UK CAPABILITY IN ZERO-CARBON AIRCRAFT TECHNOLOGIES

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

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01. EXECUTIVE SUMMARY

The UK has world-leading capability in technology areas critical to realising zero-carbon emissions commercial flight – especially wings and aerodynamic structures, fuel systems, gas turbines and high efficiency electric motors.

New zero-carbon emission aircraft will require development of disruptive technology. To win content on these aircraft, UK companies must be ready to demonstrate new systems based on disruptive technologies in the next one to two years for sub-regional aircraft and by 2025 for larger aircraft.

To obtain a leading position in systems for hydrogen aircraft, the UK will have to design, build and test capability for cryogenic hydrogen. Leading aerospace companies in the EU and Japan have made a concerted start on hydrogen-powered aircraft. Some countries have the added advantage of a deep understanding of cryogenic hydrogen as a result of having a space sector with capability in hydrogen propulsion.

The size of the zero-carbon aircraft market is projected to be £87bn in 2050 with a cumulative size between 2021 and 2050 of £800bn [46]. The UK's share of the kerosene powered aircraft market is estimated at 13% today. With the right focus of funding at the right time, the UK could grow that share in a market that will become dominated by zero-carbon technology; the ATI has estimated an opportunity of increasing it to 20% by 2050.

New aircraft will require more integration than before between the powertrain and the airframe. This could change where the historic aircraft interfaces fall, and who takes ownership of which system. This could in turn impact the structure of the global supply chain. As these are new technology areas, the barriers to entry are currently lower for new entrants from across the globe.

To maintain its leading aerospace position, the UK must invest in these technology areas to both transition incumbents and foster new entrants.

01.1 APPROACH

This report covers the key new technologies required, mapped alongside the UK's current capabilities. It identifies the opportunities for expanding the UK's future industrial footprint while identifying the challenges faced in maturing solutions for market adoption. The information was gathered through a combination of engagement and desk-based research. The ATI FlyZero team carried out a series of engagements with industry – both with incumbent aerospace companies and potential future technology providers from organisations across the UK research landscape. Key messages from these activities are included here.

The report includes an assessment of the global maturity of each technology using the technology readiness level scale defined by NASA (see **Figure 3**).

To secure work on a large international programme, the UK needs to have areas of technology leadership, by having higher technology maturity (TRL) and demonstrable manufacturing maturity at rate, to secure long-term production jobs.

01.2
KEY TAKEAWAYS BY TECHNOLOGY

Hydrogen Fuel System and Tanks

UK suppliers are actively developing aerospace cryogenic capability with OEMs via strategic technology programmes.

Investment in this technology provides an opportunity for other industries, including energy and marine, improving the potential return on investment.

Industry-wide aerospace standards and specifications for cryogenic hydrogen applications need to be developed and approved.

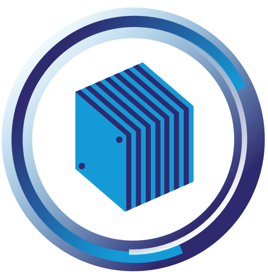
Hydrogen Gas Turbines and Thrust Generation

There is currently no UK supplier capability for liquid hydrogen burning gas turbines for aerospace applications. There are only a limited number of potential UK suppliers with capability in this technology area. There is however potential for collaboration between the aerospace and energy sectors.

There is currently no UK liquid hydrogen test infrastructure for aerospace gas turbines at engine, system or sub-system level.

The combustor is identified as a key development challenge for delivering hydrogen gas turbine technology due to specific attribute management e.g. flashback, auto ignition and thermo acoustics.

Hydrogen Fuel Cells



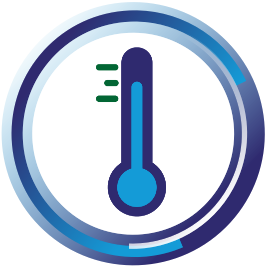
Fuel cell technology is still relatively new for aerospace, however the UK is leading in proton exchange membrane (PEM) technology, making this a potential area of high opportunity for a UK “play to win”.

PEM technology requires hydrogen with high purity levels which affects the business economics.

Key enabling technology developments required to enable successful use in aerospace include; lightweighting of the fuel cell stack, improved thermal management and balance of plant optimisation.

The rapid growth of fuel cells is being led by the automotive sector, targeting especially large land-based vehicles such as buses and trucks. In aerospace, without a further breakthrough in energy density, their application as a primary power source will be limited to sub-regional and regional flight.

Thermal Management

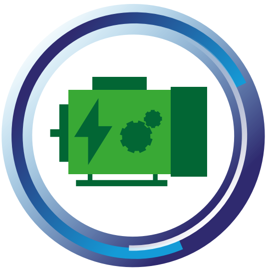


Hydrogen capable heat exchangers will be a key technology. Development is at early stages.

The UK supply chain is very active in the development of additive manufacturing capability for heat exchangers. Several key manufacturing challenges need to be addressed to make the technology viable.

There is recognition of the challenge of materials and sealing technologies required within cryogenic systems, along with the required test capability covering the full range of thermal cyclic conditions.

Electrical Systems

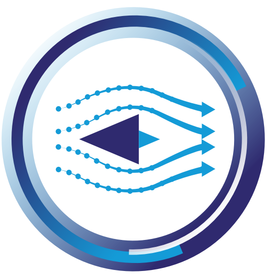


There are good emerging capabilities in electric aerospace motor design in the UK built up from the strong foundations of academia and industrial start-ups. This presents an opportunity to scale up and capture the market.

There is little evidence of any production-rate capable facilities for an aerospace electrical drivetrain at these higher power levels. This represents an opportunity for the UK to establish itself as a global supplier of high-power electric drivetrains.

Current test capacity is orientated around academic facilities. There is little capacity for full environmental testing operating a continuous duty cycle.

Aerodynamic Structures



The UK supply chain has world-leading competency in wing design and manufacture and significant capability in other aerodynamic structures. Automation and digitalisation of manufacturing is enabling greater onshoring of high technology component manufacture back into the UK. The potential move to a dry wing design for a liquid hydrogen aircraft presents both an opportunity and threat to the incumbent suppliers.

The research network and industry are developing automated assembly techniques that will drive capacity, and thus rate improvements, whilst positioning the UK as a leader on cost competitiveness.

01.3 SUPPORT NEEDED TO ACCELERATE TECHNOLOGY DEVELOPMENT

UK industry will need to grow rapidly in a number of areas in order to develop its competitiveness in emerging technology markets. This will require investment from industry and government in infrastructure and technology development as well as enabling policies.

- Test infrastructure for cryogenic hydrogen components, sub-systems and whole aircraft systems does not currently exist, limiting the pace of development. Founding a hydrogen technology centre to act as a centre of excellence, and bring together skilled individuals, prototyping and test facilities would be a key enabler and provide an anchor for industry in the UK.
- Where the development of highly novel disruptive technologies is required, the supply chain would benefit from shorter (12-18 month) investment projects in order to develop and secure intellectual property (IP) but this requires more agile funding mechanisms than exist today.
- Bringing revolutionary technologies to market is not without cost and risk, especially to achieve the scale and pace required. Providing funding beyond initial R&D (typically beyond TRL 6) must be considered to create and secure the UK industrial footprint. There are examples of EU programmes and the French and German governments providing funding that supports the industrialisation and production ramp-up activity to develop initial rate capability.

02. INTRODUCTION

Larger aircraft are responsible for a higher proportion of emissions and so, to make the biggest impact on commercial aviation, the FlyZero project has focussed on energy solutions with potential to scale (see **Figure 1**).

Hybrid primary energy systems, based on hydrogen fuel cells and batteries, have potential for sub-regional and regional aircraft, whilst hydrogen burned in a modified gas turbine can also power larger commercial aircraft **[2]**.

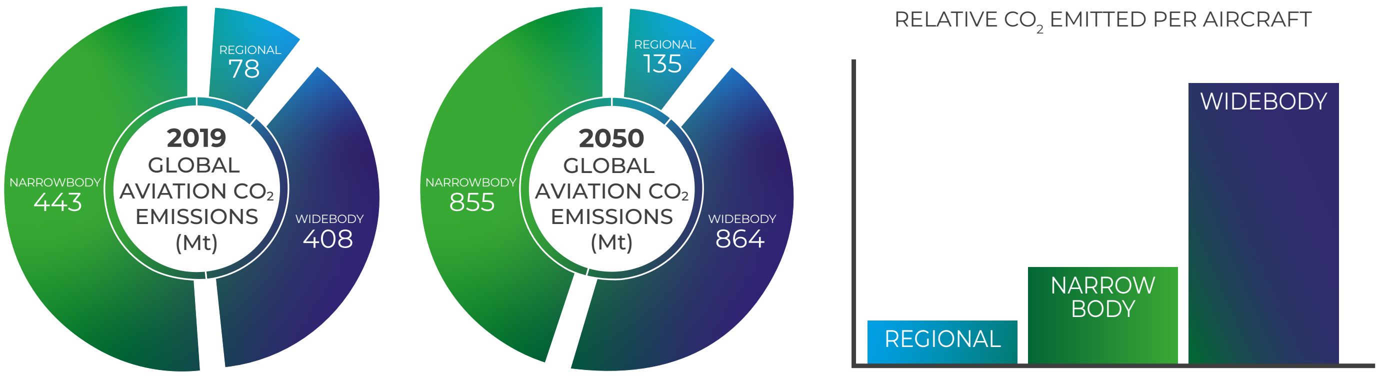


Figure 1 – Commercial aviation addressable CO_2 emissions by aircraft size, in 2019 and 2050 without zero-carbon aircraft data derived from The International Council on Clean Transportation report CO_2 emissions from commercial aviation [1].

In creating this report, FlyZero spoke to over 40 companies in the respective technology areas to gather insights, using a series of focused workshops and one-to-one meetings, following initial desktop-based assessments.

FlyZero has identified a number of on-aircraft and underpinning technologies that are critical to realising zero-carbon emissions aircraft powered by hydrogen gas turbines and hydrogen fuel cell systems, referred to by FlyZero as ‘technology bricks’. **Figure 2** shows relevance of the technology bricks to aircraft types. This report provides an initial overview of the UK’s capability in these technology bricks.

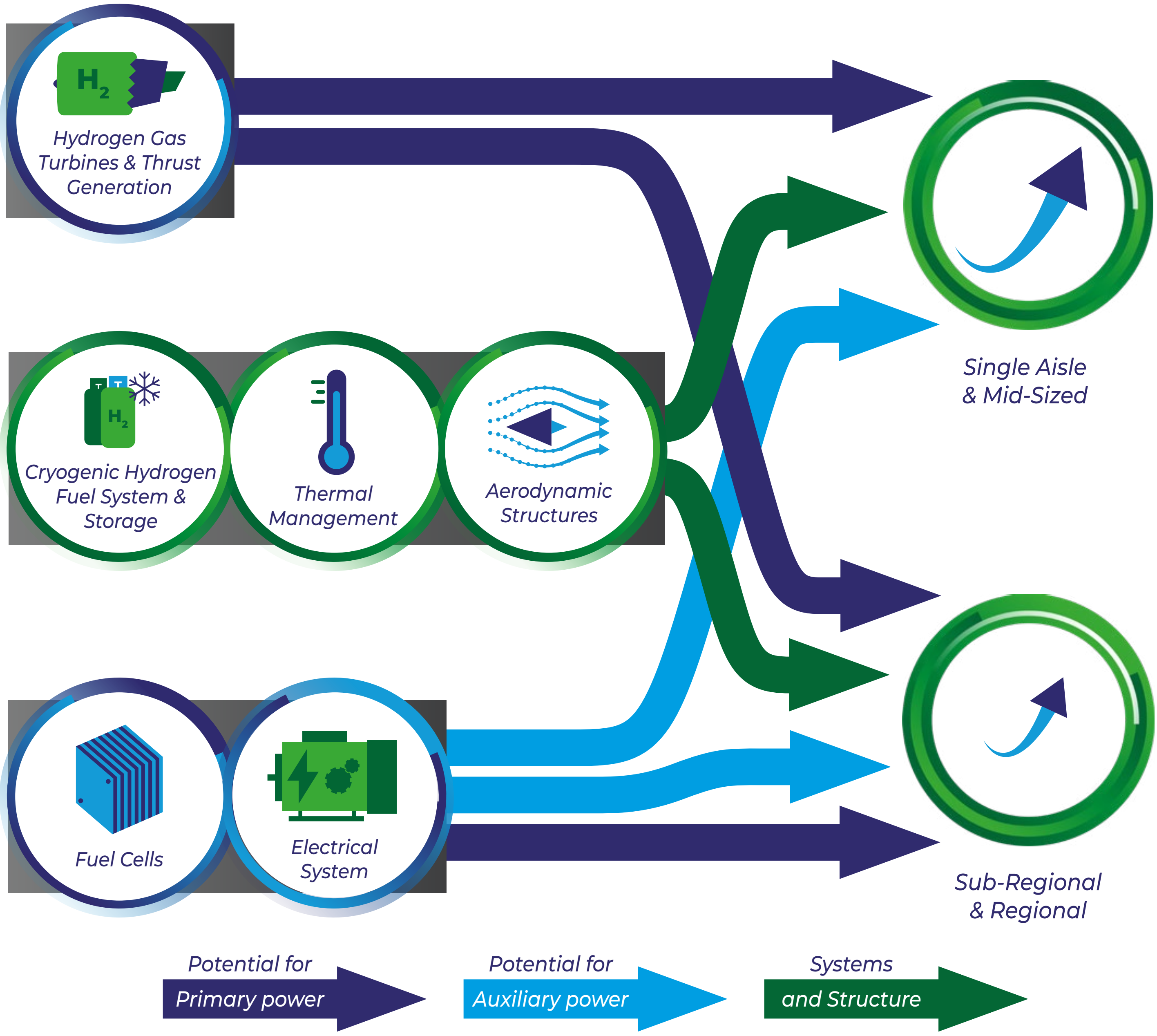


Figure 2 – FlyZero technology bricks and their relevance to market segments

Sections 3 to 8 of this report provide an initial overview of the UK's capability in the technology bricks, including an assessment of the global maturity of each technology using the technology readiness level (TRL) scale defined by NASA (see **Figure 3**).

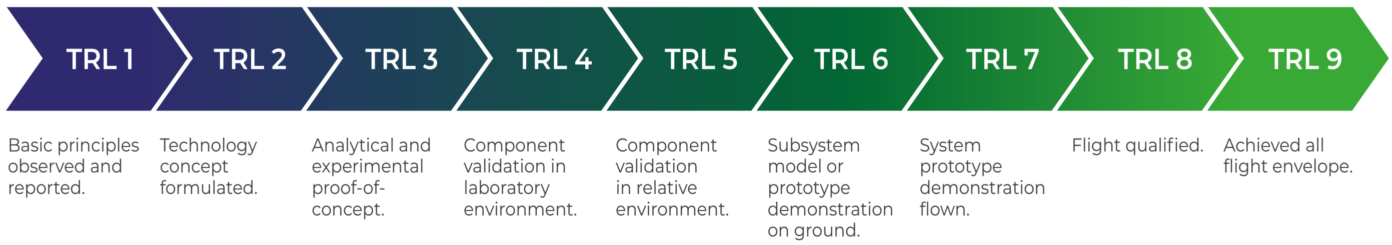


Figure 3 – NASA technology readiness level (TRL) scale.

This is followed by key messages that cut across all of the bricks (**Section 9**), opportunities from sector adjacency (**Section 10**) and a summary of overseas funding and capability (**Section 11**).

03. HYDROGEN FUEL SYSTEM AND TANK

Hydrogen fuel system and tank covers the fuel system design and integration in the aircraft from the aircraft fill point (including the tank, control, and distribution) to the point of consumption. The key technologies for this brick are the hydrogen tank and the hydrogen fuel distribution system.

To achieve the energy density needed for flight, hydrogen will have to be cooled to its liquid form, below –253°C. The volume of liquid hydrogen needed to power an aircraft for an equivalent range is four times greater than the volume of kerosene [2]. Unlike kerosene, hydrogen cannot be stored in the wing. Several alternative locations are being considered by the FlyZero project e.g. fuselage, pods.

Fuel storage will consist of multiple large, insulated tanks. Material types being evaluated for the tank wall are metallics, composites and multi-material hybrids. The thermal cycling of the tank as it is filled and drained will determine its life, which, in turn, will dictate the tank replacement strategy. Sustainability will therefore be a significant consideration in material choice.

H2GEAR [3] is a UK technology collaboration demonstrator led by GKN Aerospace consisting of a hydrogen fuel cell system and cryogenically cooled super-conducting motor/drive providing insight in this area (see **Case Study 1**).

FlyZero has assessed the global technology readiness level as TRL3 (**Figure 4**).

Figure 4 – Global TRL level for hydrogen fuel tank technology.

Case Study 1 – GKN H2GEAR Zero-Emission Technology Demonstration

GKN Aerospace is leading a ground-breaking UK collaboration programme called H2GEAR, to develop a liquid hydrogen propulsion system for sub-regional aircraft, which could then be scaled up to larger aircraft. Liquid hydrogen will be converted to electicity within a fuel cell system.

This electricity will then efficiently power the aircraft, eliminating CO2 emissions and leaving water as the only by-product of flight. The £54m programme is supported by £27m of ATI funding, matched by GKN Aerospace and its industrial partners. Collaboration partners are Intelligent Energy, Aeristech, Newcastle University, University of Manchester and the University of Birmingham.

image © GKN Aerospace

The hydrogen fuel distribution systems, including systems for fill, vent and drain, are made up of components including valves, pumps, expanders, connectors, couplings, ventilation, pipes, etc. These components will need to be redesigned for liquid hydrogen aerospace applications. The fuel distribution system will need to be able to handle hydrogen in the liquid (during storage) and supercritical (during distribution) phases. High tolerance sealing surfaces capable of absorbing the effects of thermal expansion across a wide temperature window will be required. FlyZero has identified cryogenic high-pressure pumps as a particular challenge with read across from the space sector as an opportunity.

Modelling of fluid flow (computational fluid dynamics) at temperature extremes was identified as a capability gap. Additionally, development and approval of industrywide aerospace standards and specifications for the hydrogen fuel system was identified as a key requirement, in parallel with those currently governing and guiding the specification design, and testing of tanks, pumps and other fuel system units for kerosene operation (e.g. SAE AIR1408B, SAE AIR7975, and SAE ARP1401B). These standards will need to consider the specific characteristics of hydrogen fuel and address the full lifecycle, including refuelling, defuelling, purging, venting, insulating, coupling, sealing, pumping, monitoring and controlling the fuel supply. The opportunity to develop a cryogenic centre of excellence in the UK was also raised by the supply chain as a good way to anchor UK jobs.

The data required to establish materials capability across this group of technologies has been identified as a key knowledge gap. The materials used for existing cryogenic component and systems manufacture in other industries will need to be evaluated and tested for compatibility with hydrogen across the temperatures and pressures in which it will be stored and transferred in aerospace applications. There are currently no UK facilities capable of conducting large-scale mechanical tests at cryogenic temperatures and in a hydrogen environment. Creating one would mean significant infrastructure investment. Achieving ambitious entry into service dates for hydrogen powered aircraft (late 2020s for sub-regional and 2030s for larger aircraft), will require aggregating existing materials data for preliminary design and then conducting mechanical testing in parallel during the later stages of the programme.

Airbus is developing solutions for its ZEROe demonstrator [4]. Airbus's Filton site is its main location for fuel systems design globally. Major suppliers with a UK base with relevant competence include Eaton, Cobham Mission Systems, Parker Hannifin and Meggitt. The UK also has capability in cryogenic systems within the industrial sector (e.g. Parker Hannifin) and space sectors (e.g. Lena Space). Developing collaborations between aerospace incumbents, the industrial sector and space, the UK has capability to develop cryogenic fuel systems for future aerospace applications.

To ensure the functionality requirements of components for a liquid to gaseous hydrogen system can be met, critical manufacturing competencies will also need to be established in both the component suppliers and further down the supply chain. With the ongoing level of consolidation in this sector, such as Eaton's acquisition of Cobham Mission Systems and Parker's proposed acquisition of Meggitt, it is important to ensure key manufacturing opportunities are clearly understood and anchored in the UK.

FlyZero has assessed the global technology readiness level as TRL3 (**Figure 5**).

Liquid hydrogen pump, fill, vent and control valves all at concept stage with plans to scale up from ground based component manufacturing for aerospace qualified components.

Figure 5 – Global TRL level for hydrogen fuel system technology.

03.1 OVERSEAS LANDSCAPE

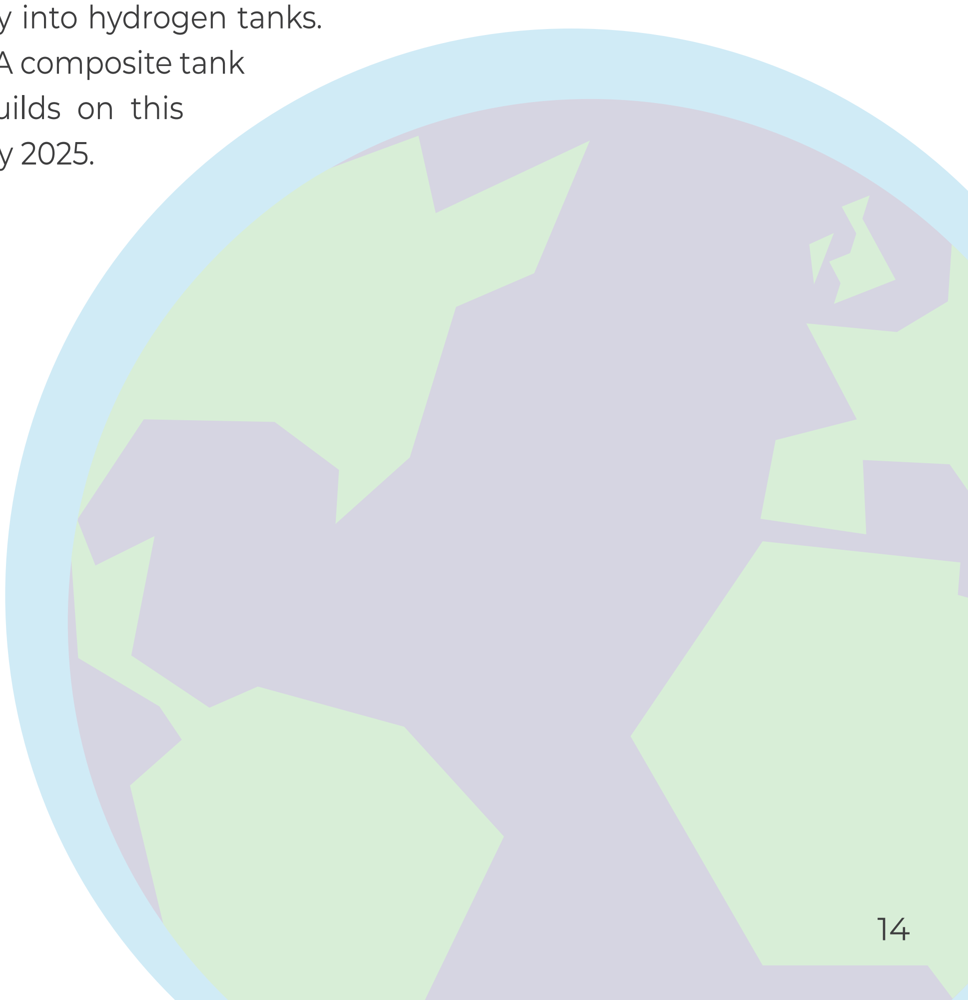
Outside the UK, the countries that are leading the development of hydrogen fuel systems and tanks are France, Germany, USA, Canada, Japan, and South Korea.

Germany has covered the creation of green hydrogen and its use - including hydrogen storage and distribution for aviation - under its national hydrogen strategy. The development of a hydrogen fuel cell powered regional aircraft demonstrator is the core of the BALIS project **[5]**, which will also cover on-aircraft hydrogen fuel system and tanks. Airbus has established zero-emissions development centres in Germany (Bremen), France (Nantes) and most recently in Spain. All three centres will investigate hydrogen tanks, covering between them both metallic and composite solutions.

The USA is actively developing hydrogen storage and distribution technologies within the US Department of Energy-led HydroGEN consortium. Canada's National Research Council (NRC) Low-emission Aviation programme features specific streams on aircraft technology integration and hydrogen applications.

Japan has a world-leading position in hydrogen with strong activity in its industrial sector. Novel fuel storage in aerospace is a key element of Japan's national strategy towards net-zero, with industry-leading hydrogen development programmes with potential to translate into strong hydrogen storage and hot section gas turbine capability.

In South Korea, Hanwha Solutions' acquisition of TK-Fujikin in 2019 marked their entry into hydrogen tanks. Their subsequent acquisition of NASA composite tank manufacture start-up, Cimarron, builds on this with commitment to invest $100m by 2025.



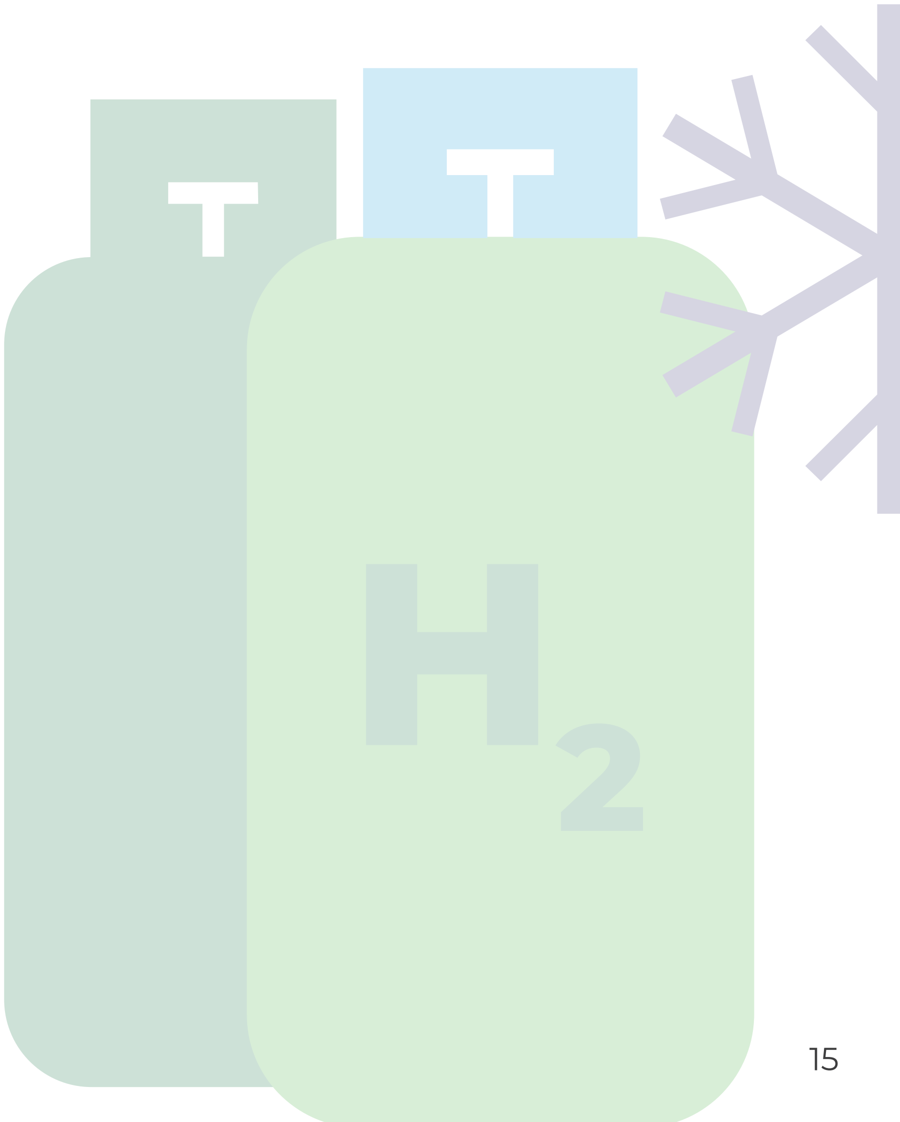
03.2 KEY MESSAGES AND OPPORTUNITIES FOR UK DEVELOPMENT

The UK is well placed to develop a cryogenic hydrogen capability for aerospace applications. Airbus's site in Filton is its main site for fuel system design globally. UK companies have cryogenic components available commercially today for land-based industrial applications, and the UK has capability within its space sector. UK suppliers are actively participating in the development of aerospace cryogenic capability with OEMs on strategic technology programmes. However, the UK does not currently have the same depth of expertise on cryogenics as exists in other countries, particularly those that have hydrogen space launch capability. Developments in this technology area can be used across multiple sectors, including energy and marine.

The UK should support the creation of an open access centre of excellence for hydrogen systems design, prototyping and test, including cryogenics in order to rapidly build skills, to accelerate technology development and provide an anchor for industrial development in the UK. This capability could be a national asset and could potentially be shared with other sectors. FlyZero's final reports to be delivered in 2022 will highlight the requirements for infrastructure.

Investment is needed to create and adapt UK test capability and capacity. This test capability needs to cover the generation of basic material mechanical property data all the way through to component and system testing when operating at cryogenic temperatures.

Nationally and internationally, there are limited standards and regulations on the use of liquid hydrogen for aerospace applications. There is an opportunity to use standards and regulations for e.g., refuelling and tank design from industrial land-based applications as a starting point.



04. HYDROGEN GAS TURBINES

The scope of 'hydrogen gas turbines' includes the turbomachinery from the fan through to the turbine and ancillary mounted systems (e.g., gearbox, controls etc.), including conversion of the fuel from supercritical temperature and condition to end use. Integral to this solution is the need for a hydrogen-compatible combustor, which is expected to be architecturally different from current products because of the significant difference in combustion properties between kerosene and hydrogen. These new combustor designs may require different manufacturing processes to produce them at the required rate and volume.

There is currently no UK supplier capability for liquid hydrogen-burning gas turbines for aerospace applications. The barriers to entry into aerospace are high, especially for systems with complex integration challenges such as the gas turbine, increasing the likelihood that an existing aeroengine manufacturer will be first to market with a hydrogen-burning gas turbine engine.

Rolls-Royce is a leading aeroengine manufacturer headquartered in the UK with a long-established track record in delivering aerospace gas turbine technology programmes (see **Case Study 2**). Rolls-Royce Power Systems in Germany is investigating hydrogen for power generation applications, including fuel cells and the Rolls-Royce MTU 500 'hydrogen-ready' reciprocating gas engine **[6]**.

Rolls-Royce previously owned combustor manufacturing capability but it recently integrated its former combustor manufacturing site in Hucknall, UK into ITP Aero (a subsidiary headquartered in Spain) before selling ITP Aero to Bain Capital in 2021 **[7]**. Reaction Engines in conjunction with Airborne Engineering along with S&C Thermofluids have tested gaseous hydrogen combustors on a research programme in the UK.

Case Study 2 – Rolls-Royce UltraFan®

Rolls-Royce has made significant technology strides in the development of the UltraFan® engine demonstrator, utilising a range of UK (ATI), German (LuFo) and European (Clean Sky) funding sources to enable critical technology developments that aim to deliver a 25% fuel efficiency improvement compared with the first generation of Trent engine.

The programme has also attracted high levels of support from the UK and German governments along with wider European collaboration, creating a potential framework for future opportunities. Assembly of the first demonstrator is underway at its Derby facility with the engine scheduled for completion by the end of 2021 after which the first test run will be conducted using 100% Sustainable Aviation Fuel (SAF) as part of the journey towards zero-carbon aviation.

There is no UK engine testing capability for liquid hydrogen gas turbines. Rig testing capability for liquid hydrogen systems will be required that can deliver cryogenic hydrogen to a full-scale combustion test chamber and monitor specific features of hydrogen burning (e.g. flashback).

UK academia is very active in combustion technology. Cranfield University has successfully burned hydrogen within the EU-funded ENABLE H_2 project. Cardiff University also tests with a range of gases including hydrogen in its Gas Turbine Research Centre. Loughborough University (National Centre for Combustion Aerothermal Technology) is heavily used for the testing and development of current combustion technology, and is expected to be able to burn hydrogen for rig testing. Cambridge University's Whittle Lab also undertakes activity across the whole turbomachinery landscape. Manufacturing technology development has historically been undertaken across the UK's network of research organisations including in the High Value Manufacturing Catapult.

Due to the expected novelty in the hydrogen handling, system control and burning of hydrogen within the combustor, the global technology maturity is assessed at TRL2 (**Figure 6** - TRL level for hydrogen gas turbine technology).

Very early concept formulation and combustion trial work accompanied by early plans for manufacturing validation and development.

Figure 6 – Global TRL level for hydrogen gas turbine technology.

04.1 OVERSEAS LANDSCAPE

The countries with leading hydrogen gas turbine capability are France, Germany, USA, Japan, and Sweden.

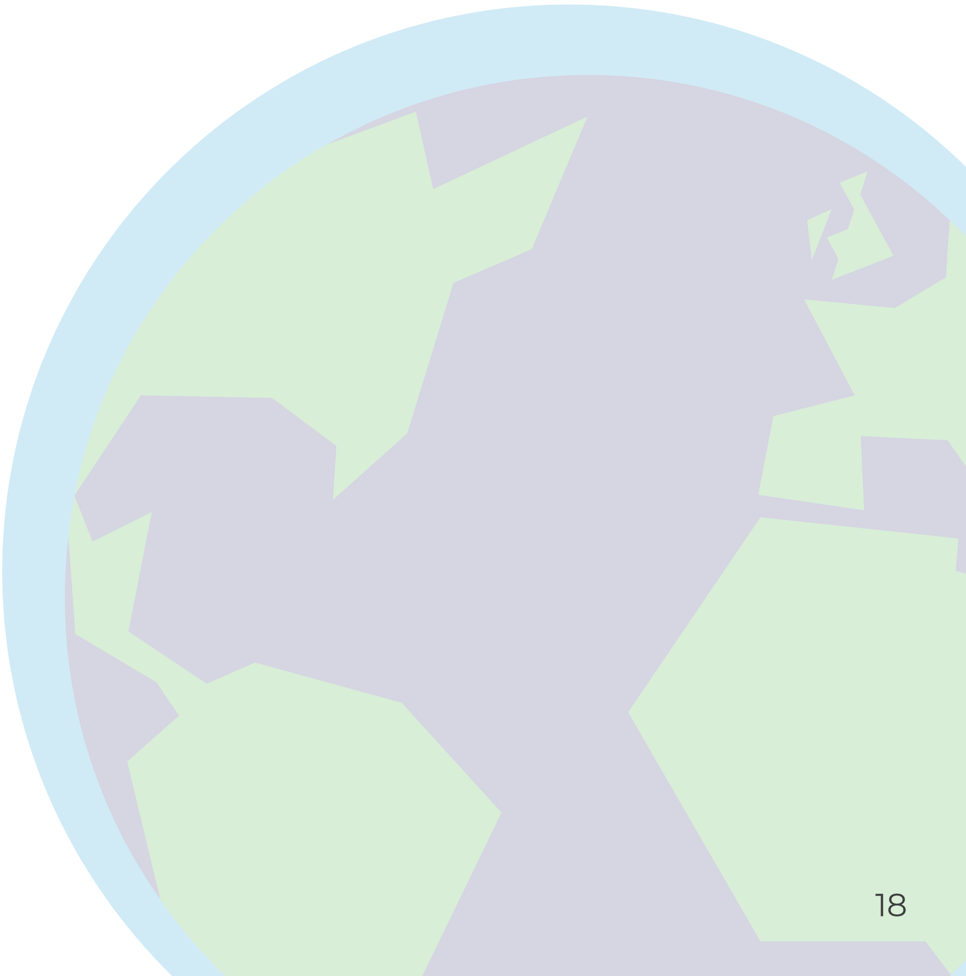
In France, an aerospace and space industry consortium including Safran will utilise hydrogen propulsion knowledge from the space industry to develop hydrogen gas turbines under the Hyperion project **[8]**. Safran and GE Aviation have also partnered on project RISE **[9]** which will develop an open fan engine capable of running on hydrogen.

Siemens Energy in Germany is aiming to run 100% hydrogen for power generation applications by 2030 and has already demonstrated 100% hydrogen burn on some systems **[10] [11]**.

In the USA, GE Gas Power has experience in running gas turbines on hydrogen **[12]**.

Japan is developing hydrogen storage, pumping and combustion research seeking to transfer technology from space and hypersonic successes under the Japanese Aerospace Exploration Agency (JAXA) programmes, along with aiming to have an industrial gas turbine running on 100% hydrogen by 2025.

In Sweden, the Zero Emission Hydrogen Turbine Centre (ZEHTC) has developed a power distribution demonstrator facility centred around a hydrogen-burning gas turbine.



04.2 KEY MESSAGES AND OPPORTUNITIES FOR UK DEVELOPMENT

Development of a hydrogen burning gas turbine will require the establishment of test infrastructure at whole engine, system, and sub-system level. The key technology development work for the design and manufacturing communities will focus on designing novel features in the combustor. Test infrastructure will be required from single sector combustor at sub-scale up to a full size multi-burner combustor module. The FlyZero team has not identified existing UK test facilities capable of delivering cryogenic hydrogen to a full-scale combustion test chamber.

The UK has extensive capability in the design and manufacture of combustor components for kerosene powered aeroengines through Rolls-Royce and its supply chain. There is strong capability in combustion within the UK research community, for example Cambridge, Cardiff, Cranfield and Loughborough Universities.

05. HYDROGEN FUEL CELLS

Hydrogen fuel cells are systems that convert hydrogen fuel and oxygen into electricity through the reverse electrolysis process. Proton exchange membrane (PEM) fuel cells are typically used in automotive applications. Other types of fuel cell, such as alkaline fuel cell (AFC) and solid oxide fuel cell (SOFC) are used on larger applications such as stationary power, maritime applications and the rail industry. AFCs have a low specific power and are not suited to aerospace applications. SOFCs have been experimentally demonstrated in aircraft as auxiliary power units using readily available, lower cost, reformed fuels, rather than pure hydrogen. The SOFC technologies are unsuitable for aerospace applications; they have a lower power density, meaning that they weigh more for the same power output and typically take 20-30 minutes to reach operating condition, and then a similar period for a staged shutdown. Burning fuel over this extended operating cycle results in increased fuel consumption. For aircraft applications, the PEM fuel cell offers the best technical attributes.

PEM fuel cell technology presents a good opportunity for exploitation in multiple sectors since many of the attributes desired for aerospace applications (e.g., power density, volume, and quick start-up considerations) are also needed for large land vehicles, such as heavy goods vehicles. The downside of the PEM fuel cell is the high level of the purity of the hydrogen fuel required to avoid poisoning the catalyst and degrading performance. This may be less of a concern within the aviation sector, which is already used to dealing with tight controls around fuel than in the automotive sector.

Over half the weight of the fuel cell system is the cooling system, making opportunities around weight reduction and improving the efficiency of the thermal management more important. The development and manufacture of the heat exchanger is covered within **Section 6** - Thermal Management.

The core technology dependencies are:

- Lightweighting of fuel cell stack components.
- Improved thermal management and cooling schemes.
- Balance of plant optimisation.

These opportunities can be considered as tuning of the fuel cell for aerospace application. See **Case Study 3** - Intelligent Energy PEM hydrogen fuel cell.

Case Study 3 – Intelligent Energy PEM Hydrogen Fuel Cell

Loughborough-based Intelligent Energy (IE) has over 30 years of experience in developing PEM fuel cells for use in multiple markets including automotive, stationary power and unmanned aerial vehicles. Additionally, IE is developing scalable, power-dense solutions for aerospace based upon their patented evaporatively-cooled fuel cell stack technology. This technology is incorporated in the GKN-led H2GEAR project with IE's hydrogen fuel cells offering a genuine route to true zero carbon. Alongside attracting ATI research and development funding through H2GEAR, IE has also successfully been awarded Defence and Security Accelerator (DASA) funding to scale fuel cells for Ministry of Defence requirements, along with funding from the Advanced Propulsion Centre (APC) to bring fuel cell powertrains into passenger cars, trucks and buses.

image © Intelligent Energy

The UK has industrial capability in hydrogen fuel cell technology in Intelligent Energy, Core Technology, Johnson Matthey, Ceres, Fuel Cell Sytems and AVL. In the ATI-funded H2GEAR programme [3], GKN Aerospace is developing a hydrogen fuel cell powered propulsion system with fuel cell manufacturer Intelligent Energy [13]. The UK also has significant research strength in this sector [14].

The UK is leading in PEM membrane technology within the fuel cell, making this a potential area of high opportunity for a UK "play to win".

A typical fuel cell stack currently takes 1.5 days to build by hand, with a high potential for build errors culminating in leaks that trigger rework. AMRC Cymru, part of the High Value Manufacturing Catapult, is setting up a cell to demonstrate and optimise the automation of fuel cell assembly, to improve rate capability and achieve a repeatable build. The technology readiness level for a generic fuel cell is TRL8, with its incorporation growing in commercial road transport applications. Globally there are several flight-based trials where the fuel cell is being evaluated in flight and operating at TRL5 (**Figure 7** - TRL level for PEM fuel cell).

Early flight-based trials where the fuel cell performance is being evaluated, manufacturing rate development taking place.

Figure 7 – Global TRL level for PEM fuel cell.

05.1 OVERSEAS LANDSCAPE

The countries that are leading in fuel cells are Germany, Japan, South Korea, Sweden, the USA, Canada, and China.

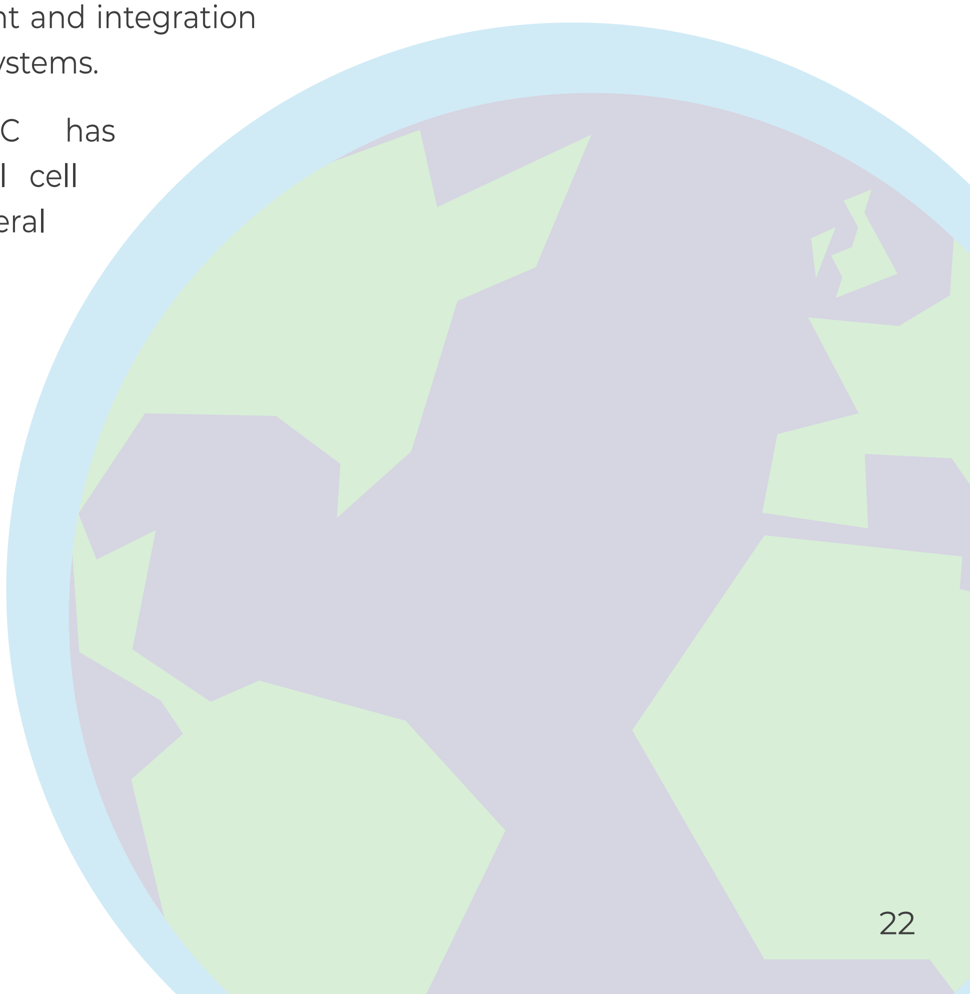
In Germany, Liebherr and General Motors **[15]** have created an aerospace/automotive partnership on fuel cell development. The German Aerospace Centre, DLR, is working on fuel cell powered demonstrator aircraft projects, BALIS **[5]** and DLR-HY4 **[16]**. Projects APUS H2 **[17]**, H2FLY **[18]** and the joint ElringKlinger/Airbus project **[19]** are industrially funded fuel cell demonstrator projects in Germany complementing the work at DLR. Sweden's PowerCell has supplied fuel cells for ZeroAvia's UK-based demonstrator aircraft **[20]**, USA's HyPoint and Hyzon motors have also both supplied fuel cells for evaluation to ZeroAvia **[21]**. Another USA supplier Magnix has partnered with Universal Hydrogen to deliver hydrogen fuel cell powered aircraft **[22]**.

Japan's strong position in fuel cells comes from its automotive industry which has ambitious plans to deploy 300,000 fuel cell electric vehicles by 2030.

In South Korea outside of aerospace, Hanwha is industrialising hydrogen fuel cell power generation technology, with the recently completed Daesan plant claimed to be the world's first and largest hydrogen fuel cell plant **[23]**.

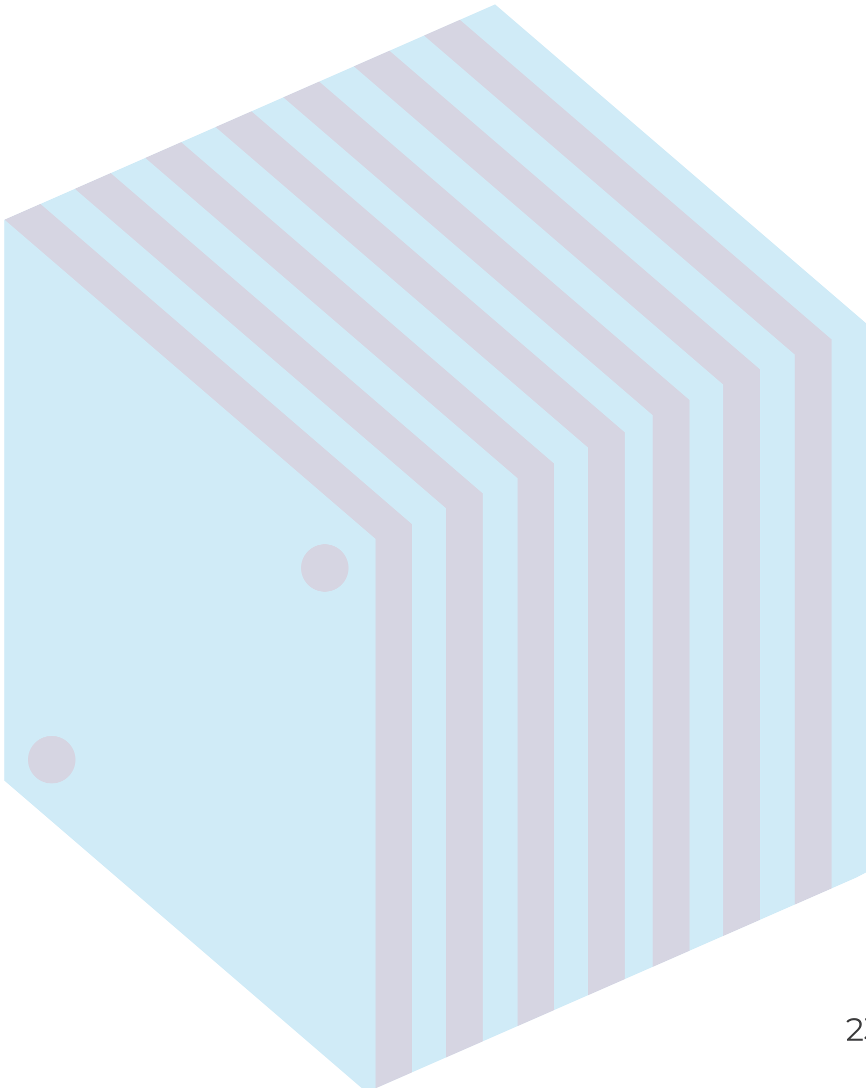
The National Research Council of Canada's Low-emission Aviation programme aids the aviation sector's decarbonisation transition including the development and integration of fuel cells into aircraft propulsion systems.

In China, state-owned COMAC has been developing a hydrogen fuel cell demonstrator which performed several successful test flights in 2019 **[24]**.



05.2 KEY MESSAGES AND OPPORTUNITIES FOR UK DEVELOPMENT

Hydrogen fuel cells are relatively mature in other sectors so there is an opportunity for technology transfer. However, given the high safety standards required by aviation, the levels of production control will be more stringent. Production facilities for aerospace applications will likely cost more than for automotive applications due to the higher levels of quality assurance required by aerospace. There is no incumbent UK industrial capacity for manufacturing fuel cells for aerospace applications at required production rates.



06. THERMAL MANAGEMENT

The thermal management technology brick focuses on the thermal management of hydrogen gas turbines and hydrogen fuel cells. These two propulsion systems have their own challenges and require different technologies; both are covered here. Aerodynamic drag, weight and thermal efficiency are the key challenges to be addressed for aerospace applications.

06.1 FUEL CELL THERMAL MANAGEMENT

The thermal management challenge for hydrogen fuel cells is dominated by the need to radiate very large quantities of heat, generated by the fuel cell, to the ambient air. In addition, the separate air and hydrogen fuel sources required by the fuel cell to generate electricity also require thermal conditioning before they can be received by the fuel cell.

The large air radiators will require novel architectures to enable low aerodynamic drag and high power density heat exchange. Conventional aerospace materials can be selected for these relatively benign operating thermal environments, however, the assembly and manufacturing for the larger scale and complexity of these heat exchangers, at high volume rates, will need development. Current mature heat exchanger technology cannot meet the performance requirements of aircraft without incurring a size and weight penalty.

Novel air radiator heat exchanger designs coupled with a commercially attractive manufacturing method presents a potential area of high opportunity for the UK. An example of this novel technology is shown in **Case Study 4** - Reaction Engines Sabre heat exchanger.

Globally, the heat exchanger technology relevant to fuel cells has been demonstrated on a test rig to TRL5.

Air radiator heat exchanger demonstrated on rig, initial evaluation of manufacturing planning for rate production underway.

Figure 8 – Global TRL level for air-to-air heat exchanger.

Case Study 4 – Reaction Engines SABRE Heat Exchanger

Reaction Engines, based in Oxford, is adapting thermal management technology developed under the SABRE (Synthetic Air Breathing Rocket Engine) programme, which has been receiving funding from the UK Space Agency since 2015 to create next-generation thermal management based on micro-tube and micro-channel technology. This technology can be applied across a range of net-zero aircraft applications including fuel cell aviation and hydrogen combustion cycles. Technology applications in energy and electric vehicles are also being developed to address the wider carbon challenge.

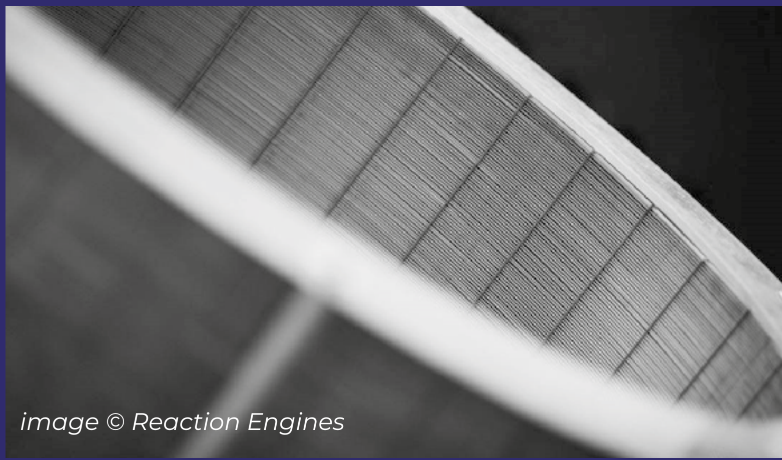


image © Reaction Engines

06.2 GAS TURBINE THERMAL MANAGEMENT

The thermal management challenge for hydrogen gas turbines is associated specifically with the thermal management of the hydrogen fuel, enabling the hydrogen to be heated from cryogenic temperatures to temperatures enabling both efficient combustion and reduced fuel consumption.

Some of the hydrogen heating can be achieved from the need to cool oil, requiring a direct fuel to oil exchanger (FOHE). Further heating of the hydrogen can be achieved with a recuperator, making direct use of the hot gas turbine exhaust. Liquid hydrogen will flow through these products and drive a number of the common challenges identified in **Section 3** (Hydrogen fuel system and tanks) including materials, sealing and unit testing. The availability of cryogenic testing facilities for gas turbine heat exchangers is a clear gap in current capability. The scope of verification will be similar to current testing of aerospace heat exchangers, but testing at cryogenic temperatures will be challenging with new facilities required. Tube-shell and plate-fin heat exchanger designs will need to demonstrate their compatibility with hydrogen. An active assessment of how additive manufacturing may enable more complex geometries that are not currently achievable is also required. The combination of additive manufacturing with novel geometry supports weight reduction. An example of plate-fin and tube-shell technology is shown in **Case Study 5** - Meggitt next generation thermal management.

Case Study 5 – Meggitt Next Generation Thermal Management

Meggitt PLC secured and matched a £3.7 million grant provided through the ATI to develop new technologies which will enable the design of lighter, more compact thermal management solutions to maximise performance or next-generation energy efficient ultra-high bypass ratio (UHBR) aero engines. This investment consolidates Meggitt's manufacturing at its new Midlands-based thermal management centre of excellence while generating opportunities for its wider UK supply chain.

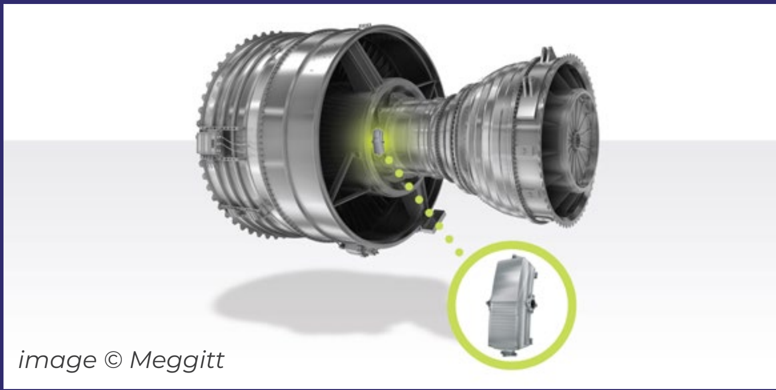


image © Meggitt

Fluid heat exchangers for cryogenic hydrogen systems are assessed to be at TRL3 globally for aerospace applications due to lack of testing with hydrogen and under conditions representative of aircraft operations, limited materials data combined with the requirement to develop sealing technology (see **Figure 9** - TRL levels for fluid heat exchanger).

Fluid heat exchangers assessed at TRL3 for cryogenic hydrogen systems due to lack of testing at low temperatures, under conditions representative of aircraft operations.

Figure 9 – TRL level for fluid heat exchanger.

Examples of UK capability in design and manufacture for aero heat exhanger technology include Meggitt, Reaction Engines, HS Marston (a division of Collins Aerospace), and HiETA.

Oxford University's Thermofluids Institute is a recognised leader in the field of fluid and thermal management research in the UK. Other universities with thermal management expertise include Imperial, Loughborough, Cambridge, Southampton and Manchester. However expertise is needed in modelling and managing the thermal effects and in materials development. There is also work underway in UK research organisations including the High Value Manufacturing Catapult and TWI to exploit latest manufacturing technologies for this commodity; automated laser welding and additive manufacturing techniques are both actively being pursued.

06.3 OVERSEAS LANDSCAPE

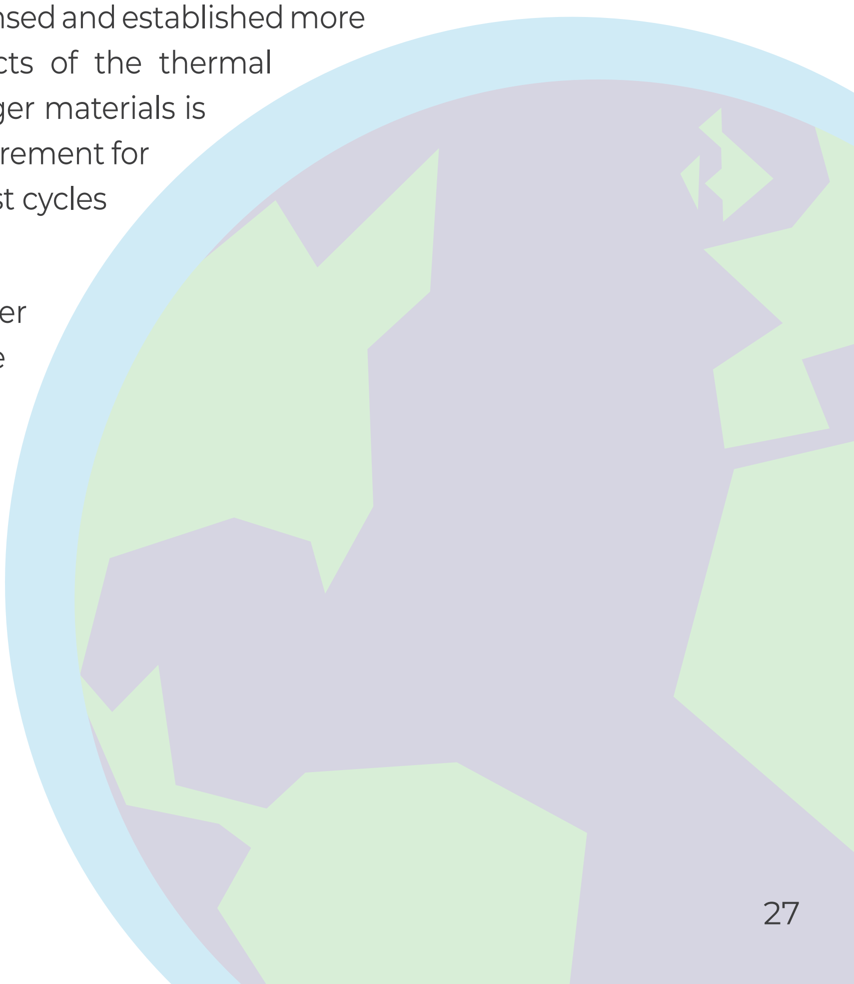
Outside the UK, the leading countries in fluid and thermal management are Germany and the USA.

In Germany, the DLR is developing thermal management capability through fuel cell demonstrator aircraft such as the BALIS project and H2FLY. Liebherr provide heat exchanger systems for rail applications **[25]**, as well as aerospace products **[26]**. In the USA, a NASA-led electric powertrain flight demonstration (EPFD) programme is developing thermal management solutions to support megawatt-class powertrain system ground and flight demonstrations. There are options to develop heat exchanger technology in adjacent sectors and then apply the principles in aerospace, for example the increased use of cooling schemes in electric vehicles to enhance motor performance.

06.4 KEY MESSAGES AND OPPORTUNITIES FOR UK DEVELOPMENT

The UK is world leading in thermal management. To anchor the technology in the UK, suitable test environments need securing in order to develop new heat exchanger technologies. The FlyZero team saw evidence of UK companies electing to test in the US where the regulatory environment allows testing facilities to be licensed and established more quickly. Understanding the long-term effects of the thermal cycling and the permeability of heat exchanger materials is a further challenge which again drives a requirement for facilities that can accommodate extended test cycles down at cryogenic temperatures.

There is also an opportunity to move to higher performance heat exchangers through the design freedoms (complex geometries) allowed by new manufacturing processes such as additive manufacturing.



07. ELECTRICAL SYSTEMS

INCLUDING BATTERY, POWER ELECTRONICS AND MOTORS

07.1 BATTERY

Current battery technology has the potential to power sub-regional aircraft but has insufficient performance to power larger aircraft. Although batteries are not suitable as a primary energy source on large aircraft, their development is essential for small aircraft and providing auxiliary power on large aircraft more efficiently.

The battery application and the power demand through the flight cycle determines the selection of the battery chemistry. Four battery chemistries are candidates for a typical short-range flight profile: lithium ion, lithium sulphur, sodium ion and zinc air. Lithium air is a further potential chemistry option but is at a lower level of maturity, assessed at being 20 years away in technology development.

A battery fuel cell hybrid is an option for primary energy, which would deliver a proportion of the take-off power from a battery while reducing the full-rated power required from the fuel cell. FlyZero is reviewing this to understand the potential technical performance benefits, such as overall system weight reduction. All the fuel cell systems considered require a start-up battery which is small in capacity and do not require any new technology or battery capability.

Case Study 6 – Electroflight High Energy Battery System

At its Gloucester facility, Electroflight designs and manufactures lightweight bespoke battery systems with very high levels of safety and energy density. A recently announced partnership with a Swedish start-up Heart Aerospace and compliance experts, enabled through funding of over €1.5 million from a joint UK/Swedish bilateral call for research and development projects.

This follows on from Electroflight's involvement in Rolls-Royce's ACCEL initiative where it is supporting the design and build of the first high-performance electric aircraft.

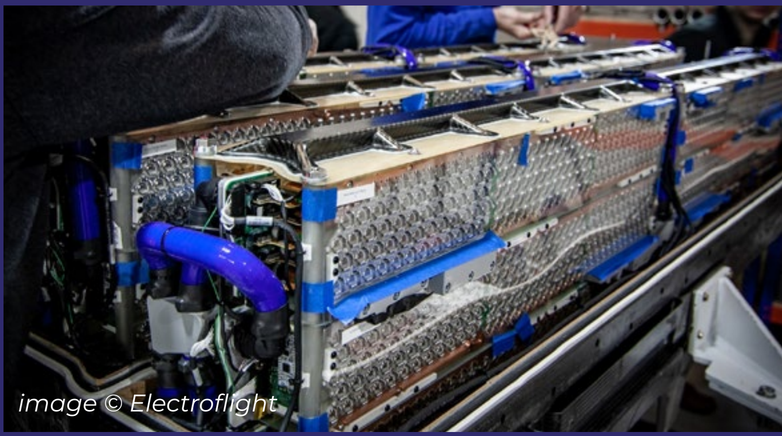


image © Electroflight

Electroflight and Rolls-Royce have developed a lightweight, cooled 'Spirit of Innovation' battery pack for the all-electric flight speed record **[27]** (see **Case Study 6**) and Electroflight have been selected to provide the battery system to the Heart Aerospace ES-19 **[28]**. Outside of the aerospace sector, Williams Advanced Engineering has held contracts (2014-2018) to supply the battery system to the whole Formula E grid and are looking to regain this from 2023 onwards **[29]**. This demonstrates that while others hold mass market automotive battery supply contracts, the UK can move to a position of leadership on higher technology aerospace batteries for primary power that are lightweight and operate at high discharge cycles. These technologies are core to the research delivered through the Faraday Institution and the UK government's Faraday Battery Challenge to develop high-performance, low-weight batteries.

07.2 ELECTRIC MOTOR

In this report the electric motor scope is purely the motor body and excludes the gearbox. For this analysis, the electric motor is powered by a fuel cell which drives the gearbox, which in turn drives the propellers. Electric motors are becoming popular due to their power density. There is an opportunity for the UK to focus on development of increasing the achievable power densities.

Technology Basis	*2030 projected power density*
Current mature motor	*<5 kW/kg*
State of art axial flux motor	*10 – 16 kW/kg*
Superconducting motor	*25 – 40 kW/kg*

Axial flux motors offer the capability to increase the power density beyond 10kW/kg, with a motor architecture that operates at higher speeds of around 15,000 rpm requiring a reduction gearbox to achieve an efficient propeller speed. Current motor technologies are being rapidly adapted, scaling up from automotive architectures (see **Case Study 7** - YASA next generation axial-flux electric motor), and with higher efficiencies from advanced topology machines, e.g., axial flux motors. The capability development for these motors is targeted at components including alternative coil technologies to minimise losses. From a broader perspective, the replacement of rare earth magnets with iron nitride alternatives, as an example, is still at a low level of technology maturity.

Case Study 7 – YASA Next Generation Axial-Flux Electric Motor

YASA, a spin out of Oxford University, has developed a revolutionary electric motor based on an 'axial flux' design, to replace the legacy 'radial flux' drive solutions that have been in use for the past 50 years. The company says its unique design can deliver average efficiencies of 96%, providing automotive OEMs with 5-10% range improvements, thanks to its motor being one third of the weight and three times the power density of traditional solutions. In 2019, YASA announced Ferrari as its first OEM customer for volume production and in 2021, it became a wholly owned subsidiary of Mercedes-Benz, providing e-motors & controllers for the company's next generation electric-only platforms.

YASA has improved power density (kW/kg) at a rate of 15% per year, making it well placed for opportunities in sectors including aerospace, where it has already supplied the electric motors for the Rolls-Royce initiative 'project ACCEL' which recently broke the record for the world's fastest electric flight. Earlier this year, YASA spun out Evolito ltd. to industrialise YASA's IP for the aerospace industry.

image © YASA

There is no current industrial base for volume manufacture of aerospace standard motors in the UK. The FlyZero team anticipates an investment in the range £50-100m would be required to build an aerospace-certified facility for motor manufacture.

Whilst the UK supply chain is developing significant capability in high power electrical machines, none of these programmes have yet transitioned to full production rate. Examples include Aeristech developing power-dense motors in the H2GEAR programme and Yasa, who are working with Rolls-Royce to develop the world's fastest electric plane in ACCEL [27]. Rolls-Royce is developing the electric powertrain for the Vertical Aerospace VA-X4 [30]and the Tecnam P-Volt [31]. Safran's Electrical and Power division in Buckinghamshire and their ENGINeUS motor was selected by Bye Aerospace for their eFlyer 800 aircraft [32].

The UK has a strong base of industry, consultants and research organisations developing solutions for automotive including Magtec, Denis Ferranti, Ricardo, ProDrive, AVL, Newcastle University, University of Nottingham, Oxford University and WMG. The UK is also investing in electrical powertrains through the £80m Industrial Strategy Challenge Fund Driving the Electric Revolution. Large-scale commercial aviation is out of scope but it is addressing applications in agriculture, maritime and rail.

Application of proven technologies from other sectors, opportunity to understand manufacturing rate capability considerations from automotive sector.

Figure 10 – Global TRL level for aerospace electric motor.

07.3
POWER ELECTRONICS

Power electronics are required to take the output from the DC power from a fuel cell and convert it into multi-phase AC power suitable for driving the electric motor. In the UK, power electronics development is being led by the ground-based transportation sector with Formula E driving technology advances. Developments focus on using gallium nitride as an alternative to silicon carbide for switching and packaging technology.

The capability roadmap for power electronics is highly dependent on the voltage range selected. Within a 1-3kV range current silicon carbide switching devices provide the level of capability. Using gallium nitride technology may potentially generate much higher power densities and lower losses for applications than established silicon carbide technology. This switching technology is currently assessed at TRL 3 globally. The opportunity to cool the electronics within the thermal management of the system improves switching efficiency levels by as much as 30%. This has been incorporated in automotive applications and assessed at TRL9, but is untested in aerospace applications.

Application of proven technologies from other sectors, transition of technology and manufacturing for aerospace applications considered low risk.

Figure 11 – Global TRL level for aerospace power electronics.

Incorporating power electronics within the motor casing provides an opportunity for weight reduction of the overall electrical drivetrain. Further weight reductions can be achieved if the voltage range is increased beyond 3 kV, or superconducting technologies are incorporated in the system. UK capability for the higher voltage power electronics and superconducting is below TRL 2 for aerospace applications. The development of power electronics in the UK is highly dispersed across industry and academia. The universities of Cambridge, Nottingham and Warwick have programmes pursuing switching technology. Industrial developments are spread across several companies too, including ATL Transformers, Clas-SiC, Dynex and Nexperia.

High power electrical systems are under constant development; competitive fields like Formula E motor racing are continually pushing boundaries of bulk power extraction and efficiency. In Formula E, these systems are rated at 250 kW, operating at 800 V with silicon carbide switching. This niche application represents the leading edge of high-power automotive technology. Suppliers for mass market applications such as for Tesla power switching [33] are based in Italy and Japan. In the UK, Delphi Technologies holds a robust market share in a specific sub-set of the e-automotive sector, with three out of the four premium automotive manufacturers using their systems [34].

07.4 OVERSEAS LANDSCAPE

The leading countries for batteries, power electronics and motors are Japan, South Korea, USA, and EU member states collaborating on international technology programmes.

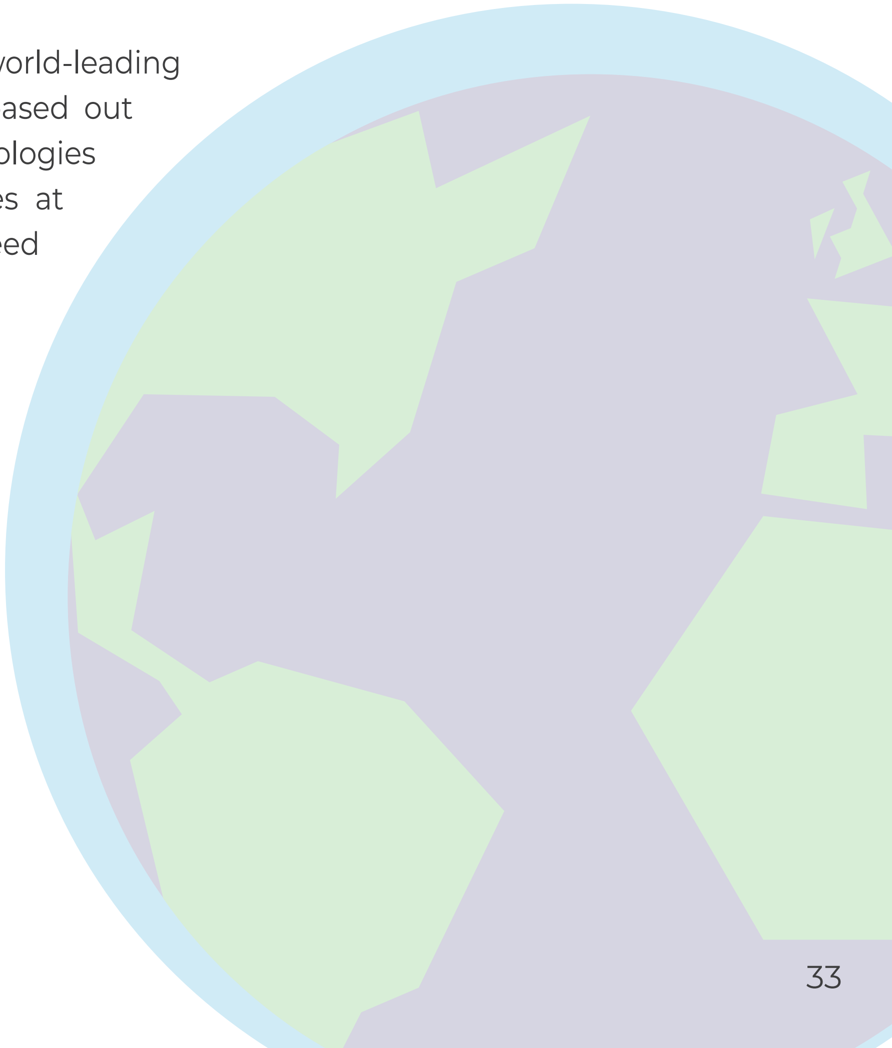
Japan and the USA are leading the development of batteries for electric vehicles, for example manufacturing large volumes of batteries for Tesla at their Nevada gigafactory. US-based firm Cuberg supplies batteries for battery-electric aircraft manufacturers BETA technologies and Ampaire, and hybrid-electric aircraft manufacturer VoltAero **[35]**. South Korean battery manufacturer Kokam is the selected battery supplier for electric aircraft produced by Pipistrel **[36]** **[37]** and Eviation **[38]**.

US-based firm Magnix **[39]** is one of the leading developers of high-power electrical machines for aviation applications. Its drivetrain is used, amongst others, in Eviation's Alice aircraft, Aerotec's eCaravan **[40]**, and the Harbour Air e-plane **[41]**. Honeywell and Denso have partnered to deliver powertrains for electric aircraft, initially targeting the urban air mobility market **[42]**.

Finally for power electronics, Japan is home to companies with strong superconductor manufacturing capabilities such as Fujikura, Japan Superconductor Technology, and Furukuma Electric Co.

In the USA, there are Cryomagnetics Inc, Hyper Tech Research Inc, and Superconductor Technologies Inc.

Additionally, Magnix manufactures world-leading electric drivetrains for aerospace. H3X based out of Denver, Colorado is developing technologies around silicon carbide switching devices at high power densities with a high-speed operation.



07.5 KEY MESSAGES AND OPPORTUNITIES FOR UK DEVELOPMENT

The UK capabilities around specialist battery applications in Formula E could be developed and applied in the aerospace sector; the two applications share common requirements such as, for example, lightweighting and high discharge demand. There are good emerging capabilities in electric aerospace motor design in the UK built up from the strong foundations in academia and industrial start-ups. This platform presents an opportunity to scale up and capture market share. This could also be combined with the incorporation of other motor topology advances, e.g., coil and magnet.

There is a lack of industrial test capacity for these larger machines. Current test capacity is orientated around academic facilities and there is little capacity for full environmental testing operating a continuous duty cycle. Similarly, there is little evidence of any production rate capable facilities for an aerospace electrical drivetrain at these higher power levels. This presents an opportunity for the UK to establish itself as a global supplier of high-power electric drivetrains. Currently, there is no global expertise for high-voltage power electronics capable of operating in an aerospace environment and this presents an opportunity for the UK to take the lead in developing this technology.

08. AERODYNAMIC STRUCTURES

This tech brick focuses on the developments required to support zero carbon in all the aerodynamic structures - fuselage, nacelle, pylon, empennage and moveables, but with a focus on 'dry wing' technologies. The UK has world-leading capability in wing design, manufacture and assembly. Today's aircraft store fuel in their wings; however as cryogenic hydrogen is introduced, it will drive the need for optimised tanks, which could be stored either in the fuselage, in the wing, in 'cheek' pods or in external pods. The potential for a dry wing, where fuel isn't stored in the wingbox, offers significant opportunities for radical new wing design and manufacture. These can be grouped into four key streams of development.

The first stream is performance improvements which include enabling laminar flow, lift-to-drag ratio improvements, wing morphing and improved moveable devices. These range from TRL 2-5 globally. Some of the nearer term opportunities include improved moveable devices such as flaps and one shot composite 'moveables', with full wing laminar flow or wing morphing further into the future.

Large primary one-shot composites, proof of concept demonstrated. Development of rate capable automated manufacturing is an opportunity for the UK.

Figure 12 – Global TRL levels for aerodynamic structure performance improvements.

The second stream centres on load reduction to optimise design, including passive and active load alleviation, semi aero-elastic hinges, inertia relief, and aero-elastic tailoring. Most of these technologies are TRL 2-3 globally.

Load reduction activities, proof of concept demonstrated. Launched initial development of manufacturing technology strands.

Figure 13 – Global TRL levels for load reduction activities.

The third stream for development activity is structural optimisation, including novel designs and architectures, such as a truss-braced wing, new leading and trailing-edge architectures, advanced pylon structures, folding wingtip, distributed propulsion and biomimicry structures. All of these structural developments are assessed as being at the lower end of the TRL scale globally, spanning TRL 2-4, with the most novel at TRL 2.

Structural optimisation activities, technology formulation only. Launched initial development of manufacturing technology strands.

Figure 14 – Global TRL levels for structural optimisation activities.

The fourth stream, based around manufacturing optimisation and improvement, including new processes, bonding and joining technologies, out-of-autoclave cure and new processes to create wing moveables, such as spoiler manufacture in a closed mould, is as high as TRL8. This manufacturing-orientated stream also covers the implementation of advanced composites, using programmable or health monitoring materials, self-healing materials for lower maintenance and increasingly sustainable materials.

Manufacturing optimisation activities, demonstrations well developed for smaller and subscale components, for larger components the TRL level drops. Rate development activities identified as an opportunity for the UK.

Figure 15 – Global TRL levels for manufacturing optimisation activities.

The UK has world-leading capability in the design and manufacture of wings and sub-structures. Companies operating in this space are Airbus, Spirit AeroSystems & GKN Aerospace, (see **Case Study 8** - Airbus Wing of Tomorrow). Sub-tier technology providers, who provide materials, manufacturing and assembly technologies, as well as sub-components for manufacturing, are also dispersed across the country. The UK is increasingly capturing not only assembly, which has traditionally been its strength, but also on-shoring of high technology component manufacture. This is a huge opportunity in the case of both a hydrogen dry wing and conventional wings for aircraft powered by kerosene or by sustainable aviation fuels.

Digitalisation and manufacturing automation technologies coming to market are improving to a point that will allow the UK to compete with lower-cost countries. In this space, out-of-autoclave composites are a significant area of development which can potentially significantly reduce manufacturing's carbon footprint.

As the use of lightweight composites in structures increases, technologies for recycling also become increasingly important. These are largely at early TRL 2-3 today. In terms of conventional manufacturing, wing manufacture and assembly activities are very mature at TRL 9, and the UK is capable of production at full rate. When considering what a hydrogen aircraft wing may look like, the TRL then drops to between 2-4 with no proven manufacturing rate capability. The High Value Manufacturing Catapult network is active in aerostructures as well as The Welding Institute (TWI). Significant sub-tier developments in this space are still reliant on overseas technology however, such as large-scale composite tooling providers, material development and manufacture.

Case Study 8 – Airbus Wing of Tomorrow

The Wing of Tomorrow technology programme led by Airbus is exploring materials, manufacturing and assembly technologies that have the potential to enable improved fuel burn and increased manufacturing rates at reduced cost. In 2016, Airbus received an £18.6 million investment through the ATI to develop a new wing integration centre in Filton (AIRTeC). Additionally, a recent £20 million investment by the Welsh government in AMRC Cymru, where Airbus is the first major tenant, sees a further extension of the transnational research network which is capturing knowledge from demonstrators to understand scalability limitations and ensure engineering and industrial capability for any expected future wing design.


image © Airbus

08.1 OVERSEAS LANDSCAPE

Aerodynamic structures capability exists globally, with leading countries including France, Japan, Sweden, Canada and the USA.

In the USA, Collins Aerospace, Boeing, Lockheed Martin, Spirit Aerosystems and Triumph Group are leading companies. SAAB AB, as a large Swedish aircraft manufacturer and Bombardier as a large Canadian manufacturer both have leading aerodynamic structures capabilities. French and German aerodynamic structures capabilities are dominated by Airbus and its supply chain. In Japan, Mitsubishi Aircraft Corporation, Subaru Aerospace and Kawasaki Heavy Industries have the greatest presence in aerodynamic structures.

08.2 KEY MESSAGES AND OPPORTUNITIES FOR UK DEVELOPMENT

The dry wing – a wing without fuel stored within it – is a key differentiator between kerosene-powered and liquid hydrogen-powered aircraft. This change presents an opportunity for the UK.

There are several live projects operating to develop and optimise automated manufacturing. The FlyZero team has engaged with the High Value Manufacturing Catapult network, specifically the NCC and AMRC Cymru, whose work to deploy automated assembly techniques for aerodynamic structures will benefit future aircraft manufacture. Manufacturing of aerodynamic structures forms a significant part of the UK's aerospace footprint.

Capability to deliver at rate is a key consideration of airframers when selecting suppliers. Without a funded rate demonstration, the UK is potentially at a disadvantage. French and German organisations are accessing economic development funding to support rate growth; this is a threat to the UK's leading position on wing manufacture.

09. COMMON CHALLENGES

In addition to the challenges specific to the technology bricks described above, the industry players consulted also identified some common challenges relevant for all the technology bricks:

Swift access to investment to support technology research and development

In this emerging market where the pace of innovation is high, the competitive advantage of UK companies could be improved by quicker access to R&D funding, even if just for smaller amounts of money to enable early-stage development and the capture of initial IP.

Access to grant funding

Grant funding at internationally competitive intervention rates for early development especially for high-risk but high-reward technologies like hydrogen would significantly increase the likelihood that companies embark on the technology development. Companies working on relevant technologies outside the aerospace sector particularly highlighted this, since the barriers to entry for aerospace are high and the timescales for business case payback is longer than in their current target sector.

Access to facilities and skills to support prototyping and testing

The capital investment required for these can be very high. Facilities that can be shared for developing systems for hydrogen and electric flight across industry (and even with other sectors developing related products) could reduce the capital cost and attract companies to locate in the UK, mirroring the model of the UK Battery Innovation Centre and the Catapults.

Manufacturing capability development

Manufacturing process technologies and manufacturing rate capability need to be developed in parallel with aircraft technologies. Delivering development in parallel will accelerate the entry into service of zero-carbon aircraft. In addition, since the skills and equipment for manufacturing are often different in type or scale from those used for technology development, aerospace companies can decide to create a new base at the point at which they start to build manufacturing capability. Therefore, investment in manufacturing capability provides a strong anchor for long-term manufacturing jobs.

UK national and regional support for industrialisation could be more competitive

Other countries offer strong incentives via regional economic funds. These are highest for clean sheet technologies, like hydrogen fuel system, where there is little incumbent industry to be supported.

Greater certainty on the size of the emerging market opportunity

Confidence on market size and the required production capacity would catalyse the UK's ability to secure market share.

Regulation and standards

Clear requirements, standards and regulation can be enablers of innovation in the supply chain, for companies in the aerospace sector and outside.

Capability and skills

The capability and skills to deliver the future workforce with access to tools and facilities are needed to develop next generation aircraft.

Aerospace is a global industry

Many of the major customers and projects to develop zero-carbon aircraft are outside the UK. Opportunities to form relationships with these customers during technology development increases the likelihood of winning market share.

Due to the high commercial risk involved with R&D for aerospace, the availability of government funding affects companies' choices on where to locate. During early technology development, receipt of a government R&D grant increases the likelihood of bringing in significant private investment, as government funding is seen by investors as recognition of the technology's potential. Both small companies (start-ups) and large multinationals have flexibility in their choice of location and can choose to locate where R&D funding is available at gearing levels that are competitive internationally. Later in the development and industrialisation lifecycle, companies review their location again, seeking to benefit from government support for large capital investments.

10. ADJACENT SECTORS

Disruptive technologies will be required to deliver zero-carbon aircraft architectures and major sub-components. This will create significant openings for new market entrants, and an opportunity for shared learning with established players from other sectors, many of which are ahead of aerospace in the journey to net-zero tailpipe CO_2 emissions, or already using hydrogen.

Figure 16 – Aerospace Adjacent Sectors from which technology push and pull could emerge.

Nuclear

- Manufacturing technologies for heat exchangers.
- Hydrogen generation and storage.

Energy

- Hydrogen generation and storage.
- Cryogenic systems – storage and distribution.
- Wind turbine synergies with power electronics and structure manufacture.

Automotive

- Whole infrastructure maturity.
- Synergies in electric and fuel cell technologies.

Space

- Cryogenic systems – storage and distribution.
- Heat exchanger technologies.

Defence

- Whole system synergy – dual use read across.
- Synergies in structures and gas turbine components.

Marine

- Cryogenic re-fuelling package solution.
- Hydrogen combustion sensing technologies.

Figure 17 – Adjacent Sector opportunities.

Many of the disruptive technologies including e.g., hydrogen tanks, hydrogen fuel cells etc., have applications across multiple sectors. Aerospace applications often drive to higher performance requirements than other end use applications. Performance gains driven by aerospace can then be translated back into other applications – a 'technology circularity' as shown in **Figure 18**.

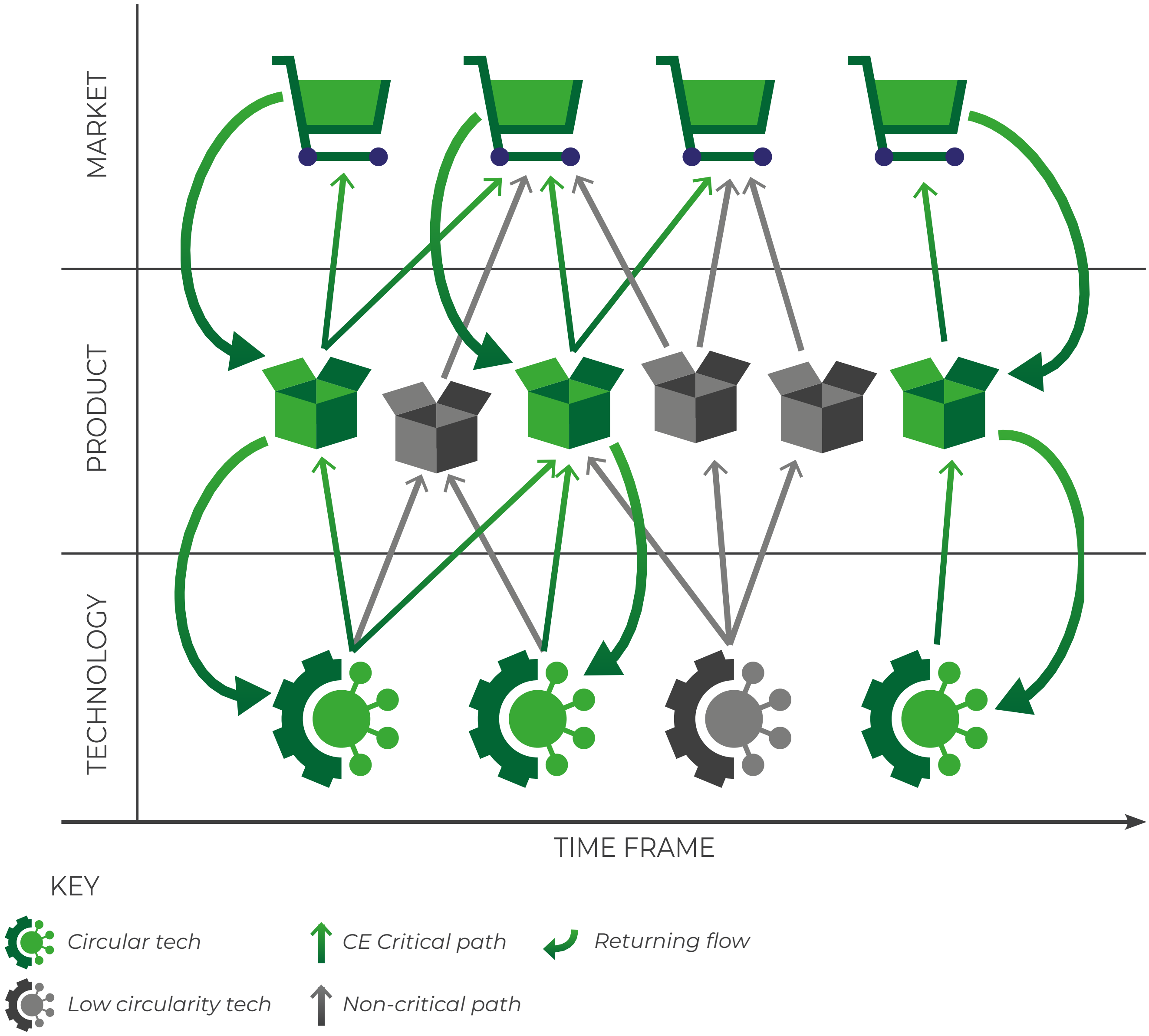


Figure 18 – Technology circularity [43].

11. OVERSEAS COMPARISON

The growing pressure on businesses and countries to demonstrate environmental responsibility is driving the urgent need for green technologies. Both France and Germany have announced policies to ban domestic flights where journeys can be completed by rail. With this background, other nations are already aggressively pursuing clean aircraft technology development.

The chart below (Figure 19 - Estimated overseas spend on clean aircraft technologies) shows the level of investment other nations are making. It indicates annual spends of £0.5b per annum for leading European nations, the USA, and Japan. Even allowing for the effect of budget cycles, there is a clear international financial commitment to fund sustainable aviation in the three-year block from 2022 through to 2024.

Key public-funded sustainable aviation investments

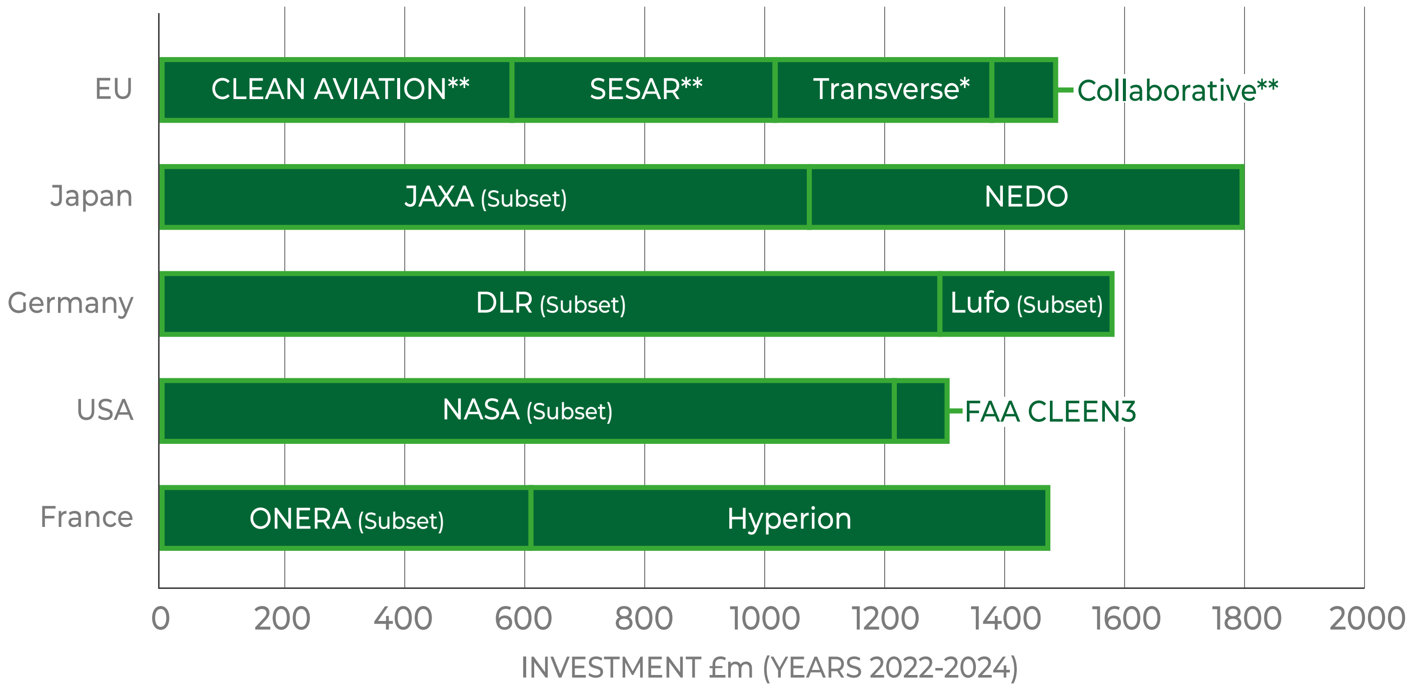


Figure 19 – Estimated overseas spend on clean aircraft technologies.

Both the EU Clean Aviation and SESAR programmes are long-term activities, running through to 2027. The collaborative research programmes (marked **) are focusing on aviation, while the transverse programmes (marked *) are looking to align technology development across multiple sectors. Programmes marked (Subset) reflect the sum of the clean aircraft technologies designated within a top level budget.

The Japanese Aerospace Exploration Agency (JAXA) has committed funding for zero-carbon technology development up to 2030 and beyond. NEDO - the Japanese New Energy and Industrial Technology Development Organisation - is currently funded up to 2025 for energy systems research including hydrogen production, storage refuelling and bio-jet fuels, and advanced lightweight batteries.

In Germany, Lufo and DLR research funding is actively committed up to 2025. NASA's zero-carbon aerospace technologies programmes are funded at $565m a year beyond 2025. The USA's current CLEEN 3 programme is set to complete its third phase at the end of 2025. Finally, in France, the Hyperion programme is funded up to the end of 2023. Overseas activity by technology is summarised in **Table 1**.

	Brazil	Canada	China	France	Germany	Italy	Japan	South Korea	Spain	Sweden	USA
Hydrogen Fuel System and Storage				✓	✓		✓	✓	✓	✓	✓
Hydrogen Gas Turbines				✓	✓		✓			✓	✓
Fuel Cells		✓	✓		✓		✓	✓		✓	✓
Thermal Management					✓						✓
Batteries, Power Electronics and Motors			✓	✓	✓		✓	✓		✓	✓
Aerodynamic Structures	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓

Table 1 – Summary of overseas activity by technology brick.

There are significant opportunities for partnerships with other countries. These could involve pre-competitive collaborative R&D partnerships, programme collaborations, or alignment of government funding. FlyZero's initial analysis shows potential partnerships with the USA and Japan for high-power electrical machines, drives, power electronics and thermal management solutions; with Germany, Japan, and Sweden for hydrogen fuel cells; and with South Korea and Japan for battery capability development could add value to the UK.

The UK should explore the opportunity for international collaboration (UK participation in international programmes or international participation in UK programmes). Some opportunities naturally exist within the global companies being considered. For example, Airbus has significant capabilities in the UK, France, Spain and Germany, and Rolls-Royce has significant capabilities in the UK and Germany. Similarly, GKN operates in the UK, the Netherlands and Sweden, and Spirit AeroSystems is headquartered in the USA, with operations in Prestwick and Belfast.

12. CONCLUSIONS

The UK has world-leading capability in technology areas critical to realising zero-carbon emissions commercial flight – especially wings and aerodynamic structures, fuel systems, hydrogen gas turbines and high efficiency electric motors.

New zero-carbon emission aircraft will require development of disruptive technology. To win content on these aircraft, UK companies must be ready to demonstrate new systems based on disruptive technologies in the next one to two years for sub-regional aircraft and by 2025 for larger aircraft.

To obtain a leading position in systems for hydrogen aircraft, the UK will have to design, build and test capability for cryogenic hydrogen. Leading aerospace companies in the EU and Japan have made a concerted start on hydrogen-powered aircraft. Some countries have the added advantage of a deep understanding of cryogenic hydrogen as a result of having a space sector with capability in hydrogen propulsion.

New aircraft will require more integration than before between the powertrain and the airframe. This could change where the historic aircraft interfaces fall and who takes ownership of which system. This could in turn impact the structure of the global supply chain.

As these are new technology areas, the barriers to entry are currently lower for new entrants from across the globe.

To maintain its leading aerospace position, the UK must invest in these technology areas to both transition incumbents and foster new entrants.

13. NEXT STEPS

This report provides an initial overview of the UK's capability in these critical technologies. Further content on UK capability will be published as part of the FlyZero roadmaps in 2022. These will outline the technologies required and the timescales to achieve zero-carbon flight.

The ATI has put forward a proposal for a mission-led programme of technology development and demonstration delivered in partnership with industry.

Beyond that, to fully realise zero-carbon emissions flight, a wider programme of intervention will be needed that covers hydrogen including support for building supply chain capability, skills and airport infrastructure.

FLY ZERO AEROSPACE TECHNOLOGY INSTITUTE

UK AEROSPACE HYDROGEN R&D OPPORTUNITY

A Summary of Key Regional Capability Relevant to the Development of Hydrogen Aviation

The UK aerospace sector across its nations and regions has the capability to deliver the hydrogen aircraft technologies identified by FlyZero, accelerating the introduction of zero-carbon emission air travel.

Scotland *5% of current UK Aerospace jobs*

Strengths: Through life service, including design and manufacture of aerodynamic structures, maintenance repair & overhaul.

Opportunities: Candidate location for testing of hydrogen components and aviation demonstrations.

Northern Ireland *6% of current UK Aerospace jobs*

Strengths: Design and manufacture of aerodynamic structures, cross sector hydrogen experience.

Opportunities: Candidate location for development and testing of hydrogen components, hydrogen tank demonstrations.

Wales *10% of current UK Aerospace jobs*

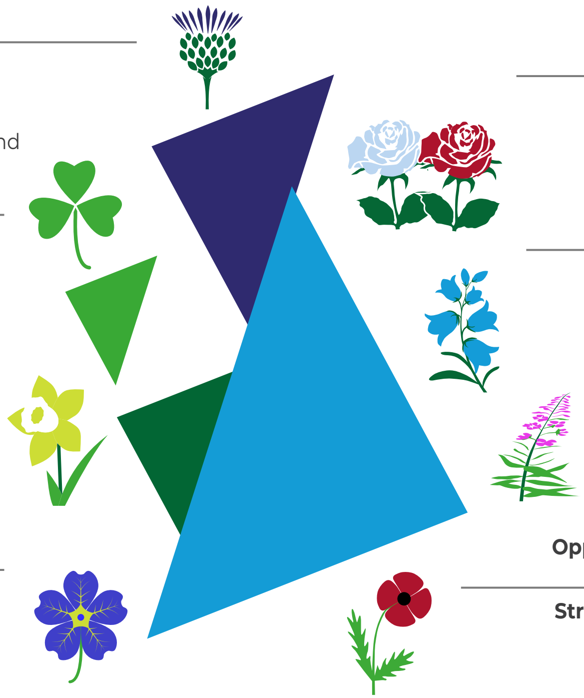
Strengths: Manufacture and assembly of aerodynamic structures and cross sector hydrogen experience..

Opportunities: Candidate location for development and testing of hydrogen components, dry wing and integrated energy demonstrations.

South West *19% of current UK Aerospace jobs*

Strengths: Design of wings and fuel systems, electric and hydrogen whole aircraft integration and emissions testing.

Opportunities: Candidate location for wing and fuel system development and iron bird, dry wing and operational demonstrations.



Yorkshire and the North *17% of current UK Aerospace jobs*

Strengths: Make-to-print manufacturers, specialist machine tool manufacturers, planned hydrogen production.

Opportunities: Manufacturing development, rapid prototyping and integrated energy demonstrations.

Midlands & Ox-Cam *23% of current UK Aerospace jobs*

Strengths: Gas turbines, including fuel control and combustion research capability, thermal management, e-machines, fuel cells, actuation systems. whole aircraft integration and emissions testing.

Opportunities: Candidate location for engine test bed, fluid management test, component development and test and aviation demonstrations.

London *1% of current UK Aerospace jobs*

Strengths: Policy support, major airports.

Opportunities: Longer term aviation development and demonstrations.

South East *19% of current UK Aerospace jobs*

Strengths: Fuel systems and cross-sector (space) presence in hydrogen.

Opportunities: Fuel system development and component test.

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