Zero-Carbon Emission Aircraft Technology Bricks

International Landscape

September 2025

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1 Executive Summary

The ATI's Hydrogen Capability Network (HCN) has undertaken an international review of the six technology bricks identified during the FlyZero project to understand important areas for development which represent opportunity for the UK. This review identified the **cryogenic hydrogen storage and fuel system** technology brick as a vital area for further development and targeted support especially as it will be a vital part of any future liquid hydrogen (LH2) powered aircraft, whether they are powered by gas turbines or fuel cells. Among the disruptive technologies needed to use LH2 as a fuel source, this technology brick requires the most significant technology development to reach TRL6.

The engineering capability and specialist knowledge that is needed to develop cryogenic hydrogen storage fuel systems is novel, but it can also apply to multiple other technology bricks. There are strong links to the thermal management, fuel cells, electrical systems, and hydrogen gas turbines technology bricks. Any LH2-powered aircraft will benefit from thermal integration of these systems utilising the cold sink of the LH2 fuel to improve the efficiency of the electrical and propulsion systems through optimised heat exchangers and thermal management. A focus on the cryogenic hydrogen storage and fuel system has the potential to unlock and anchor development and integration of the other technology bricks.

Other technology bricks required for zero-carbon emission flight require lower levels of disruptive change. Fuel cells and electrical systems require some new technology, but these are currently at a more advanced level of development. Gas turbines require some modification to run on hydrogen and initial testing to prove the concept has already been complete, plus the timeframes for hydrogen gas turbines on commercial aircraft are further out than those for fuel cells and battery (or hybrid electric) systems. The aerodynamic and structural changes needed to accommodate different propulsion or fuel storage systems (such as the need for dry wings), are linked to the expected design evolution of the fuel system and tank development. The aerodynamic structures technology brick will benefit from technology evolutions on the next generation of ultra-efficient conventional aircraft and additional technology development for these is therefore less urgent than for cryogenic hydrogen storage and fuel systems and thermal management.

The UK has a strong opportunity in cryogenic hydrogen fuel systems based upon its existing capabilities, current industrial presence and policy support, but there is competition from the US, Germany, France, and Japan. The United Kingdom currently faces a shortfall in LH2 expertise, especially regarding fundamental research and testing infrastructure. Both of these areas are essential foundations for advancing mid-TRL research and supporting industrialisation efforts.

Support for both fundamental research and test infrastructure will be highly beneficial for other technology bricks beyond cryogenic fuel systems, particularly thermal management. Due to the cryogenic nature of the fuel, LH2 fuel systems link very closely with thermal management themes, and it is beneficial to consider the two systems holistically. The support will also bolster the UK's existing capabilities and enable the country to become a leader across these technology bricks. Realising zero-carbon emission technologies in the UK depends on having design expertise and capability together with a strong understanding of LH2 properties and safe-handling.

2 Introduction

The UK has an opportunity to become a world-leader in zero-carbon emission aircraft technologies. The FlyZero project, led by the Aerospace Technology Institute (ATI) developed a report in 2022 which evaluated overseas and UK capabilities in six key technology bricks which are relevant to zero-carbon emission aircraft, shown in Figure 1.

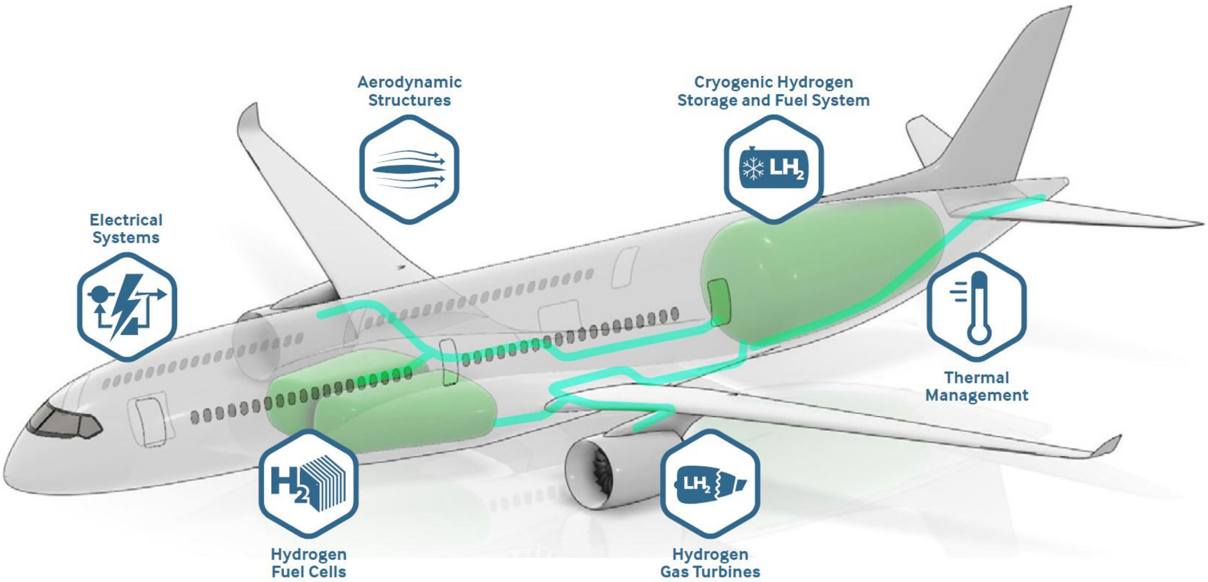


Figure 1: Key Technology Bricks for Zero-Carbon Emission Flight

The UK has significant expertise in existing aircraft technologies through OEM and Tier 1 manufacturers, a strong network of research institutions and an established supply chain. The ATI's market analysis [2] estimates that the UK has around a 10% share of the global aerospace market. UK Government's Advanced Manufacturing Sector Plan [3] targets an increase in the UK's share to 15% in 2050, driven in part by the development of ultra-efficient and zero-carbon technologies.

Future market share opportunities for the UK need to be considered through both technology requirements and a global landscape perspective. The level of development needed to mature the different technology bricks differs, however some research sits across and supports multiple bricks. For example, cryogenics research and capability is needed for hydrogen storage and fuel systems, thermal management and electrical systems. Furthermore, hydrogen fuel systems and thermal management technology developments could be integrated to improve fuel cells and gas turbines. Conversely, aerodynamic structures development for LH2 or electric-powered flight are needed for efficiency and scale but will likely utilise existing or next-generation architectures.

2.1 Methodology

Six comparators have been used to consider countries' current levels of capability in each of the six technology bricks. These key comparators are:

- Current aerospace sector capabilities (in conventional aircraft technology) and market presence.

- Test infrastructure relevant to supporting the technology brick.
- Low-TRL academic capability and ongoing research.
- Mid-TRL research and development funding commitment and projects underway.
- National or non-governmental body policies and roadmaps.
    - Current cross-sector capabilities in the technology brick (cryogenic or gaseous hydrogen). These capabilities vary for the different technology bricks. For example, cryogenic capabilities are relevant to LH2 fuel systems whereas power generation with hydrogen is relevant for LH2 gas turbines.

An average of the comparators without weighting is taken as an indicator of overall position for each country.

While there are pockets of excellence across the globe, there are five countries which have consistent levels of research and investment across all six technology bricks. These are Japan, France, Germany, the United States and the United Kingdom. These countries have differing levels of expertise from active space programmes and/or existing cryogenic facilities, enabling industry and academia to use learning from these areas in LH2 flight development.

Beyond these five countries, there are regions or countries which have areas of excellence in one or more of the technology bricks and/or key comparators. The countries which have been considered in these more detailed investigations are Australia, Brazil, Canada, Czechia, Italy, the Netherlands, New Zealand, Spain, South Korea and Sweden. For example, Australia and New Zealand are working with Japan and South Korea on LH2 shipping and storage, which relate to fuel systems and thermal management. In parallel, these countries are also developing their own national capabilities. Sweden has research expertise in gas turbines and fuel cells, while Spain has multiple research groups and centres which work closely with industrial companies advancing zero-carbon technologies such as Airbus.

Although it is known that there is a large amount of research and industrial development occurring in China, details about the type of work, funding and test infrastructure are not available. Although some publicly available information exists regarding COMAC [4], detailed company information is not as readily accessible as it is for other companies. For these reasons, China is not included in the country comparators in this report. The HCN's Cryogenic Hydrogen Fundamental Research Summary provides more information on the significant number of patents and low-TRL research which is coming out of China and putting the country in good stead to develop zero carbon emission technologies in the future.

There is also uncertainty on the future of aerospace research funding in the United States, as shifting political priorities and budget constraints cast doubt on the long-term commitment and sustained investment in aerospace research and innovation.

Finally, many national funding programmes, such as those for Germany and France, do not publish full details on the projects they fund, making the full picture of the national landscape difficult. The data used in this report is taken from published sources however, political changes may affect policy, mid-TRL research and test infrastructure use.

3 Technology Bricks

The six technology bricks have different weighting of importance for zero-carbon emission flight. For technology demonstrator prototypes and first commercialisation, changes to aerodynamic structures may be minimal. Startup companies and research institutes are investigating retrofitting existing aircraft to run on LH2 or purely electric power. However, if LH2 is going to be used commercially, then fuel systems and thermal management need to be developed to a certifiable level of maturity for aviation. Similarly, any electric or hybrid electric aircraft require suitable electrical systems.

3.1 Cryogenic hydrogen storage and fuel system

The cryogenic hydrogen fuel system on an aircraft comprises the storage of the LH2 fuel and distribution up to its point of use in either a gas turbine or a fuel cell. Within this technology brick, the hydrogen fuel will change from being a low-pressure liquid at -253 degrees Celsius to being either a gas or a high-pressure supercritical fluid. This phase change presents significant technical challenges as well as opportunities for novel and disruptive technologies when compared to conventional aircraft fuel systems. The tanks in which the LH2 is stored need to be lightweight and well-insulated to minimise heat ingress while the required thermodynamic state of the fuel at its point of use will depend upon whether the hydrogen is being used in a fuel cell or a gas turbine.

From the tanks, LH2 will move through a series of valves, pumps, pipework and more until it enters its point of use either as a gas or supercritical fluid. There will also be a series of heat exchangers, linking with the thermal management technology brick, incorporated within this system. These components will be subject to rapid and large changes in temperature, pressure, and flow which are larger and more drastic than those found in systems in current aircraft. In some cases, the temperature change may be in excess of 300K. These changes bring significant technical challenges which need to be overcome through pioneering research and development.

In comparison to relatively passive current kerosene aircraft fuel systems, liquid hydrogen fuel systems are required to be more active given the dynamic behaviour of the fluid as it will undergo phase change from storage to point of use. Therefore, accurate monitoring and control of the fuel is vital. This sensing forms an important part of the fuel system and separate work has been undertaken to understand the relevant sensing landscape. See the HCN's report: **Cryogenic Hydrogen Sensors Technology Landscape**. Heat exchangers will also form a key part of the hydrogen fuel system, but these are considered separately in thermal management (see Section 3.4).

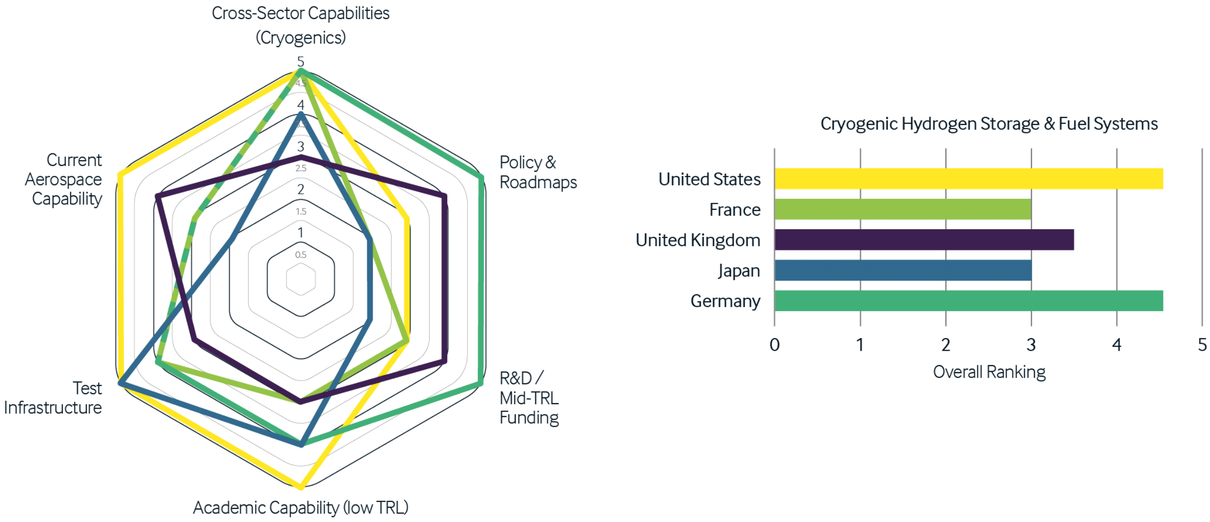


Figure 2: Cryogenic Hydrogen Storage and Fuel System - Country Comparison

Figure 2 shows how each of the five different countries compare in key comparators, with their overall ranking shown on the right.

Germany has the most advanced capabilities with a mixture of strong research and development work, policies and roadmaps and knowledge from the wider cryogenics industry given the presence of Linde [5] and contributions to the European space programme. The German Aerospace Centre's (DLR) Lampholdhausen site has advanced liquid hydrogen infrastructure, projects and development from fundamental research to product development [6]. This site is well-positioned to work with H2FLY [7], who are developing an LH2-powered prototype aircraft which has completed multiple flight tests to demonstrate their cryogenic fuel system. This co-location and cross-TRL development allow for more rapid development of technologies and systems.

The US has strong academic capability and test infrastructure based around NASA and the space sector (such as their LH2 facilities [8]). US expertise in development of items for LH2 delivery to combustion systems is the best in the world and this mid-TRL expertise links closely with academic capability and industrial presence. There are also multiple large aerospace companies with expertise and global presence in fuel systems for conventional aircraft. However, the US does not have as strong a national policy in this technology brick (or, indeed, in support for LH2-powered flight) when compared to the other countries considered in this report.

Expertise in **Japan** stems from much of the space work occurring with JAXA. Japanese universities in collaboration with JAXA have world-leading low-TRL experimental capabilities for understanding LH2 as well as test infrastructure. From an industry and cross-sector perspective, KHI in Japan are working on large-scale LH2 shipping [9], but the company also works with the Japanese space agency (JAXA) on similar projects. However, information on mid-level TRL research focusing on aerospace fuel systems and associated roadmaps has not been identified.

In **France**, AirLiquide is working with GroupADP to support hydrogen infrastructure in airports [10]. There is also industrial expertise through companies such as Absolut Hydrogen and Airbus with its associated ZEROe programme [11] [12]. However, little information is available on the ongoing projects with ONERA, the French aerospace laboratory, and the policy and roadmaps related to hydrogen in aerospace are older than in other countries.

The UK has a large amount of current aerospace capability, policy and systems research but it lacks in hydrogen test infrastructure and low-TRL research as there has not been significant industrial activity around LH2 to date. There is strong existing mid-TRL support and industrial interest around cryogenic hydrogen storage and fuel systems with a number of UK companies active, but the underpinning LH2 research understanding is not present in the UK to the same extent as it is in other countries such as Germany, Japan and the US.

Summary of UK Opportunity

Cryogenic hydrogen fuel systems are vital for any form of LH2-powered aircraft, whether it is powered by fuel cells, turbines or as a hybrid. Significant technological advancements are needed to enable safe, reliable and efficient hydrogen fuel systems to be deployed on future aircraft. Developing low-TRL research and test infrastructure for this brick will also bring significant benefit to other bricks enabling better integration between them and supporting the UK's position across the whole aircraft development. For LH2 aircraft the boundary between the fuel system and the propulsion system is less distinct, therefore this is both a threat and opportunity for the UK which must be considered.

The UK has very strong expertise in kerosene aircraft fuel systems. As such, there is an opportunity if this expertise can be translated to LH2 fuels systems as the value of the cryogenic hydrogen storage and fuel system is likely to make up a larger proportion of aircraft's total value. Existing mid-TRL research provides a strong basis for this development, however additional test infrastructure and further low-TRL research is needed to cement the UK's status in this technology brick. This disruptive change, along with the increased market opportunity, makes this technology brick a vital area for UK development.

3.2 Hydrogen Gas Turbines

Hydrogen combustion has different properties compared to kerosene or hydrocarbon-based combustion. While existing turbines can use hydrogen as a fuel, the difference in combustion properties results in non-optimal efficiencies and potentially shorter lifespans. The fuel input into the turbine system links closely with the cryogenic hydrogen fuel system design both in terms of initial fuel conditions but also in terms of sizing and suitable LH2 storage. It also links to thermal management and electrical systems, where the cryogenic fuel may be able to provide some cooling function in specific environments. The work that is required to develop these turbine systems does not equate to the step change that is required for other technology bricks such as LH2 fuel systems.

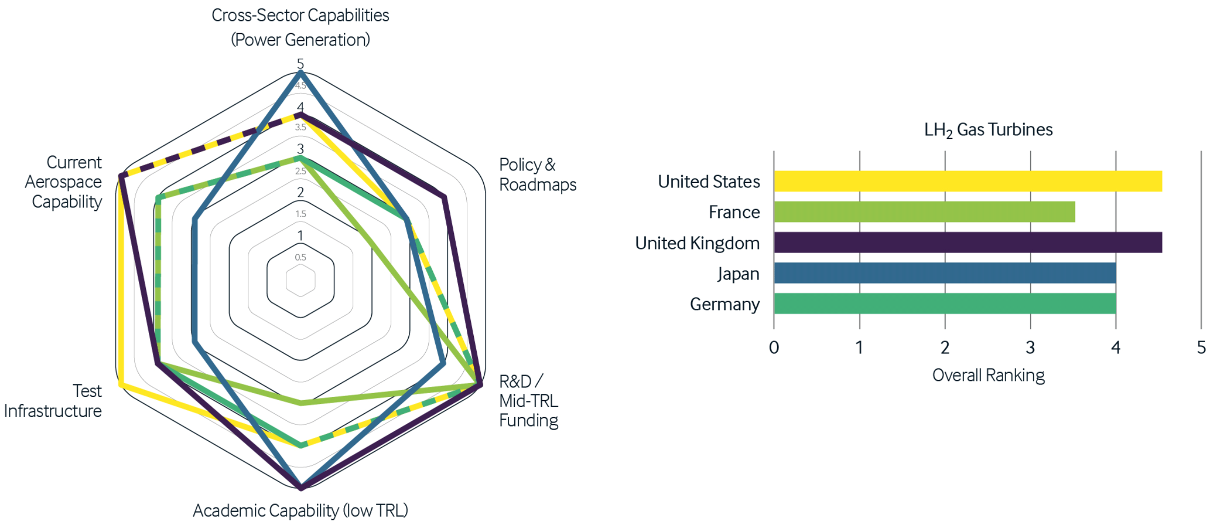


Figure 3: LH2 Gas Turbine - Country Comparison

Figure 3 shows that the UK and the US are the leading countries in this technology brick due to strong industrial presence, strong research heritage and ongoing mid-TRL research in the field. Cross-sector expertise in ground power generation is one of Japan's main strengths, although existing aerospace capability is not as strong as other countries. France has some strong funding support and their 2025 science and technology roadmap [13] provides some information on the key technologies being supported to deliver ultra-efficient and zero carbon platforms.

In **Germany**, Rolls-Royce Deutschland has multiple gas turbine testing sites and strong existing gas turbine capability, along with other aerospace manufacturers. Both low and mid-TRL research is supported through universities and the DLR, such as the Institute for Space Propulsion (which has LH2 facilities) or the Institute for Propulsion Technology. The latter has undertaken tests in hydrogen combustion in aerospace conditions. There are pockets of existing industrial expertise through MTU AeroEngines and Rolls-Royce Deutschland, but other countries such as the US and UK have more integrated design and manufacture capabilities.

In **the US**, the NASA Stennis Space Center is one of the only sites capable of large-scale hydrogen gas turbine testing and America's largest propulsion test site [14], giving the US a strong advantage in test infrastructure. Many aircraft OEM or tier one suppliers such as Rolls-Royce and GE Aerospace, undertake large-scale turbine testing, including pure hydrogen fuel turbine testing, at Stennis [15] [14], even if they are based in other countries. The US also funds mid-TRL research in gas turbines through the Advanced Research Projects Agency – Energy (ARPA-E) [16], and there are existing research groups who investigate fundamental hydrogen heat transfer and combustion phenomena.

Japan is investigating using hydrogen in gas turbines for power generation as well as combined heat and power systems to a larger scale than the other countries considered in this document. For example, KHI have developed hydrogen-specific (or hydrogen-blend) technologies for gas turbines [9] and the company is now are working with JAXA on building facilities for developing hydrogen-powered aircraft [17].

France also has a strong industrial background in hydrogen gas turbines, particularly for aerospace. For example, Safran are leading a consortium of companies on BeautHyFuel, a project with the French civil aviation authority (DCAG), which links ground tests of a LH2 fuelling system to a gas turbine [18]. However, published policies and roadmaps linked with this technology brick are out-of-date. From a cross-sector perspective, Siemens Energy has completed testing in France using pure hydrogen in a gas turbine.

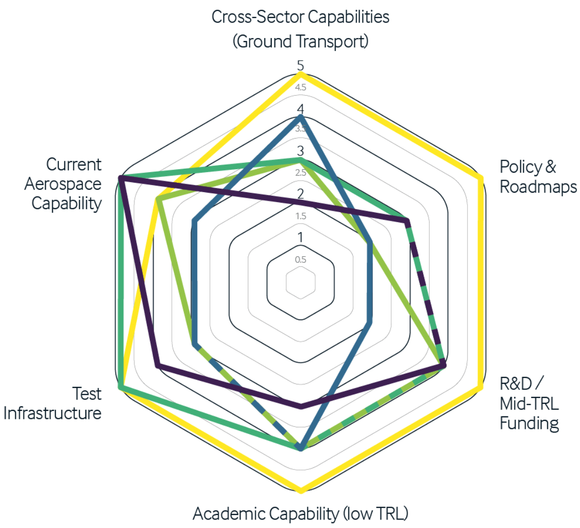
The UK has a strong aerospace gas turbine presence through Rolls-Royce and associated companies. Turbine and combustion development is also supported through research, with companies and universities being included in some of the larger Clean Aviation hydrogen combustion projects as well as ATI projects. Support to aeroengine gas turbines is also strong through roadmaps and policy initiatives. Research into gas turbine technologies at universities and institutes is strong, but there is a lack of hydrogen testing and available infrastructure.

Summary of UK Opportunity

The changes needed to enable a reliable and efficient hydrogen gas turbine are more incremental when compared to those required for other technology bricks, such as cryogenic hydrogen storage and fuel systems and thermal management. The UK has a long industrial heritage in this area as well as strong combustion research capabilities. Expertise in hydrogen combustion and support through large-scale infrastructure is more focused in the US and Japan, with specific areas of support and development found in continental Europe. The existing UK support for this technology brick is in line with the required trajectory for development given the longer timeframes available, when compared to other technology bricks, and the incremental changes needed in technology.

3.3 Hydrogen Fuel Cells

Hydrogen fuel cells can be used to produce electricity to power electric motors on LH2-powered flight. Prototype aircraft, such as those developed by Pipistrel and Project APUS, have already been developed using these fuel cells. Fuel cell systems comprise of multiple elements including heat management and system integration. For this technology brick evaluation, only the fuel cell stacks have been included. Multiple fuel cell technologies exist, with the most promising solution for aviation being proton exchange membrane (PEM) technology due to its higher power density and rapid start times. It is acknowledged that heat rejection is a key challenge for aerospace fuel cell systems, so there is a desire to increase the heat rejection temperature. This can either be done through new stack technologies such as high-temperature proton exchange membranes (HT-PEM) or through novel system design. As such, hydrogen fuel cells and their integration links closely with the thermal management technology brick.



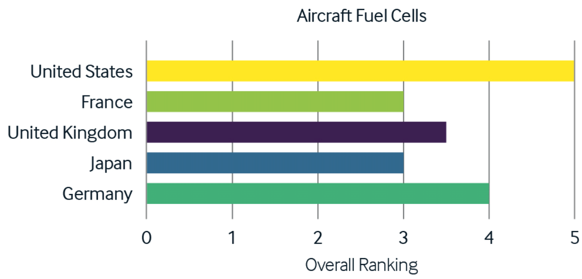


Figure 4: Aircraft Fuel Cell - Country Comparison

Figure 4 shows that the UK funding into aerospace fuel cells is strong compared to its main competitors.

In **Germany**, fuel cells for aerospace applications are being developed with the support of national and EU funding bodies. The H2FLY project uses hydrogen fuel cells and its first successful flight with fuel cells was in 2016 followed by their first LH2-powered flight in 2023. EKPO Fuel Cell Technologies GmbH is a joint venture between ElringKlingerAB and OPmobility who develop hydrogen fuel cell systems for cross-sector applications. Aerostack GmbH is a partnership between ElringKlingerAB and Airbus which is developing fuel cell stacks for aerospace applications [19]. The DLR has multiple sites (such as the Lampholdhausen and Balis facilities) with large-scale test capabilities to support integration across the TRLs, enabling research and development at these different levels to occur concurrently. Europe, particularly Germany and France, also has benefits of research and industry working closely together with both Clean Aviation and the Clean Hydrogen Joint Undertakings supporting fuel cell development.

The **United States** has a dedicated Hydrogen and Fuel Cells Technology Office which has published a detailed multi-year plan [20] with specific targets on multiple areas of hydrogen production, infrastructure and use. This gives strong cross-sector and infrastructure support to the wider fuel cell industry. The US also has strong cross-sector use of fuel cells in off-road ground transport, as can be seen in companies such as Plug Power [21].

The **Japanese** government announced plans to spend ~$26.3Bn to develop a fuel cell based aircraft [22], although specifics on this project have not been disseminated. Japan has strong cross-sector expertise and support through the use of fuel cells for ground transport with a focus on cars and trucks. There are multiple fuel cell manufacturers based in Japan, although most do focus on non-aerospace applications. One exception is IHI Aerospace who are developing a fuel cell electric propulsion system [23].

France: H3 Dynamics, which has offices in France, the US and Singapore, develops fuel cell systems for aerospace and is the planned supplier of fuel cells for Stralis [24]. H3 is also supporting other zero-carbon flight initiatives, including the Airbus ZEROe project, Joby and the TUDelft student-led zero-carbon flight project.

In **the UK**, there is industrial expertise and support for both fuel cell development and its use in aerospace. Intelligent Energy (IE) is primarily focused on LT-PEM with some moderately higher studies underway, including those for eVTOL applications [25]. ZeroAvia's Kemble facility is leading on HT-PEM technologies. They are using fuel cells for their prototype aircraft and have in-house fuel cell development capabilities following its acquisition of HyPoint in 2022 [26]. These companies and others have received funding from both the ATI Programme and Clean Aviation. This includes the H2GEAR project led by GKN Aerospace, to develop the technologies and move towards certification for commercial flight.

Aside from the countries listed in Figure 4, there are several other countries who are strong in fuel cell development. **South Korea** is targeting wide-scale use of fuel cells through a large level of financial investment and strong national policy, focusing on ground transport rather than aerospace. **Sweden** has a strong industrial presence in aerospace fuel cells, such as through PowerCell [27], who work with zero-emissions aircraft companies. **Switzerland** also has multiple companies which support aircraft fuel cells as well as lower TRL work.

Summary of UK Opportunity

The UK has a strong aerospace fuel cell presence in a technology space which is gaining attention internationally. The main aerospace competitors are found in Germany and Sweden. The wider market for fuel cells across the transport sector and the amount of funding and policy support for fuel cells is considerable, particularly in the United States and in Asia (such as in South Korea). The ATI Market Model estimates that the UK could secure almost 25% of the global market share of aerospace fuel cells by 2050, and the existing support and interventions can enable the UK to meet this goal.

3.4 Thermal Management

A key part of thermal management for LH2-powered aircraft is heat exchanger technologies and their integration to meet the novel thermal challenges associated with cryogenic fuels. The integration of heat exchangers is related to most other technology bricks, as well as the overall thermal balance of plant of the aircraft. Significant opportunities for the structural integration of heat exchangers have been noted by airframers. Similar to the cryogenic hydrogen fuel systems technology brick, disruptive technology is needed to develop lightweight and reliable heat exchangers which can manage effectively both cryogenics and high temperatures. This disruptive technology requires fundamental research as well as a step change in technology capability to enable efficient and suitable thermal management and balance of plant across an aircraft.

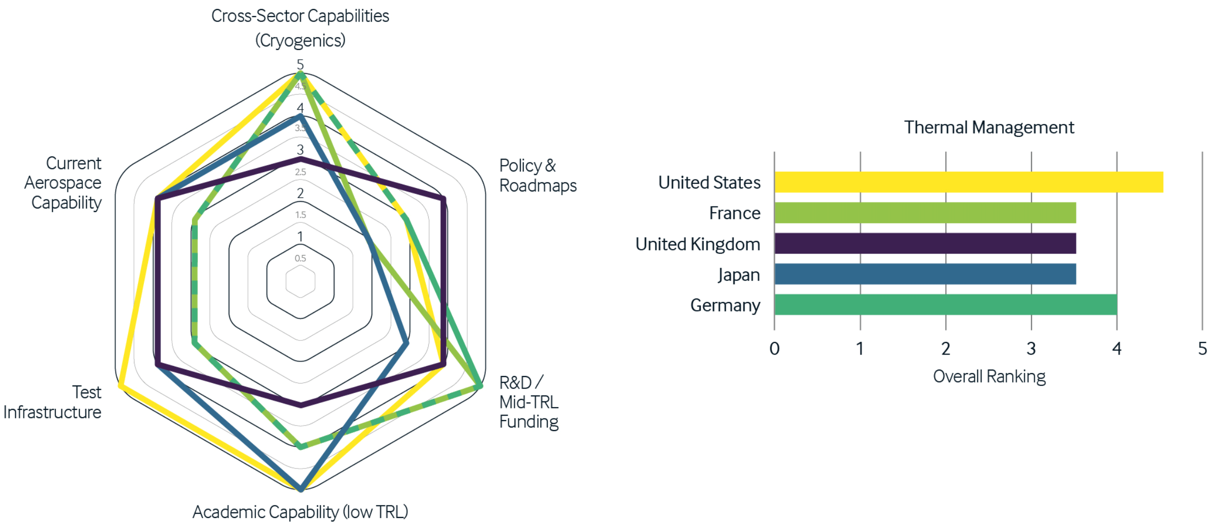


Figure 5: Zero-Carbon Thermal Management - Country Comparison

Figure 5 shows that on balance, the US and Germany have the broadest capabilities relating to thermal management, followed closely by the UK, France and Japan. The UK has strength in current aerospace capabilities, policy and mid-TRL research and development. Other countries have strong industrial cross-sector capability in cryogenics, including LH2 for example, Linde and Air Liquide in continental Europe. The US and Japan develop and transport LH2 for multiple uses and lead the world in fundamental research in LH2 heat transfer.

In **Germany**, Linde has expertise in LH2 thermal management, although the heat exchangers used in creating and transporting LH2 will be very different to those on aircraft. The test infrastructure and mid-TRL research abilities link closely with those for the cryogenic fuel systems technology brick, although specifics on heat exchanger development are less forthcoming and less prominent in project descriptions.

In **the US**, NASA has been a world-leading expert in thermal management relating to hydrogen systems since the 1960s due to its space programmes. NASA, with its collaboration with research institutes, continues to be at the forefront of thermal management technological development in heat exchangers, thermal system design and more. There are also a variety of smaller companies linked with novel heat exchanger design to support the extreme conditions seen in LH2-powered aircraft. However, little information is found in their policy and roadmaps related specifically to heat exchangers or wider aircraft thermal management.

Japan has some industrial aerospace capability in thermal management including Sumitomo developing heat exchangers and heat management systems for aerospace [28]. There are some links with aerospace manufacturing and OEMs however, the main strengths come from research and development linked with JAXA. JAXA and associated Japanese universities are undertaking experimental LH2 heat transfer work which will link directly with this technology brick. Similar capabilities are found only in the US.

Like Germany, **France** has strong cross-sector expertise from the cryogenic sector. However, details on relevant aerospace projects that are funded by ONERA, as well as its future strategy and roadmap, are not available; the ONERA roadmap has not been updated in the past several years, and not all information on ONERA projects is made public. However, multiple Clean Aviation projects linked with other technology bricks show a link to thermal management.

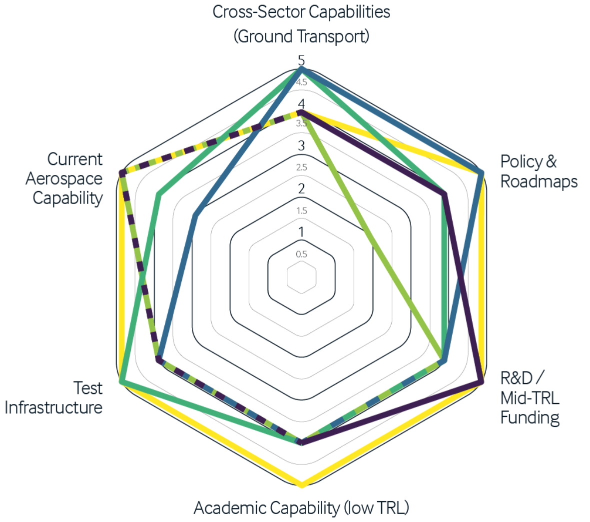
The UK has many organisations and companies who are working on hydrogen fuel systems and thermal management solutions. There are also specialist companies supporting electric aircraft development and incorporating thermal management. For example, QDot, based in Oxfordshire, is investigating thermal management for zero-carbon emission UAVs integrating fuel cells and batteries with heat exchangers and thermal management [29]. Multiple large organisations such as Parker Meggitt, GKN Aerospace, Eaton and others are involved in large projects supporting thermal management in aircraft, specifically heat exchangers. Conversely, the UK lost significant thermal management expertise when Reaction Engines went into administration in 2024. From a research perspective, the UK has strong low-TRL research in heat transfer and technology for heat exchangers, but unlike Germany and France, the UK does not have current expertise or facilities in LH2 heat transfer.

Summary of UK Opportunity

Liquid hydrogen testing facilities for thermal management and fluid flow are not available in the UK as of March 2025, but the provision of these would allow expertise and development to grow further. The current key areas for experimental research are the US and Japan, while Germany and France also have strong cross-sector capabilities and mid-TRL research abilities. The UK has an existing industrial landscape and healthy ongoing funding for mid-TRL projects. Continued funding for thermal management, such as through the ATI Programme and government initiatives, will keep the UK in a strong competitive position.

3.5 Electrical Systems

This technology brick focuses on electrical systems that are required to enable electric or hybrid electric aircraft. In order to achieve both the energy densities and power outputs required, more efficient motors and more energy dense batteries need to be developed. Improved cooling systems are also required, linked with the thermal management technology brick. Considerable work is already ongoing to advance these technologies.



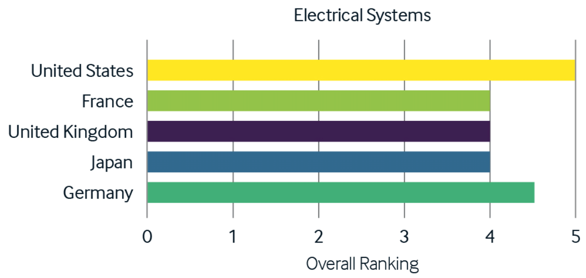


Figure 6: Zero-Carbon Electrical Systems Country Comparison

Figure 6 shows that the five main countries considered in this document are all relatively advanced in supporting the electrical systems technology brick. There is strong overlap between existing aerospace industrial capabilities and the requirements for zero-carbon emission flight. There are also parallels between the requirements for ground transport and aerospace. Figure 6 shows that this technology brick is relatively advanced when compared with others.

The DLR in **Germany** has multiple sites with suitable test infrastructure to support the development of electrical systems in aerospace such as the battery laboratory and the research power plant. Most of the large existing industrial companies have some presence in Germany but not to the same level as in France, the UK and the US. However, both H2FLY (through Joby Aviation) and Diamond Aircraft (Previously Volocopter) are based primarily in Germany [30]. H2FLY requires electrical systems to support the fuel cells currently used on its prototype.

The **United States** has the largest electrical systems market for existing capabilities, with companies such as Collins and Honeywell having large design and manufacturing bases across the country. Multiple eVTOL aircraft companies are operating in the US, including Joby and Archer Aviation [31] [32]. Mid-TRL development is also well-supported through the ARPA-E programme as well as NASA, who are supporting work on high density batteries for aircraft applications and are working with companies such as MagniX.

Japan has a strong cross-sector industry in electrification of ground vehicles as well as clear policies and roadmaps for the development of more advanced electrical systems. Japanese expertise in electric machine design especially at larger scales see many Japanese companies developing solutions for automotive applications, as well as heavy machinery, rail and space. Superconducting technology is also being researched and developed by several Japanese industries, including JASTEC and Furukuma Electric [33]. This technology is anticipated to contribute to advancements in future aerospace power electronics. The Japanese government announced further support for electric battery production, which will be relevant to the first generation of electric aircraft. Toshiba are also supporting the Airbus ZEROe programme with the development of superconductors and electric propulsion [33].

France has a strong existing electrical systems industry focused around Safran and Thales, but also with company presence from other large aerospace suppliers. Airbus in France is pioneering the ZEROe programme which is being supported by their UpNext centres found in France, Spain, and Germany. Companies in France are linked to multiple Clean Aviation projects with information in the ONERA annual reports indicating that aerospace electrification projects are ongoing.

United Kingdom: Through companies such as Eaton and Collins, the UK has a strong existing market and industry for electrical systems. GE's Electrical Power Integration Centre (EPIC) in Cheltenham is a state-of-the-art facility that will develop avionic control technologies for military and civil aerospace applications. Vertical Aerospace [34] are developing electric eVTOL aircraft and opened their Vertical Energy Centre in 2023 to advance battery capability. Many UK companies working on other technology bricks, such as GKN Aerospace and ZeroAvia, are also developing electrical systems. The ATI Programme supports the development of this technology brick by funding multiple projects which link electric motors and hydrogen propulsion, such as the H2GEAR project. The research landscape is also well-supported through national initiatives alongside EU projects. The 'Driving the Electric Revolution' industrial centres are a good example of mid-TRL support as well as collaboration between academia and industry [35].

Summary of UK Opportunity

Fully electric small aircraft prototypes, such as eVTOLs, are in an advanced stage of development with flight testing taking place and commercialisation on the horizon. Existing technologies and companies working in electrics for conventional aircraft are well-placed to develop this technology brick further. The primary step changes needed for this technology brick focus on improving power outputs and increasing energy densities. The scope of these challenges is defined, and while they are considerable, these challenges do not require the same disruptive development as other technology bricks such as cryogenic fuel systems and thermal management.

3.6 Aerodynamic Structures

Liquid hydrogen cannot be stored in aircraft wings in the same way as conventional aviation fuels or sustainable aviation fuels. Instead, it needs to be stored in tanks, probably in the fuselage due to the increased volume per unit energy relative to kerosene. The need to minimise the surface-area-to-volume-ratio of the storage vessel makes spherical tanks the optimum shape, although the most likely shape is cylindrical for volume efficiency. As fuel will no longer be stored in the wings, LH2-powered aircraft will have 'dry' wings, meaning that the structural layout needs to be reoptimised to account for the significant change in load cases. Many wing technologies under development for ultra-efficient aircraft, such as advanced lightweight composites, high aspect ratio wings and folding wing tips, will also provide efficiency benefits to zero-carbon clean sheet designs.

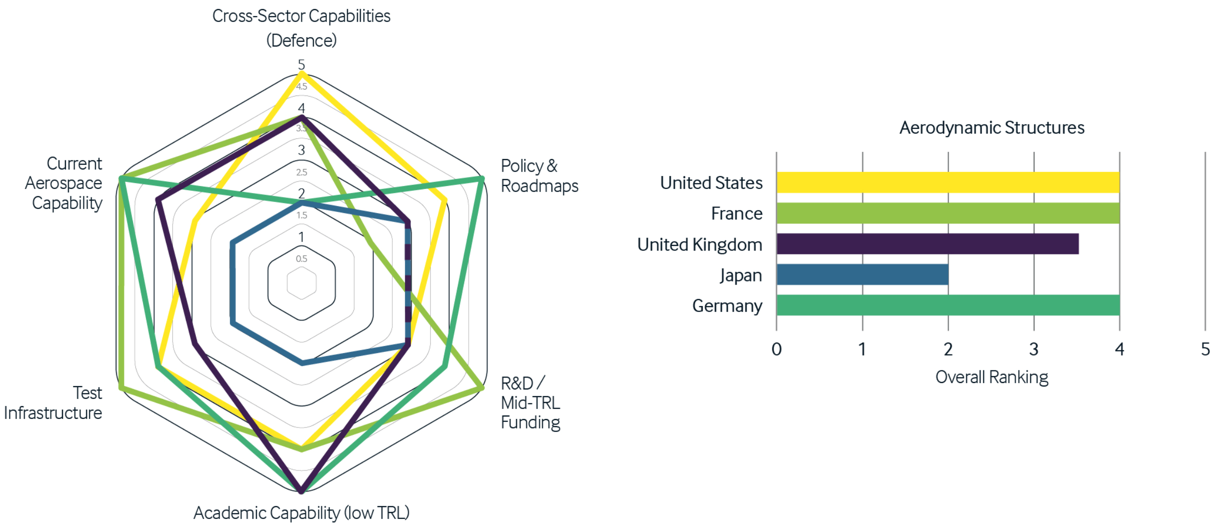


Figure 7: Zero-Carbon Aerodynamic Structures Country Comparison

Figure 7 shows that while the US has the highest overall ranking, the UK, Germany and France have similar overall capabilities. While Japan has some strong policies and research development opportunities, our analysis indicates it does not have the same industrial presence or overall capabilities.

The DLR in **Germany** supports aerodynamics research across multiple TRLs. Germany is also one of the main recipients of funding for projects focusing on zero-carbon emission aerodynamic structures from Clean Aviation. DLR is Europe's largest and most capable aerospace research organisation and supports many zero-carbon emission aircraft aerodynamic structures projects.

The US has a significant airframe and aerodynamics industry through Boeing. Although Boeing has not signalled the same intent to develop zero-carbon emission aircraft as Airbus, its expertise and capability is considerable, mainly due to its aerodynamic and structural research projects in civil, defence and space industries. Alongside industrial capabilities, the US has the largest and most comprehensive suite of wind tunnels and other test infrastructure required to support the structural changes associated with LH2-powered aircraft.

While the **Japanese** government has announced plans for a new fuel-cell powered aircraft [22], the existing aerostructures industry in Japan is small. Beyond the government announcement, the aerodynamics industry is supported by JAXA through low and mid-TRL research and development.

Airbus in **France** has its ZEROe programme to develop zero-carbon emission aircraft as well as multiple aerodynamics research and development centres in France, Germany, Spain and the UK [36] [37]. Like the DLR in Germany, ONERA supports research across TRLs. An example of this support is the AWATAR project, a European project focusing on wings for hydrogen-powered aircraft. France also has strong defence capabilities through structures and systems manufacturers such as Dassault, Thales and Safran.

In **the UK**, Airbus has the Aerospace Integrated Research and Test Centre, where wing design and testing occurs for conventional aircraft wings [38]. Further research and development, particularly at lower TRLs, is supported by universities and research institutes focusing on manufacturing and aircraft integration. The UK has world-class expertise in wing design and technologies spanning academia, design and manufacture. This knowledge base puts the UK in good stead to readily adapt and support dry wing architecture in the future.

Summary of UK Opportunity

The UK's existing market share, research and funding for wing design and manufacture means it is very well placed to maintain and secure further content in aerodynamic structures of the future. The next generation of aircraft will be ultra-efficient and will include incremental changes in materials, manufacturing, weight-savings and system integration. No additional action is required now, and the UK should maintain research across all TRLs to ensure it preserves its leadership for the next generation of ultra-efficient platforms and future generations of zero-carbon emission dry wing structures.

The ATI Market Model estimates that the UK could have 20% of the global market share of aerodynamic structures for the first generation of large commercial zero-carbon emission platforms. However, there is competition from other nations which continue to fund research in this space and from uncertainty in the future architecture and configuration of zero-carbon emission aircraft This could mean that structural design and manufacture becomes wholly, or partially integrated with other components such as engine, fuel systems, or fuselage.

4 Analysis

Of the six technology bricks considered, the **cryogenic hydrogen storage and fuel system** requires the most disruptive technology development and requires most intervention to reach TRL 6. Thermal management also requires some step changes in technology, particularly relating to on-aircraft heat exchangers. At the other end of the spectrum, the UK is well placed to maintain its leadership in aerodynamic structures as long as research is maintained across all TRLs. The critical area for development is the cryogenic hydrogen storage and fuel system.

The extreme operating conditions of cryogenic hydrogen storage and fuel systems is the main reason for the requirement of new components. The fuel system and storage technologies will be required to manage LH2 through phase-changes and into a variety of end states at the point of use. Robust understanding of LH2 and properties of supercritical hydrogen thermofluid together with an understanding of hydrogen interaction with materials are vital to the safe development and optimisation of these systems. The gaps in knowledge in these basic research areas need to be addressed to provide the building blocks for wider technology brick development.

Section **Error! Reference source not found.** shows that the UK has many core strengths in e xisting fuel system development and mid-TRL research relating to LH2 fuel systems and storage. By focusing on these disruptive technologies, other areas of the LH2 aircraft such as thermal management, fuel cells and gas turbines will also benefit from the advancements made.

According to the ATI Market Model, the United Kingdom is projected to capture a progressively larger share of the hydrogen aerospace market from 2050 onwards. Support to key technology bricks such as the cryogenic hydrogen storage and fuel system and thermal management will enable this market share to be consolidated. In the short term, zero-carbon emission technologies will likely be utilised on smaller aircraft where the market value is lower. In time, the technologies needed for these aircraft will continue to be developed and certified for larger commercial aircraft securing more significant economic and environmental benefits.

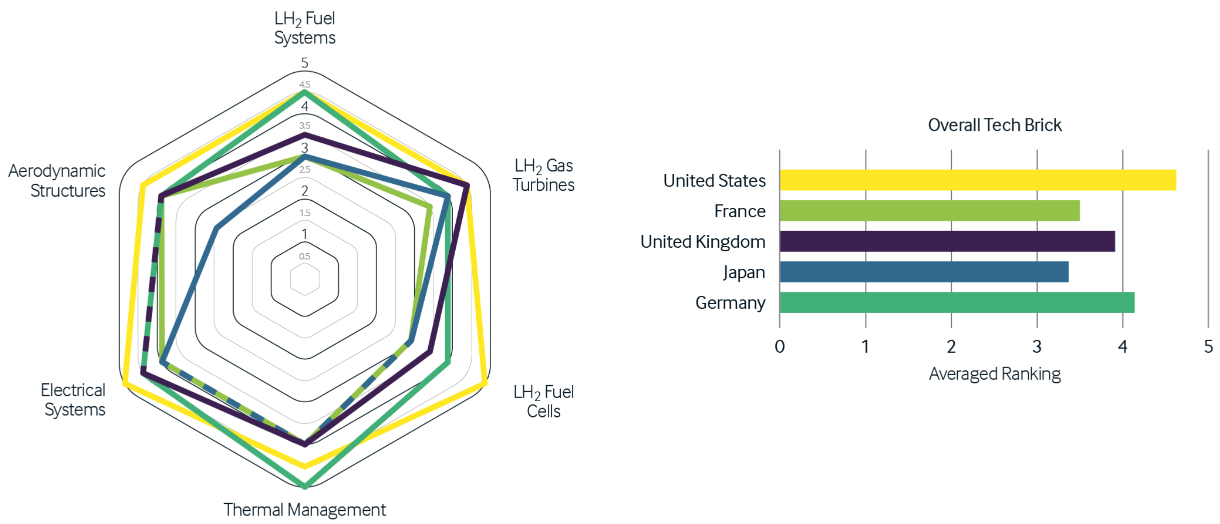


Figure 8: Overall Technology Brick Country Comparison

Figure 8 shows the overall comparisons of the five countries across the six technology bricks. The US's strong position in each of the technology bricks is underpinned by robust industrial capabilities and test infrastructure. While political and industrial roadmaps do not focus on zero-carbon emission aircraft to the same extent as those in Europe and Asia, the US has the capability to pivot to large scale zero-carbon emission aircraft if market forces change in the future.

Germany and France have very similar funding and support structures through the DLR and ONERA respectively. These institutes enable multi-level research support from fundamental research through to industrialisation. This cohesive approach is mutually beneficial for research institutions and industry, enabling more rapid development especially in disruptive technologies.

Japan's existing aerospace sector is almost entirely focused around JAXA and its space capabilities. Japan does not have the same level of presence from large industrial companies as is found in North America and Europe but there are areas in which their industrial heritage and cross-sector knowledge add value. The fundamental research abilities linked with JAXA and related research institutes, coupled with strong policy and roadmap support, indicate that Japan could have a strong presence in the LH2 aerospace sector in the future.

Beyond the five countries considered for all technology bricks, there are other countries with areas of excellence. For example, Sweden has a strong presence in the aerospace fuel cell market, and South Korea has a strong fuel cell cross-sector potential. In Australia, there is considerable interest in LH2 storage tanks and thermal management for shipping. COMAC has grown quickly in China since its founding in 2008, but information about the company and its roadmaps remains limited. A large number of patents and low-TRL research publications from China indicate significant research across TRLs in preparation for future generations of zero emission aircraft and systems (See the HCN's Cryogenic Hydrogen Fundamental Research Summary).

Zero-carbon emission aircraft are expected to drive new market opportunities which will differ in payloads, range and segments when compared to today's conventional aircraft. By supporting the key technology bricks discussed in this report, the UK aerospace sector has an opportunity to grow its world-leading position and secure market share in future generations of sustainable aircraft.

5 Conclusions

Of the six technology bricks considered, the two that require the most significant development are **cryogenic hydrogen storage and fuel systems** and **thermal management**. The global landscape for both is at an early stage of development with no single area of dominance. Unlike some of the other technology bricks, such as LH2 gas turbines or aerodynamic structures, the requirement to increase the growth rate in these two areas is time critical to secure IP in the UK, build fundamental cryogenic expertise and demonstrate confidence in the viability of the overall system.

Increased support for LH2 research is needed to underpin the technological developments required to make cryogenic hydrogen storage and fuel systems a reality in the UK. Cryogenic fuel systems are integral to any hydrogen-powered aircraft, and more disruptive technology development is required for this technology brick than the others which have been considered. The thermal management technology brick also requires disruptive technology development underpinned by LH2 research as it links closely with the cryogenic hydrogen storage and fuel system. Developing both cryogenic fuel systems and thermal management gives strong support to the propulsion and electrical system-based technology bricks.

The capabilities of five countries across six technology bricks have been compared. The UK, the US, Japan, France and Germany all have outstanding research, industry and facilities which can support the development of these technology bricks, but each has different strengths. Japan and the US have relevant experience and learning from their space programmes JAXA and NASA. In Europe, Germany and France have a strong mixture of cross-sector expertise, existing industrial experience and test infrastructure to support multiple technology bricks. Nationally funded mid-TRL projects are also ongoing in both Germany and France.

The UK has an opportunity to support the development of cryogenic hydrogen storage and fuel systems through continued mid-TRL research and support through its strong industrial presence. However, the mid-TRL research requires fundamental knowledge of LH2 thermofluids and materials properties. Test infrastructure and low TRL support will increase the overall efficiency of the technology brick development by removing barriers and uncertainties. These mechanisms will spill over to support other technology bricks and the wider zero-carbon emission aerospace industry.

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