Design	*FZO-AIR-POS-0039*

Table 2 – FlyZero Technology Roadmaps

TECHNOLOGY ROADMAPS

Technology Pathways to Enable Zero-Carbon Emission Flight

FLY ZERO

AEROSPACE TECHNOLOGY INSTITUTE