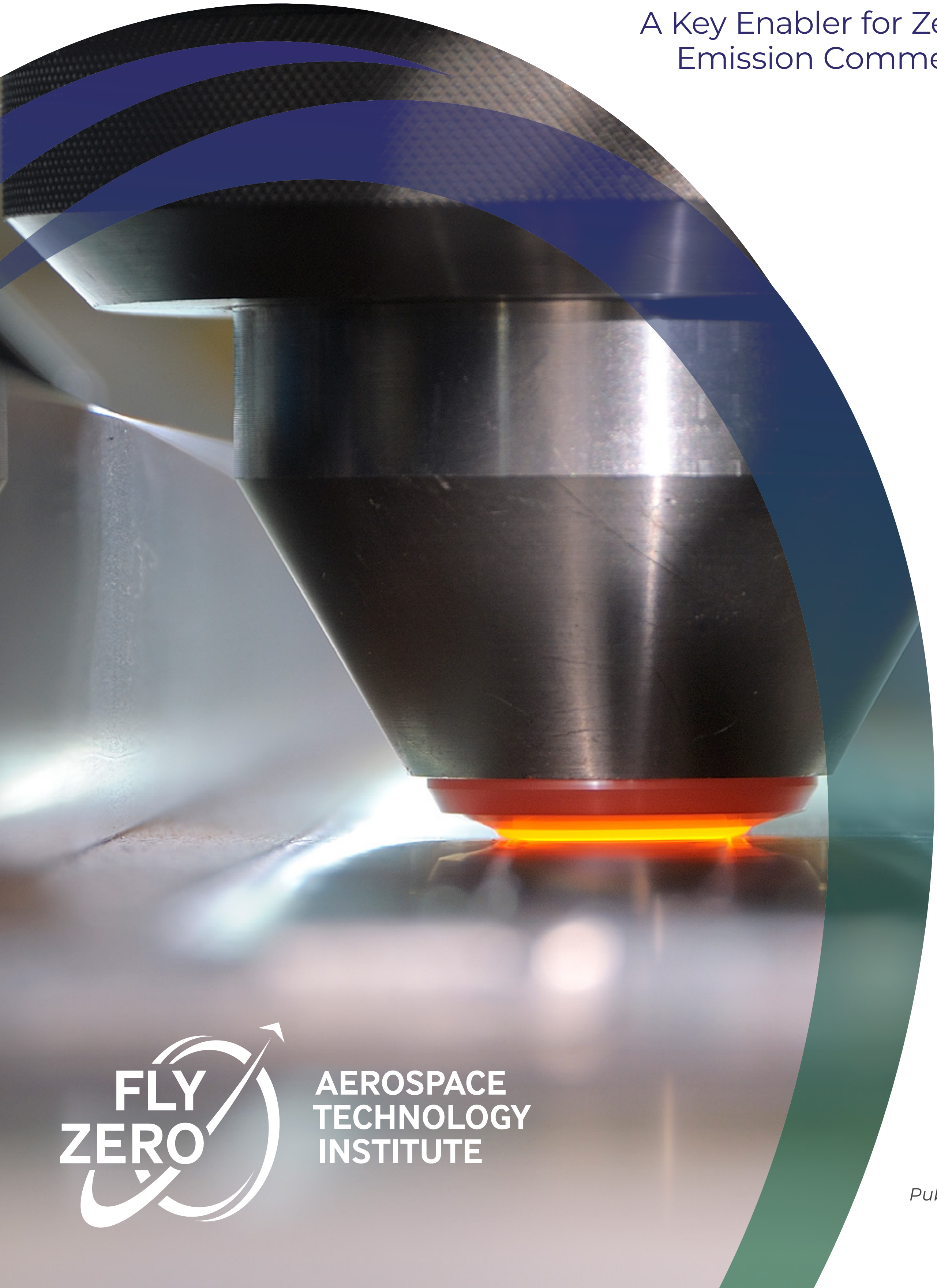
ADVANCED MANUFACTURING

A Key Enabler for Zero-Carbon Emission Commercial Flight



FLY ZERO

AEROSPACE TECHNOLOGY INSTITUTE

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ABOUT FLYZERO

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

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

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

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ACKNOWLEDGEMENTS

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Front cover image – courtesy of TWI Ltd

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EXECUTIVE SUMMARY

FlyZero has concluded that liquid hydrogen is the most viable zero-carbon emission fuel in terms of its potential to scale to larger aircraft. Manufacturing technologies will be key enablers to realising these future hydrogen aircraft. This report has highlighted manufacturing challenges and opportunities across all six of the FlyZero hydrogen aerospace technology bricks (below) but with particular challenges around tanks, light weighting of aerostructures and combustor manufacture.

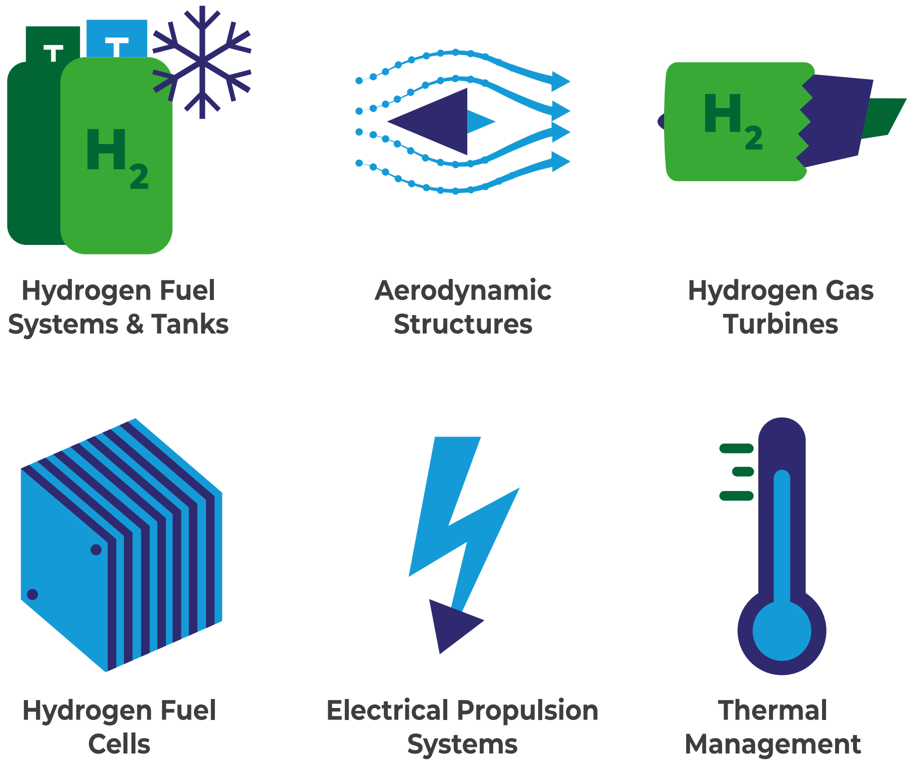


Figure 1 – FlyZero hydrogen aerospace technology bricks

Areas of manufacturing technology development identified in this paper are required to support the FlyZero technology bricks are summarised below. Many of these manufacturing developments are also highlighted in the ATI Technology Strategy, ATI roadmaps and Insight papers for manufacturing processes [1] [2] [3] [4] [5] and the forthcoming HVMC Aerospace Manufacturing and Materials roadmaps.

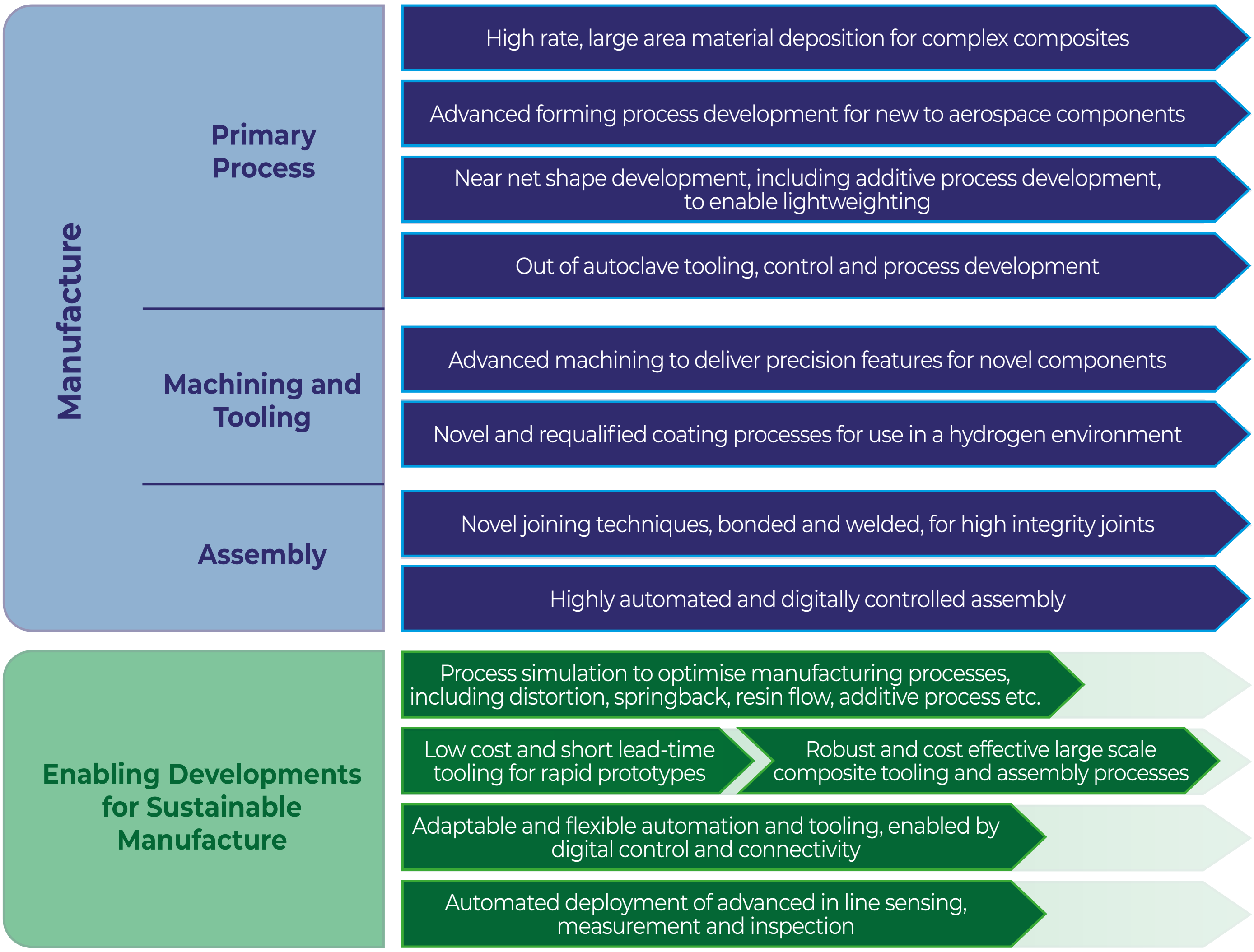


Figure 2 – Areas of manufacturing technology development identified in this paper are required to support the FlyZero technology bricks

The report also explores the actions needed to anchor the long-term production jobs associated with hydrogen aircraft in the UK, focusing particularly on production organisations and manufacturing systems and tooling providers. The report makes the following recommendations:

Recommendation 1. Accelerate research and development into rate enabling manufacturing technologies critical to realising hydrogen-powered flight.

- Accelerate research and development into rate enabling manufacturing technologies, including those identified in this report. This can be delivered through collaboration between industry, research centres and academia with support from by the High Value Manufacturing Catapult, EPSRC, Innovate UK and the Aerospace Technology Institute.
- Launch cross-sector funding targeted at product and manufacturing developments for areas of overlap that are not yet addressed by cross-sector funding initiatives in the UK. These areas are fuel cells (automotive and energy sectors) and tanks and fuel systems (space sector).
- Provide funding and support to help build pilot lines (lines that incorporate advanced manufacturing technologies and so enable its development). This development can be supported by the UK Catapult network, research organisations and academia, as well as industry.

Recommendation 2. Build manufacturing supply chain capability relevant to hydrogen in the UK tiered aerospace supply chain to anchor production in the UK.

- Accelerate investment and adoption of advanced manufacturing equipment by UK aerospace tiered supply chain. Cluster bodies, research organisations, knowledge transfer organisations and funding bodies need to collaborate to deliver programmes that cover awareness campaigns; upskilling; access to specialist expertise; access to facilities where companies can 'learn by doing' ahead of making investment decisions; support to build the business case; and support to manage change associated with the introduction of the new technology.
- Fund economic development activity in the supply chain, enabling companies to make the capital investment required to support production of hydrogen aircraft components and systems, and anchor high value jobs, and continually innovate to retain UK competitiveness.
- Help new companies enter the aerospace sector by providing support to attain aerospace accreditations through programmes used in other sectors such as e.g., Fit 4 Nuclear.

Recommendation 3. Support the foundation and scale-up of UK enterprises that develop manufacturing systems and tooling, creating an indigenous UK base for manufacturing equipment.

- Identify a pipeline of opportunities for manufacturing systems and tooling development. The ATI could support this by connecting end user requirements and solution providers. This could be done in collaboration with other sectors with common requirements, such as defence and power generation.
- Deliver programmes, like those launched by The Advanced Manufacturing and Productivity Institute, designed to support the foundation and scale-up of UK manufacturing systems and tooling providers. Cluster bodies, research organisations, knowledge transfer organisations and funding bodies need to collaborate to deliver programmes that provide access to expertise and facilities for prototyping; access to components on which they can demonstrate their technology; introduction to potential customers; commercial mentoring to help create a business plan and to win private investment; and support to scale-up their business.

Recommendation 4. Reduce emissions embodied during manufacturing at the same time as moving to aircraft with zero-carbon tailpipe emissions.

- Design carbon neutral end-to-end processes and supply chains in parallel to future aircraft, thereby ensuring emissions from the whole value chain are addressed (scope 3 emissions) in parallel with emissions from industry's own factories (scope 1 and 2 emissions).
- Develop standards for accounting for emissions through supply chains and digital tools to help monitor and reduce them. Delivery will require collaboration between industry, research organisations and academia.

01. INTRODUCTION

FlyZero has concluded that liquid hydrogen is the most viable zero-carbon emission fuel in terms of its potential to scale to larger aircraft. Manufacturing technologies will be key enablers to realising these future hydrogen aircraft. This report highlights areas of challenge and opportunity for manufacturing with the aim of focusing future developments by the UK manufacturing research community.

Hydrogen aircraft will have two major architectures. Hydrogen fuel cell electric propulsion systems have potential to power sub-regional and regional aircraft. Hydrogen gas turbines have potential to power aircraft up to midsize. FlyZero's midsize concept has an operational range of 5,250 nautical miles and carries 279 passengers [51].

FlyZero has designed three concept aircraft - a hydrogen fuel cell electric regional aircraft, a hydrogen gas turbine powered narrowbody aircraft and a hydrogen gas turbine powered midsize aircraft. Through both this exercise and through broader consultation with the UK aerospace community, FlyZero has identified the major changes in hydrogen aircraft compared to conventional kerosene aircraft that will have implications for manufacturing technology. These major changes are described in Section 2 along with wider trends and drivers for manufacturing technology. Possible production rates are described in Section 3, from the future market forecasts generated by FlyZero.

The FlyZero project has identified six hydrogen aerospace technology bricks (see Figure 1). The manufacturing challenges and opportunities associated with each of these bricks have been investigated both by the FlyZero team and, in addition, through two in-depth studies specifically on hydrogen fuel tanks commissioned from two of the centres of the High Value Manufacturing (HVM) Catapult – NCC and AMRC.

image © Rolls Royce PLC

The manufacturing challenges and opportunities related to each brick are described in **Sections 4 to 9**, with a summary at the end of each section. For this report, fuel tanks and fuel systems have been split into separate sections and fuel cells and electrical propulsion systems are addressed in one section. Further information and developments needed to take the technology brick to technology readiness level (TRL) 6 can be founded in their associated technology roadmaps [6]. In addition, papers on Lifecycle Management [7], Advanced Materials [8] and Compressed Design & Validation [9] all contain content relevant to the manufacturing community.

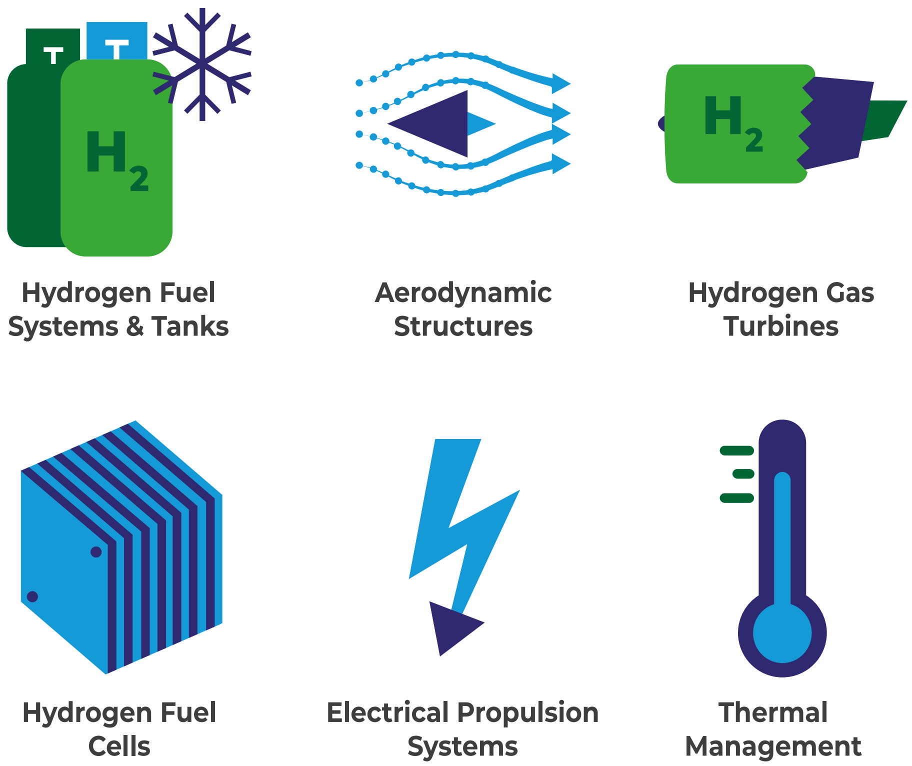


Figure 3 – Six hydrogen aerospace technology bricks identified by FlyZero project

The action needed to ensure that the UK builds a strong aerospace manufacturing supply chain through this technological revolution is described in **Section 10**. Finally, high level recommendations for the UK manufacturing community are presented in **Section 11**.

02. HIGH LEVEL DRIVERS FOR MANUFACTURING TECHNOLOGY

Hydrogen aircraft will have different architectures from conventional kerosene aircraft, driving the need for new manufacturing processes. To achieve the power density required for large or long-range aircraft (regional or above), hydrogen will have to be stored as a liquid below -253°C. The incorporation of cryogenic systems to store and distribute the hydrogen results in some of the largest architectural changes compared to conventional kerosene aircraft.

The propulsion systems of hydrogen aircraft will have a different architecture to that of conventional kerosene fuelled aircraft, which typically store fuel in the wings. The need to limit hydrogen boil-off by minimising heat transfer and the tanks' surface area to volume ratio drives a preference for spherical or cylindrical fuel tanks. However, tank positioning may be driven by space constraints and by the need to manage the aircraft centre of gravity, which may result in adoption of non-spherical tanks and different manufacturing solutions. Tanks could be situated either in the fuselage (see **Figure 4**), or in external pods suspended from the wing. Aircraft powered by liquid hydrogen would therefore have a 'dry wing', opening opportunities to radically change the wing architecture and associated manufacturing processes. Processes will also be needed to manufacture tanks that are both highly thermally insulated and lightweight.

Managing the hydrogen temperature and pressure will require additional systems and insulation, claiming space and adding weight compared to kerosene-fuelled aircraft. Manufacturing processes are needed that enable greater design freedom for system components, allowing designers to minimise mass and volume, whilst maximising performance. These systems must limit hydrogen leakage, requiring high integrity joints and high tolerance interfaces.

Components that are in contact with hydrogen must be manufactured from material that is impermeable to hydrogen, whose properties do not degrade with exposure to hydrogen and are able to withstand the thermal and mechanical cycling. The material generated by manufacturing processes will have to be validated to demonstrate that they are compatible with hydrogen. The development and qualification of materials is out of scope for this report and is covered in the ATI FlyZero 'Advanced Materials' Report **[8]**.

Figure 4 – Concept hydrogen aircraft. Left: liquid hydrogen fuel cell electric concept for a sub-regional aircraft from the GKN H2GEAR project (image © GKN). Right: FlyZero midsize concept FZM-1E with liquid hydrogen fuel tanks highlighted in green. Two tanks are located in 'cheeks' to manage the centre of gravity.

Introducing new manufacturing processes on an existing aircraft is often challenging due to the high cost of change, including the burden of certification or new equipment and tooling, which tends to limit the amount of change once a product is launched. The freedoms of a clean sheet aircraft design offer the chance to exploit the benefits provided by novel materials and manufacturing processes, which can deliver greater geometric and material complexity, part consolidation, and multifunctional components. At the same time, more sustainable solutions can be explored that have lower material usage, lower material waste, more recyclable and lower energy consumption to produce. Accurate commercial modelling of new and conventional aerospace manufacturing methods are needed to support trade studies and inform design and manufacturing decision making. Consideration is also needed for how more components with high levels of material complexity (composites, functionally graded materials etc.) can be reused and recycled.

There are numerous opportunities across future aircraft to design in multi-functional components. These offer benefits including weight saving and other performance improvements in systems and at an aircraft level and in reduced assembly time. Some noteworthy examples include fluid conveyance in aerostructures (from heat exchangers to control systems) and embedded health monitoring. Novel manufacturing processes for embedding systems such as net shape manufacture and multi-material joining will be needed to realise these types of components.

Liquid hydrogen-powered aircraft need to enter service as early as possible to maximise CO_2 abatement [9]. The FlyZero technology roadmaps show technology developments needed to achieve technology readiness levels for the first generation of hydrogen technology by 2025. Manufacturing solutions will therefore need to be developed and validated for rate as rapidly as possible, concurrently with the product development. Enablers for rapid process development include rapid prototyping, early test and simulation and analytics (see ATI FlyZero report 'Compressed Design and Validation' [9]).

Trends and key drivers of change for aerospace manufacturing are similar for both hydrogen and kerosene aircraft. The drivers listed in **Figure 5** apply to all the technology bricks listed in this report and will need to be considered in the process of designing future production facilities.

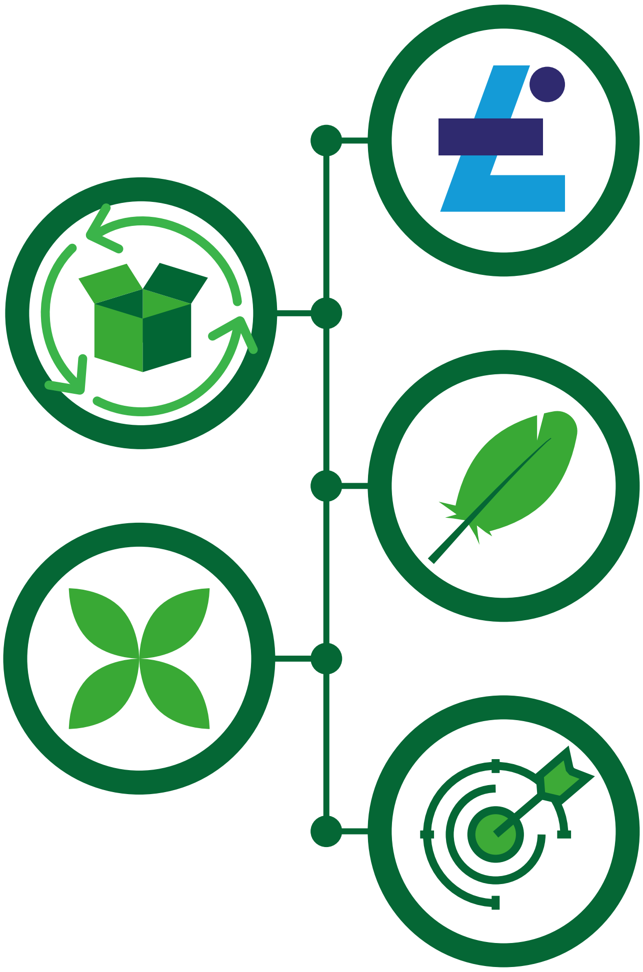


Figure 5 – Drivers for aerospace manufacturing technologies

Across all manufacturing sectors, the UK slipped from fifth or sixth biggest manufacturer based on total manufacturing output in the period 1970 to 2004 to ninth by 2015, having been displaced by China, South Korea and India [10]. Over the same period, the UK has maintained its position in aerospace manufacturing and is second largest in the world by turnover [11]. Emerging economies are increasingly targeting aerospace as a route to high value jobs. For the UK to continue to compete it must continue to drive forward productivity. UK aerospace productivity has grown by 28.6% over the ten years 2009-19 compared to 8.8% for manufacturing and 7.7% for the whole economy [12]. As aerospace continues to increase production rates, there are major opportunities for further productivity improvements through automation and digitalisation.

All sources of energy and emissions for aerospace need to be reviewed and optimised to address the aerospace sector's carbon footprint. For the FlyZero concepts, FlyZero has estimated that the lifecycle impact (in terms of 100-year global warming potential) of materials, manufacturing and maintenance, using a 2030 energy mix, is only around 1% of the impacts of fuel and emissions. This compares to about 0.3% for a fossil jet-fuelled aircraft because of its higher operating emissions. However, reducing energy use must remain a priority to reduce costs and because availability of renewable energy is set to limit the path to decarbonisation for many decades to come.

The Catapult Network estimates that ~85% of emissions embodied during manufacturing are from raw material extraction and materials processing **[13]**. Since a relatively higher proportion of these process (as opposed to component manufacturing and assembly) are carried out in other countries, the UK share of emissions may be relatively low. However, the UK must ensure that the emissions of its supply chains (Scope 3 emissions) must be net zero, as well as those emissions produced by domestic factories and processes become carbon neutral and resource efficient. Standards will be needed to enable emissions to be accounted through a supply chain and digital tools to help monitor and reduce them.

03. PRODUCTION RATES FOR FUTURE HYDROGEN AIRCRAFT

FlyZero has modelled two market scenarios for future hydrogen aircraft production – 'current trend' scenario and 'disruptive' scenario. These scenarios are aligned to the 'bookend' entry into service assumptions outlined by the ATI FlyZero 'Technology Roadmaps' [6].

- The 'current trend' scenario is broadly aligned with the perceived industry ambition that the first hydrogen regional aircraft comes to market in 2035. Hydrogen narrowbody and midsize aircraft would then reach the market in the late 2040s to the early 2050s.
- The 'disruptive' scenario is what FlyZero perceives is possible for technology to achieve if unconstrained by funding. A hydrogen-powered midsize aircraft comes to market first, in the early to mid-2030s. A narrowbody and regional aircraft follow quickly. Of the many scenarios that FlyZero considered, this scenario has the largest carbon reduction and UK market opportunity by 2050.

The production rates associated with these 'bookend' scenarios are shown in Figure 6.

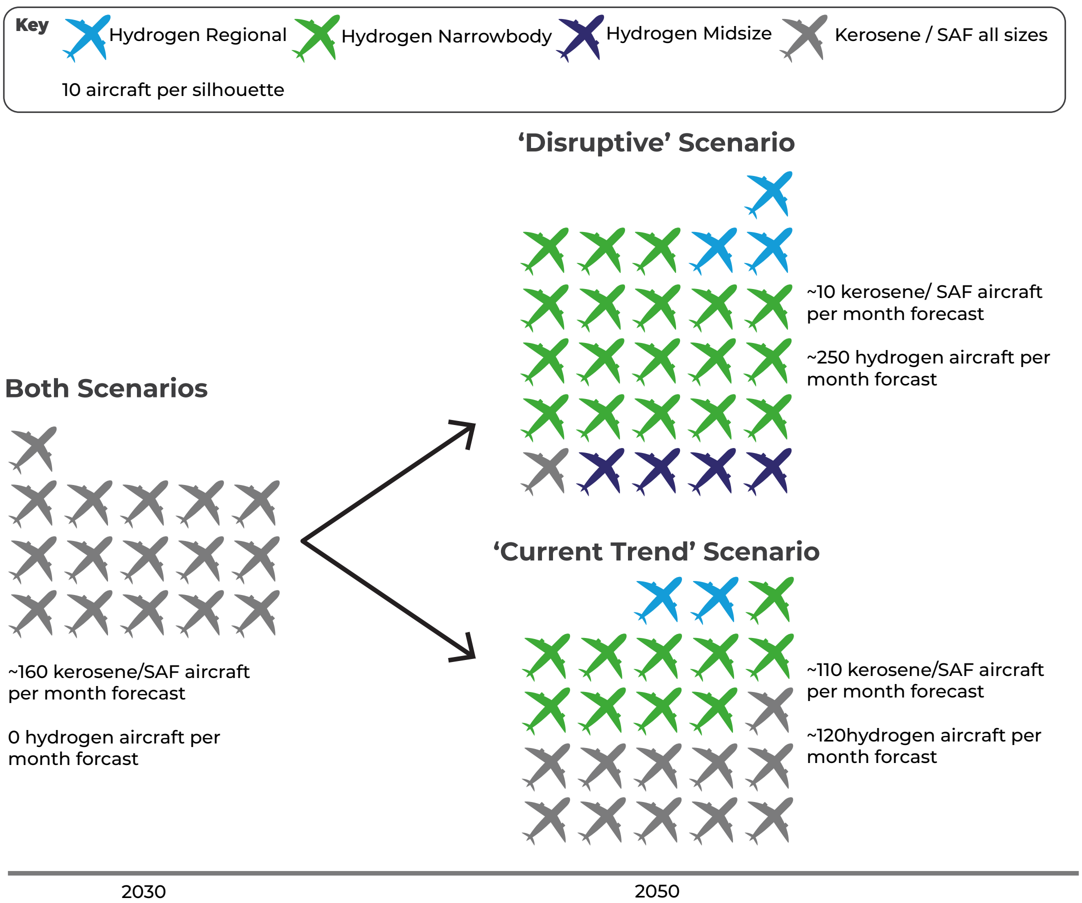


Figure 6 – Hydrogen regional and larger scale monthly production potential in 2050

A few key conclusions can be drawn from the FlyZero forecasts on market and production rates:

- During the 2030s both kerosene and hydrogen aircraft will be produced, creating a supply chain challenge. New factories and production lines will be needed as existing ones will be ramped down.
- Aerospace demand, and hence production rates, are expected to grow significantly by 2050. This will drive between 20-60% increase on today's production rates. Our 'disruptive scenario' assumes a more aggressive fleet replacement, and so larger increase in production rates, than our 'current trend' scenario.
- Narrowbody rates will continue to be the largest production challenge. The disruptive scenario assumes demand for 180 narrowbody aircraft produced per month in 2050.

New factories and production lines will be required during the 2030s. Once built, these factories could anchor production jobs for the lifetime of the aircraft, potentially decades. To secure this production, these factories must enable productivity, driving the need for higher levels of automation and digital connectivity than seen today.

The production challenge highlighted by **Figure 6** demonstrates the importance of developing manufacturing and assembly technologies concurrently with hydrogen aircraft technologies to secure UK footprint by 2050.

04. HYDROGEN FUEL TANKS

To realise large hydrogen-powered aircraft the fuel will have to be stored in tanks as a liquid around -253 °C. Kerosene fuel tanks on conventional aircraft reside in the wings. However, the requirement to limit hydrogen boil-off by minimising heat transfer results in spherical, cylindrical or tapered cylinders (see Figure 7) being preferred shapes due to their low surface to volume ratio. In the FlyZero concepts, the maximum tank dimensions range from ~1-11 m and wall thicknesses of 1-4 mm.

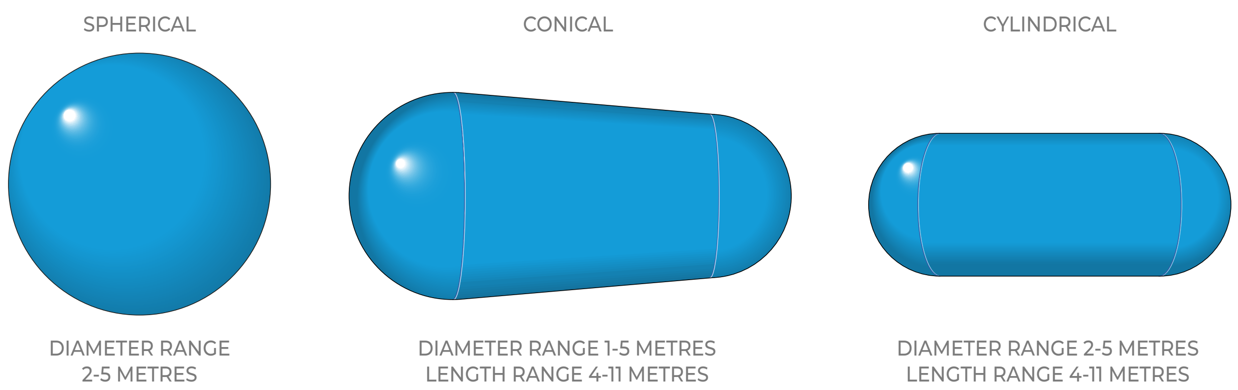
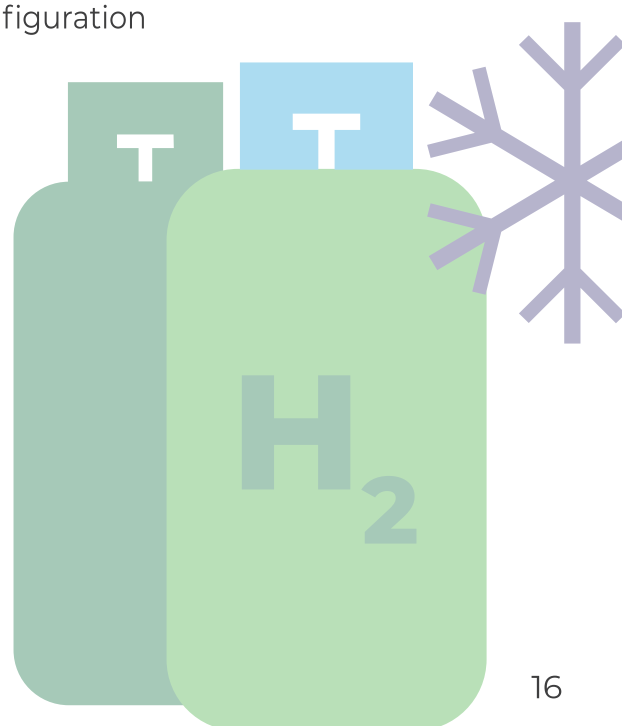


Figure 7 – Potential shapes and expected size ranges for liquid hydrogen tanks, from FlyZero concepts

The tank must maintain the hydrogen in its liquid state and optimise the effects of sloshing. Options for insulation include foam insulation, blanket insulation or a multi-layer including a vacuum layer. Tanks can be single or double walled. An outer wall can act as a vacuum jacket, or as a supporting structure. Figure 8 shows a typical configuration for a double-walled tank, including baffles to minimise the effects of sloshing. Baffles could be rings as shown or an open cellular structure, a method used in Formula 1. Appropriate materials and processes for manufacture and installation of cellular baffles may need to be investigated if this is deemed an advantageous solution by designers.



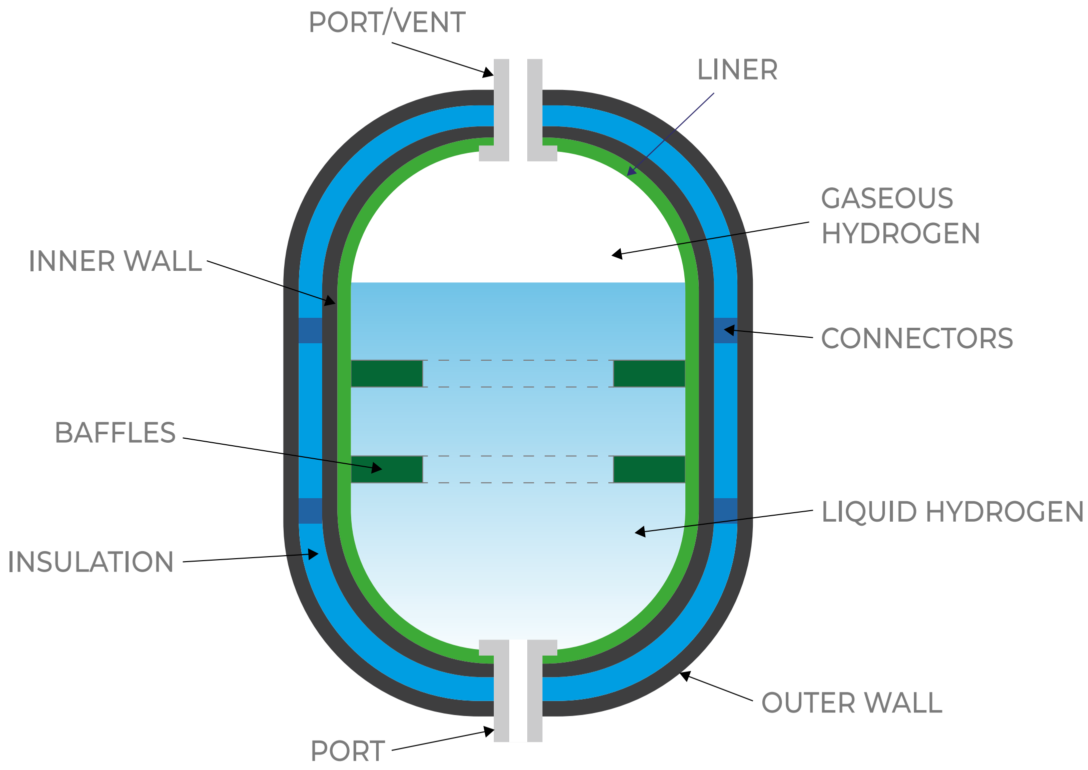


Figure 8 – Schematic view of a double-walled cryogenic storage tank (Adapted from original image provided by NCC [18])

Materials selection is a key consideration in the design of cryogenic hydrogen tanks and has a significant effect on the manufacturing process. Lightweight metal alloys, polymer composites, metal matrix composites and hybrids (e.g., a metallic tank with a polymer composite wrap) are all candidates (see also the ATI FlyZero 'Advanced Materials Report' [8]). The tank must be mounted in a way that insulates it thermally and from vibration. The design and material choice for this mounting will also affect the manufacturing and assembly process.

Metallic tanks are a potential solution for first-generation hydrogen aircraft. The manufacturing process is simpler than for composite tanks and there is more material data currently available from fuel tank applications in the space sector. Polymer composite tanks are also being assessed by airframers [14] [15]. Development needed to take fuel tank technology to technology readiness level (TRL) 6 is laid out in the ATI FlyZero Cryogenic Hydrogen Fuel Systems and Storage Roadmap Report [16]. The remainder of this section gives an overview of the manufacturing challenges and opportunities associated first for metallic tanks and then polymer composite tanks.

The following sections have been created with reference to reports commissioned for FlyZero from centres of the HVM Catapult – from the Advanced Manufacturing Research Centre on metallic tanks [17] and the National Composites Centre [18] on composite tanks.

04.1
METALLIC TANKS

Metallic hydrogen fuel tanks have previously been produced for space launch vehicles (NASA SLS [19] and ESA Ariane [20]). The aerospace requirement for tanks will be more stringent. While space launch tanks are used for one launch, tanks on aircraft will be used over much longer periods and cyclically loaded.

However, there is interesting learning to be gained from the space sector on manufacturing and materials. NASA's space shuttle liquid hydrogen external tank, for example, was of a monocoque construction of fusion-welded aluminium wall sections, with ellipsoid domed ends **[21]**. In civil aerospace, Airbus has established research centres in France and Germany to develop metallic tanks **[22]**.

Figure 9 shows a typical manufacturing flow for a double-walled metallic tank with insulation. The tank walls must be formed, machined, and then joined with high integrity welds. Insulation must be inserted between the inner and outer wall. A high strength precipitation-hardened 2xxx series aluminium alloy is a likely material of construction for liquid hydrogen tanks, with 2219 (Al-Cu) identified by FlyZero project and 2195 (Al-Cu-Li) considered as an alternative.

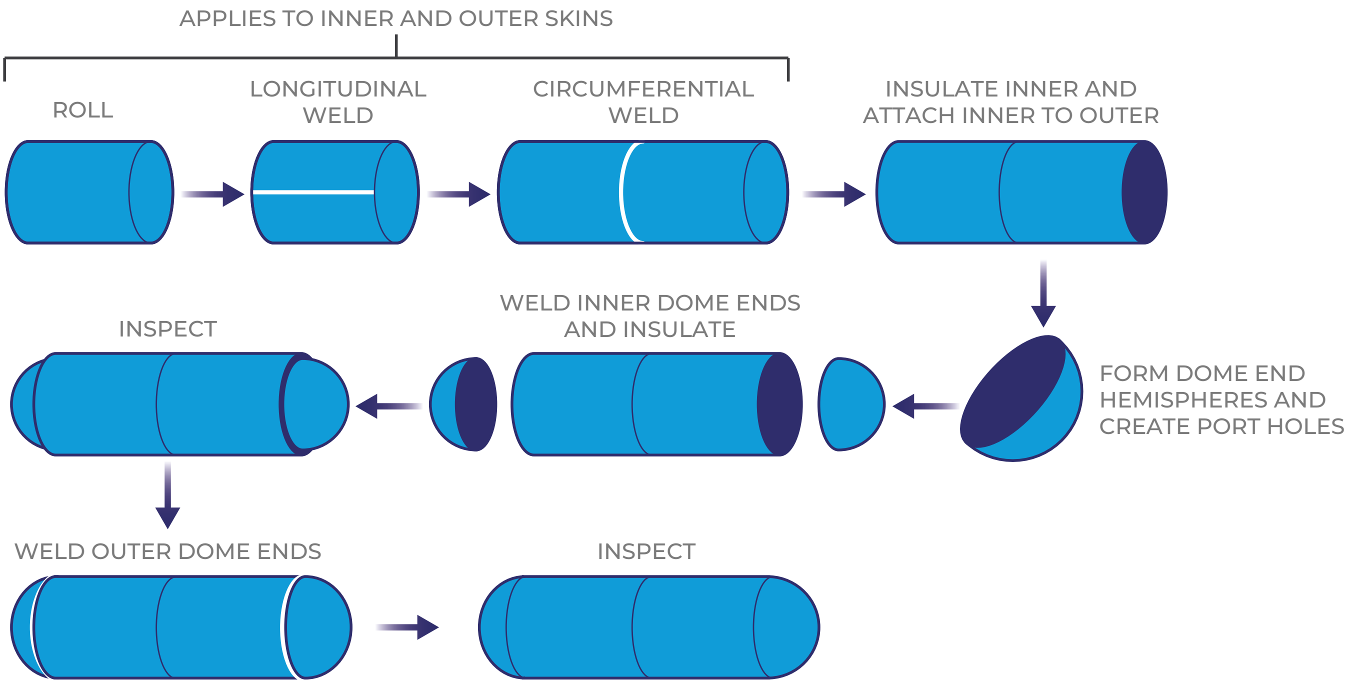


Figure 9 – Example manufacturing flow for a double-walled and insulated metallic tank

Candidate processes for each manufacturing stage were identified in an AMRC review commissioned by FlyZero **[17]**. There are a wide range of forming porcesses that could be used to manufacture metallic hydrogen storage tanks. In terms of manufacturing developments, flow forming provides an opportunity to produce components with integral stiffeners and baffles. NASA and MT Aerospace Integrally Stiffened Cylinder (ISC) flow forming process has been demonstrated on 3 m diameter cylinders for a cryogenic tank **[12]**. The dome ends could be produced with mandrel free spinning. Flexible mandrel-free spin forming technology has been scaled up to spin blanks of 2.5 m by Primetals, the University of Cambridge and the MTC **[14]**. Finally, the forming process and heat treatment could be combined. As an example, Hot Form Quench® developed by Imperial College and Impression Technologies Ltd. combines close die press forming with solution treatment quench to produce parts in the solution treated condition. The scalability of these processes would need to be assessed.

Joining of tank walls can be achieved by arc welding, high energy welding or solid-state welding. High energy welding is suited to thinner material down to less than 0.1 mm thick. Electron beam welding has been used on 6 m diameter tanks caps on the Ariane 5 rocket **[23]**. Laser welding should also be applicable to fuel tanks. Friction stir welding is a high potential candidate for aluminium tank components but development of this process is needed for thin wall components (<2 mm) **[17]**.

Wire arc additive manufacturing (WAAM) and electron beam additive manufacturing (EBAM) have been successfully demonstrated for the production of complete fuel tanks, or large dome ends by the likes of Lockheed Martin **[24]**, Relativity Space **[25]** and by Cranfield University **[26]** for Thales Alenia and Airbus Defence & Space **[27]**. Development of the additive process and demonstration of hydrogen compatability will be needed for the selected material.

Forming, heat treatment, machining, welding and inspection could all be rate-limiting process steps. Processing of such large components will incur high capital outlay – millions of pounds for machines and hundreds of thousands for tooling. Generally, selection of a simpler, more cost-effective forming process is offset by more downstream welding and machining steps to achieve the final component. AMRC found that for a tank manufactured first by plate rolling, machining would likely be the rate determining step in the process **[17]**.

Figure 10 – Titanium fuel tank deposited by wire arc additive manufacturing by WAAM3D © WAAM3D [right]

For metallic tanks for use on liquid hydrogen-powered aircraft, there is an opportunity to improve manufacturing approaches that are already being used for tank applications in the space sector through the following developments:

- **Forming processes**: For integral stiffeners and baffles, and increased rate.
- **Joining processes**: Developing an understanding of the properties of welded and solid state diffusion bonded material exposed to hydrogen and the application of advanced welding (laser welding, linear and rotary friction stir welding) and bonding processes to thin materials on large structures. Process monitoring and inspection will be required to ensure the material is defect-free to aerospace standards.
- **Process simulation**: To enable accurate prediction of deformation and spring back so that tool design and machine loads can be optimised.
- **Flexible tooling**: Developing machining and welding tools that can adapt in-process. Low cost and short lead-time tooling for forming processes could benefit companies trying to deliver rapid prototypes or supply multiple tank configurations in production.
- **Near net shape manufacturing**: A metal additive manufacturing deposition process could be used to generate complex curved components, potentially even producing sections of a double walled tank construction in a single operation. Challenges would have to be addressed for application to aerospace including rate capability, surface condition, heat treatment and inspection to confirm tank integrity.

Examples of UK aerospace companies with relevant capability include Metspin and Spincraft ETG for spin forming. Aero Fabrications has one of the largest stretch forming capabilities in the UK. Senior Thermal Engineering has a range of forming and fabrication capability. The UK is also home to providers of special purpose machines including e.g., Primetals. Although friction stir welding was invented in the UK by TWI, there are not many UK companies who offer friction stir welding as a service or supply the equipment. There are, however, many systems integrators that could develop a cell based on another company's friction stir welding head technology. Hybrid Manufacturing Technologies is a UK-US developer of deposition heads for laser additive manufacturing. WAAM3D, a spinout of Cranfield University, is a UK provider of wire arc additive manufacturing technology. TISICs has capability in the manufacture of metal matrix composites tanks. The HVM Catapult centres have relevant manufacturing research capability, including the AFRC on flow forming, the AMRC and NAMRC on large-scale machining and MTC and AMRC on additive manufacturing. The Autodesk Technology Centre in Birmingham has capability in machining and additive manufacturing. TWI has research capability around welding (and invented friction stir welding) and additive manufacturing.

04.2 POLYMER COMPOSITE TANKS

Composite tanks are increasingly being developed as an alternative to metallic tanks for storing liquid hydrogen. For space applications, composite tanks have already been demonstrated by Virgin Orbit [28], Rocket Lab [29], Omni Tanker and Lockheed Martin [30], MT Aerospace [31] and Boeing and NASA [32]. The Boeing and NASA tank is a 4.3 m diameter linerless polymer composite tank for use in the upper stage of the SLS rocket, and Boeing has acknowledged that potential applications extend beyond space and into other areas where large amounts of cryogenic fuels need to be stored, like future hydrogen-powered aircraft. For civil aerospace application, Airbus has established a research centre in Spain to develop composite tanks [14], as well as the two research centres developing metallic tank solutions [22].

Figure 11 shows a likely manufacturing flow for a double-walled polymer composite tank. A carbon fibre reinforced polymer (CFRP) inner wall is manufactured in one piece around a removable mandrel or a permanent liner. Insulation is added around this inner wall. The outer wall is then either laid up directly over the insulation or a two-piece outer wall is laid up and cured separately then assembled around the inner wall and insulation.

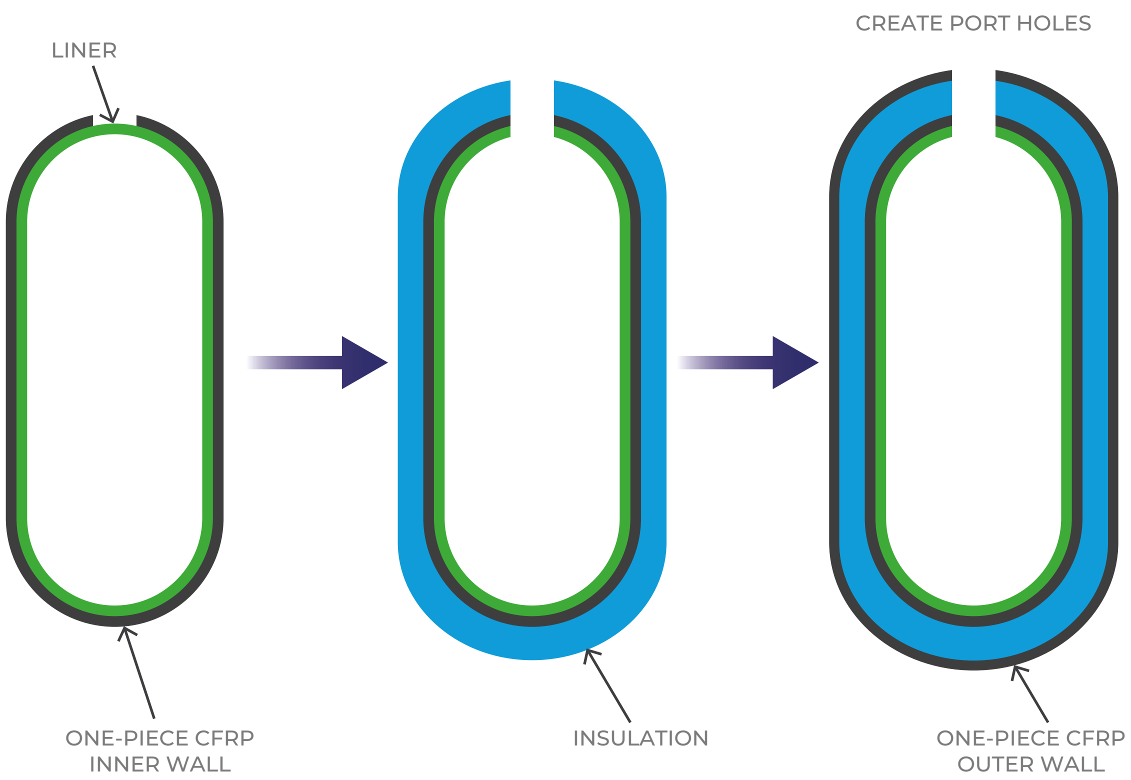


Figure 11 – Illustration of possible manufacturing process flows for double-walled polymer composite tanks

Whilst some metallic processes can manufacture tanks with integral stiffeners, this is more challenging to achieve for composite tanks at high manufacturing rates. Stiffeners are likely to be produced separately and then joined, unless a female tool is utilised. Female tooling increases complexity and slows deposition rates but allows internal features to be incorporated during the layup process. Manufacturing tapered or variable section cylinders is also more challenging for composite processes. Candidate processes for tank walls were identified in a review commissioned by FlyZero from the National Composites Centre **[18]**.

After the tank walls have been laid up, cured and demoulded, non-destructive testing of the tank walls is carried out to ensure that the composite material is free of critical defects. To determine defect criticality, an understanding is needed of both design failure modes (defect growth in service) and manufacturing process failure modes. Inspection solutions will be needed to inspect large areas of composites rapidly with high resolution. One option is to permanently install sensors so that integrity can be monitored through life.

Process steps that will limit production rate include: manual operations (assembly, tool preparation, mandrel removal), fibre deposition, cure and inspection. Manual processes could account for 50% of the total production time **[18]** so automation of these steps should be considered. Fibre deposition rates will be limited; deposition rate is not currently limited by the machine capability but will be limited by the optimisation for quality of the layup for a given geometry. Multiple deposition cells will likely be needed to achieve rate. Inspection can take considerable amount of time to complete, so in-process inspection and multiple inspections performed in parallel need to be evaluated for improving inspection cycle time.

When designing composite tanks for liquid hydrogen-powered aircraft, there is an opportunity to improve the current manufacturing approaches and composite component manufacture through the following developments:

- **Advanced, automated composite deposition**: To maximise production rate for curved tank geometries. In-process monitoring solutions would also help reduce the burden of inspection.
- **Joining processes**: To enable assembly of tank walls with liners, or tank walls with stiffeners or baffles. CFRP stiffeners could be inserted into the tank and then co-bonded or co-cured with the outer skin.
- **Out of autoclave (OOA) processes**: To reduce the process energy required and to reduce waste. OOA processes cover thermosetting and thermoplastic composites. Processes can exploit automation (i.e., manual operations, in-process monitoring and control and inspection) for increased speed and accuracy. Near term technologies for thermosets are variations on resin transfer moulding and infusion technologies.

- **Novel solutions for liners**: Liners can be used as the tool around which the component is wrapped. Liners can also be inserted after curing by inserting them through an end opening. Options include thermal spray coated liner, extrusion blow moulded liner or flexible tank liners and more novel processes like electrodeposition.
- **Novel solutions for tooling**: Tooling challenges include maintaining geometric form and stiffness in the mandrel under the loads of carbon deposition as well as scaling up some of these technologies for the larger tank sizes. Mandrels and tooling solutions are needed that are cost effective at rate. Novel solutions include segmented rigid mandrel, inflatable mandrel, collapsible mandrel or (for small tanks produced at low rate) a soluble washout core.
- **Inspection technologies**: Capable of rapid inspection at high resolution including, for example, super resolution imaging in ultrasonic testing. Developments in signal processing and data analytics will support advances in resolution and inspection speed. Embedded sensors may have potential to monitor the tank walls through life.

The HVM Catapult centre NCC is currently carrying out materials research into composite cryogenic tanks and composite pressure vessels [33]. The UK Research Centre in Non-destructive Evaluation [55] has world leading research capability in inspection technologies, with a strong track record in ultrasonics (large area inspection and embedded sensors) that could be applicable to tanks.

Companies with a UK presence that produce aircraft components using composites include GKN Aerospace, Spirit, GE Aviation, Hamble Aerostructures (part of Aernnova), Collins Aerospace and Airborne. A number of these companies have automated fibre deposition capability in the UK.

05. HYDROGEN FUEL SYSTEM

As described in **Section 2**, for future aircraft fuelled by liquid hydrogen, the management of hydrogen pressure and temperature in the tank and fuel system will require additional components and insulation. Achieving fuel system components that maximise performance, life and reliability with minimum space claim and system mass will be a major challenge for design, materials and manufacturing. Development needed to take fuel tank technology to TRL6 is laid out in the ATI FlyZero Cryogenic Hydrogen Fuel Systems and Storage Roadmap Report **[16]**.

The architecture and design principles for a liquid hydrogen fuel system are similar to those for a kerosene fuel system but the technology needs are different. The hydrogen fuel systems, including systems for refuel, feed, pressurisation, gauging and control, vent and defuel and purge, are made up of several units including, valves, pumps, heat exchangers, connectors, couplings and pipes.

Technology description	*Manufacturing challenge level*
Pipes – for gaseous and liquid hydrogen	***Significant***
Valves - non-return, shut-off and pressure relief valves	***Significant***
Pumps - cryogenic liquid boost pumps, transfer pumps, high-pressure pumps	***Significant***
Heat exchangers	***Significant*** *(see Section 9)*
Sealing – connectors, flexible joints, seals, lubrication	***Modest***
Sensing – level, temperature, pressure and flow. Leak detection and gaseous hydrogen concentration sensors	***Modest***

Table 1 – Fuel system manufacturing challenges

Insulation is required to maintain hydrogen in its liquid state while flowing through the fuel distribution lines and pipes, prevent icing on the pipework external surfaces and reduce hydrogen boil-off while the system is dormant. Twin walled vacuum jacketed pipes are an alternative to lagging single walled pipes. Twin walled pipes are readily manufacturable for short straight pipe runs and have been produced for ground-based industrial applications. Longer pipe runs, incorporating bends, need manufacturing capability development to ensure the physical and so thermal separation between inner and outer pipes is maintained, avoiding contact and fretting when exposed to vibration. This development needs to be carried out in conjunction with end fitting development, allowing pipes to be fitted on the build line, in-service and during refit/overhaul without compromising integrity. In the UK a number of companies have this capability at a low TRL and can develop from a simpler twin wall straight pipe concept to more complex pipe geometries.

Pumps and valves are available for ground-based liquid hydrogen applications. Lightweighting would be required for aerospace application. Near net shape metallic and composite manufacturing processes are needed to enable the design freedom needed to realise high performance, lightweight valves and pumps.

Sealing to minimise hydrogen leaks in valves, pumps and pipes will be a key challenge, addressed through a combination of design and manufacturing solutions. Components will need to be compatible with a broader range of temperatures than their kerosene counterparts. Materials with the right properties across the temperature range will have to be identified. High tolerance interfaces will need to be manufactured. Components with moving parts (e.g., valve stems with glandless seals) will be a particular challenge. The reverse leakage requirements for valves will be a significant driver in the equipment design and manufacturing.

The approach for installing pipes will have to be considered. Pipes can either be separate components or can be fully integrated into the structure. For separate pipe components, precision machining, bending and assembly will be required so as not to affect the integrity of the interfaces. Where possible, interfaces may also be welded to further reduce the likelihood of leaks and will require non-destructive evaluation to ensure integrity.

Due to the introduction of cryogenic fuel and the associated effect on maintainability, the ability to monitor equipment and system health is expected to have increased value and may drive requirements for manufacturing processes capable of embedding reliable sensors. This will be critical in development of these systems and will be needed to enable ground and flight tests, as well as being likely to become part of the safety system for production aircraft.

Coatings will provide chemical and thermal barriers that are necessary to enhance both the operating capability and commercial life of base materials. The deposition method for these coatings will need to be re-evaluated to confirm their performance in a cryogenic liquid hydrogen environment.

For the hydrogen fuel system, manufacturing developments are needed in the following areas:

- **Machining**: High rate, precision machining adopting technologies e.g., cryo-machining to enable manufacture of high tolerance interfaces to enable high quality seals.
- **Near net shape manufacturing:** (casting, additive manufacturing) for the manufacture of high performance, lightweight pumps and valves, for the integration of channels replacing pipes and to enable embedded sensors.
- **Flexible, automated manufacture and assembly processes**: including high accuracy extrusion and bending of single and twin-walled pipes and metrology and digital twins to enable assembly of pipes and system components.
- **Requalification of coating methods:** To confirm their performance in a cryogenic liquid hydrogen environment.

There is a significant aircraft fuel systems supply chain with a base in the UK. Examples of companies include GKN Aerospace and many others are active in technology development for next generation systems. As an example relevant to future cryogenic hydrogen applications, dual wall pipe technology is being developed at Sigma and Futaba in the UK. There are numerous suppliers with capability relevant to cryogenic fuel systems that have developed their experience outside the aerospace sector, from applications in industrial, space, chemical processing and scientific laboratory equipment. Examples of companies with a base in the UK include Parker, Thames Cryogenics Ltd, AS Scientific, and iS4 Cryogenics. The UK also has sensing developers including Oxsensis, Atout Process Ltd and Weatherall Equipment.

06. AERODYNAMIC STRUCTURES

The UK today has strong capability to deliver aerostructures such as wings, control surfaces, nacelles and pylon, landing gear and some fuselage sections. In aircraft fuelled by liquid hydrogen the fuel is likely to not be stored in the wing. This 'dry wing' is the main focus of this section. A transition to a high-rate manufacture of composite wings is also likely, meaning there will be high synergy between ultra-efficient kerosene and hydrogen research for aerodynamic structures. Development needed to take the aerodynamic structures to TRL6 is laid out in the ATI FlyZero Cryogenic Hydrogen Fuel Systems and Storage Roadmap Report [16].

Given the relative immaturity of hydrogen fuel system technology and the speed required for entry into service in the 2030s, the first generation of hydrogen fuelled aircraft are unlikely to be the optimal design for weight. Airframe weight savings and aerodynamic improvements, critical for today's product, will continue to be a crucial enabler for hydrogen, to deliver competitive products and longer-range routes. Lightweighting will minimise the volume and mass of hydrogen required for a mission, enabling range. It will also continue to be a driver of minimised cost and non-CO_2 emissions. Composites have made significant contributions to the lightweighting of commercial aircraft over a 40-year period by gradually replacing metals, enabling more integrated structure for primary and secondary applications (see **Figure 12**). The requirement for the aerospace sector to produce composite parts at higher rates and lower costs has resulted in the development of out of autoclave processing (OOA), an increase in the use of automation, increased use of thermoplastics and innovation in heating and tooling. These developments are expected to continue for hydrogen aircraft and will drive manufacturing and assembly technology implementation.

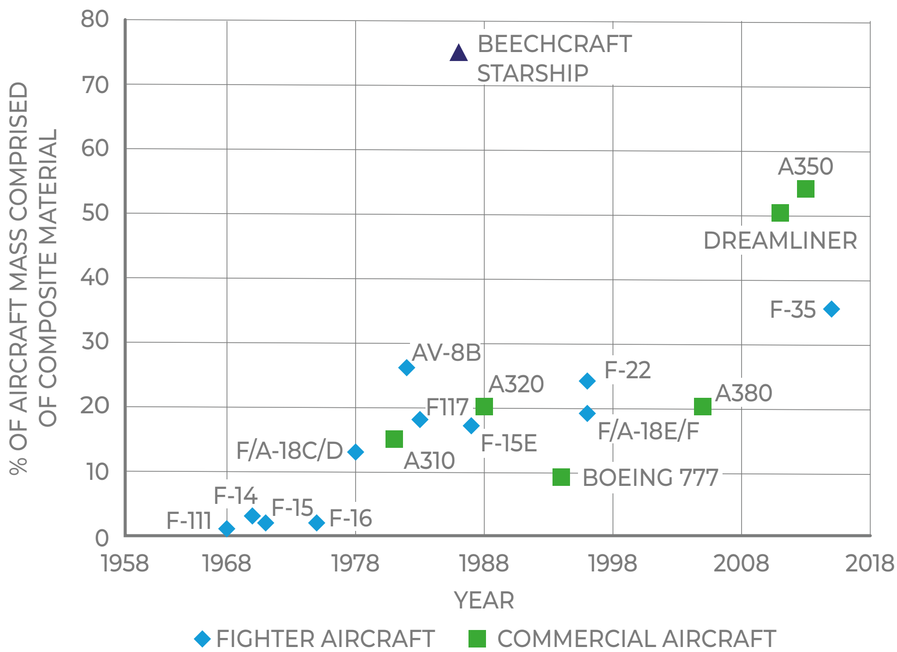


Figure 12 – Composite use in airframes. Adapted from [35], with addition of data point for A350

On the assumption that the first generation of liquid hydrogen-powered aircraft will be a tube and wing construction, much of the existing aerostructures technology developments in programmes such as the Airbus-led Wing of Tomorrow **[36]** will be equally applicable to liquid hydrogen-powered aircraft as well as conventional kerosene or future sustainable aviation fuelled jet aircraft which they are currently targeting. There are however some differences which could impact the manufacturing processes for a hydrogen product specifically.

Hydrogen specific design challenges are:

- **Enabling a 'dry wing'**: Aircraft powered by liquid hydrogen would have a 'dry wing' – a wing that contains no fuel and so creates an opportunity to radically change the wing architecture and associated manufacturing processes. Drilling and integration are problematic areas in today's aircraft. A dry wing may help to reduce hole tolerances requirements since there will be no challenges associated with maintaining fuel boundaries **[54]**.
- **Enabling cryogenic laminar flow**: With the storage of large volumes of cryogenic liquid comes the potential to utilise this to improve laminar flow, as cooling technology can potentially keep flow engaged for longer and delay the transition to turbulent flow. This alone may not drive any revolution the manufacturing process of aircraft, but increased laminarity either natural, hybrid or cryogenic is likely to drive increased focus on part and assembly level tolerances, as well as looking at manufacturing solutions which increase panel size and minimise joints, steps and gaps in critical areas.

Any new wing design, regardless of the primary fuel used (kerosene, SAF or hydrogen), is expected to increasingly employ large, integrated composites. Large, primary wing structure composites are not supplied at narrowbody production rates and costs today. The move to delivering primary wing structure composites to the narrowbody segment, which offers the largest decarbonisation potential for a hydrogen aircraft, will require process development.

High-rate composite research challenges are:

- **Enabling lower cost**: Delivering a high-rate composite wing at the same cost as the current generation metallic wings will be a significant challenge.
- **Enabling rate capability**: Narrowbody production rates for each global aerospace OEM are anticipated to be in excess of 100 per month by 2050.
- **Enabling repeatability**: Large, high value, components will require high levels of process control.
- **Enabling high accuracy**: Technologies such as laminar flow will require joints, steps and gaps to be minimised in manufacture and drive hole and fastener tolerances where they are used, to ensure flushness and continuity of aerodynamic profiles. This will drive the need for high accuracy on critical components at a detail and assembly level.
- **Ensuring sustainability**: High rates of scrap material produced by today's composite processes could be reduced by moving to processes which enable near net edge. Additionally, it is acknowledged that while employing composite materials has a sustainability benefit over the lifetime of an aircraft, the manufacture and recycling of these materials still requires significant development.

Technology changes which could contribute to delivering a next generation wing are shown in **Figure 13.**

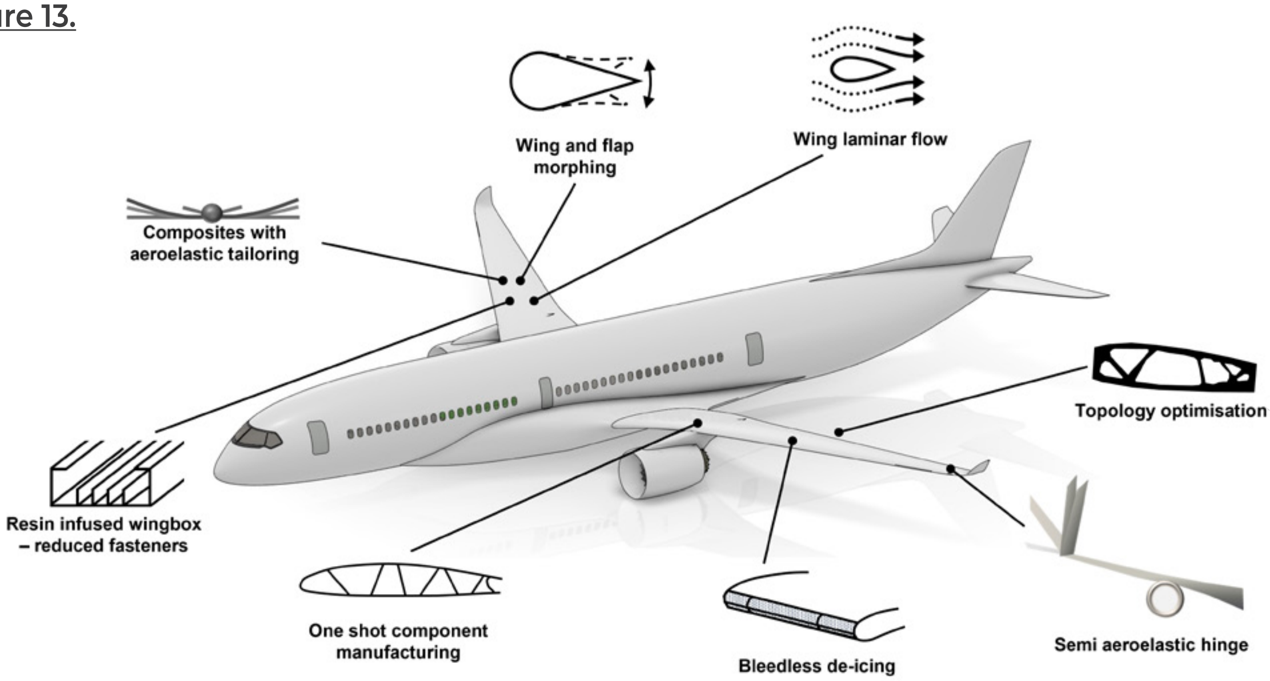


Figure 13 – Potential technologies for future wings.

Although the focus has largely been on large composite parts, as they are expected to make up a large part of the aircraft wing primary structure (covers and spars), metallic developments are also essential and will have a place in future aircraft in particular for use in pylons, landing gear and other highly loaded location points. These typically cost less to produce than a composite alternative.

The ATI Technology Strategy and the forthcoming HVM Catapult Aerostructures Manufacturing & Materials Roadmap capture developments required for future Aerodynamic Structures, across both future metallic and composite technologies.

Major onward manufacturing technology developments, which could address one or multiple of the research challenges listed above, include:

- **Joining processes**. Novel joining techniques offer performance benefits by delivering smoother, fastenerless surfaces with reduced assembly time and waste. However, the certification of wholly welded or bonded structures is known to be challenging and requires development. Recycling of these structures will also need to be considered.
- **Thermoplastic materials processing**. Thermoplastics have a high potential rate of manufacture, repairability and recycling benefit, but require both material and process developments to enable them to be more widely used on future aircraft. Advances in focused heating technologies could assist the deployment of thermoplastics [8].
- **Near net shape manufacturing**. As sustainability targets and costs drive the industry toward wasteless or low waste processes, additively manufactured components will be a key element of research and development. The potential application of technologies such as 3D printed thermoplastic composites to morphing aerostructures may drive research in this area, as well as metallic applications to replace large forgings [52].

- **One shot components**. Integrated structural components will move from smaller assemblies such as flaps and spoilers to larger structures such as integrated wing or fuselage parts. They will enable reductions in lead times, consolidation of parts, reduction in fasteners, and reductions in waste. It will, however, drive the need for increased reliability in the process and minimum probability of defects or accidental damage during manufacture, as scrapping parts will be very costly, both in terms of material cost and embedded value.
- **Advanced, automated deposition**. Composites offer the potential to use only the right material in the right place, but to achieve this in a cost-effective and rate-enabled manner technology needs to be developed to enable this lay-up. Technologies such as automated fibre placement, automated tape laying and tow steering are already under development and pilot lines to demonstrate these technologies for the next generation of aircraft will be required.
- **Out of autoclave (OOA) processes**. OOA processes have potential to reduce the large cost and time associated with autoclave cure. Appropriate OOA process selection is driven by the size of the part, the rate of manufacture required and tolerances specified. Out of autoclave processes encompass thermosetting and thermoplastic composites and all will reduce the energy required to process composites and reduce waste. All processes can exploit automation for increased speed and accuracy. Near term technologies for thermosets are variations on resin transfer moulded (RTM) / Infusion technologies.
- **Flexible, automated assembly processes**, combined with advanced metrology and inspection techniques will continue to be a critical research area to enable rate of delivery of hydrogen aircraft.

For composites, the material properties are affected by the chosen processing parameters and, conversely, the choice of feedstock material affects the process rate. Development of materials (resin systems, fibre technology etc.) must be carried out in parallel to process development - see ATI FlyZero report *Advanced Materials* [18].

The UK has significant experience in design for manufacture and process development for the technologies listed above. Airbus UK, GKN, Spirit and Hamble Aerostructures together with their partners are all actively developing these technologies, through programmes such as the Wing of Tomorrow. There is a significant footprint of supply chain companies in the UK. Additionally, UK benefits from strong cross-sector strength in composite manufacture. In automotive, companies such as McLaren have developed and industrialized high rate composites for primary structure applications, they are now working with GKN to develop technology for aerospace applications [53].

However, development of large-scale tooling and automation technologies as well as system integration of these, is still heavily reliant on support from outside of the UK. There are some positive UK developments in this area; companies such as Loop Technology, in collaboration with the UK HVMC Network, are further developing their manufacturing system integrator capability. A recent ATI initiative to create a directory of UK tooling capability identified a growing range of industry solutions; companies such as CCP Gransden and Datum have capability to create composite tooling [48]. Ultrasonic Sciences Ltd is an example of a UK producer of large automated ultrasonic testing cells. Large, OOA tools and highly automated production lines with embedded inspection are high value and could be an opportunity for UK integrators and inspection companies.

07. HYDROGEN GAS TURBINES – COMBUSTOR

Aerospace gas turbines will need to be modified to burn hydrogen. A new fuel delivery system will be required (see **Section 5**) including a hydrogen heat exchanger (see **Section 9**) to pre-heat hydrogen prior to entry into the combustor. Development needed to take the hydrogen gas turbine to TRL6 is laid out in the ATI FlyZero *Gas Turbine and Thrust Generation Roadmap Report* **[56]**. The focus of this section is the combustor. The fuel spray nozzles in kerosene combustors will have to be replaced with hundreds of multi-point injection holes (see **Figure 14**).

Combustor manufacturing research has typically centred around technologies that can address the ever-rising temperature demands, including cooling holes, thermal barrier coatings and material processes for high temperature materials (nickel super alloys, ceramic matrix composites). Preliminary design studies for FlyZero indicate that the hydrogen flame could be up to 60 K cooler than a kerosene flame. However, more work is needed to determine how that translates to the temperatures of the combustor components. Radiative heat from hydrogen combustion may be higher than that from kerosene combustion and the water content will change the thermal conductivity of the gas within the chamber. Therefore, the trend towards materials and manufacturing processes that enable high temperatures is expected to continue in hydrogen gas turbines. In addition, these combustor materials must be proven to be hydrogen compatible **[8]**.

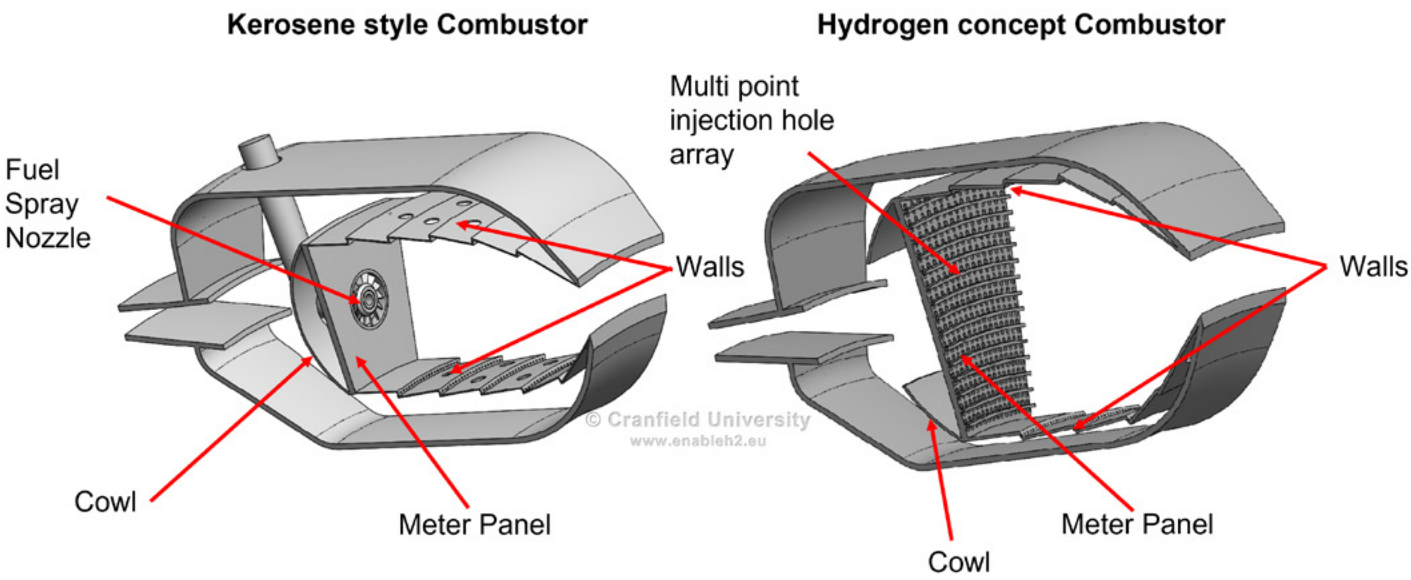


Figure 14 – Comparison of kerosene style combustor (left) and hydrogen concept combustor (right) from ENABLEH2 project. Image © Cranfield University

Creation of the hundreds of multi-point injection holes in the meter panel will present a manufacturing challenge. It is likely that the holes will need to be shaped along their axis to reduce the likelihood of flashback. The meter panel – like the walls and cowl – can be manufactured from sheet, forged or cast nickel superalloys that is then machined to final shape, with the choice of manufacturing process driven by the functional requirements, assembly requirements and material selection. The holes then need to be inserted in the meter panel. These holes are expected to be in the order of 0.3-1.0 mm diameter, shaped with high tolerances to ensure consistent flow of hydrogen. The combustor walls also contain holes for cooling, but these do not have the challenging shape requirement.

Manufacturing processes for new combustor will require development. Potential methods for manufacturing the injection holes include laser drilling, high speed electro discharge machining (HSEDM), electron beam drilling (EBD), electro chemical drilling (ECD), conventional micro drilling (CMD) and laser powder bed additive manufacture (AM). **Table 2** gives an indicative overview of process capability against key characteristics.

	Laser	*HSEDM*	*EBD*	*ECD*	*CMD*	*AM*
Hole size (assume 0.3 - 1.0 mm)				*TBD*		
Hole tolerance (+/-5% on flow)	*	*	*	*TBD*	*	*
Shaped hole capability				*TBD*		
Meter panel thickness effect				*TBD*		*N/A*
Through thermal barrier coating capable			*TBD*	*TBD*	*TBD*	**
Time per hole				*TBD*		
Cylindrical hole				*TBD*		
Line of sight access required						*N/A*
Cost per hole			***	*TBD*		
UK supply chain						

	High capability / not applicable
	Good capability
	Some capability
	Limited capability
	No known capability

** Dimensional tolerance to achieve flow is dependant on hole size but expect to range between +/-0.01 mm and +/-0.05 mm*

*** Thermal barrier coating, if required, will have to be applied to the meter panel face post-build without blocking hole flow*

**** Process is suited to high number of holes (>10k) due to the long time to draw a vacuum for the electron beam machine*

Table 2 – High level comparison of capability of processes for manufacturing combustor multi-point injection holes

All processes identified could struggle to meet the expected hole tolerance (+/-5% on flow test), especially for holes at the lower end of the diameter range. Incorporation of thermal barrier coating onto the flame-facing surface will bring further technology challenge if identified as a requirement.

Metal additive manufacturing provides a route to manufacturing the component and holes in one step. The holes are produced 'for free'. A full assembly could be printed using a metal powder bed process, depending on machine bed size. However, requirements for thermal barrier coating and mounting may make printing of a full assembly inappropriate. If additive manufacturing is adopted as an option, reaching the required rate will be a challenge. The current global supply chain is still relatively limited in capacity and in its capability to print the high temperature nickel superalloys required in combustors.

Manufacturing developments are needed for combustors in the following areas:

- **Advanced machining**. Novel drilling to produce shaped holes for multi-point injection:
  - Laser drilling - development in laser beam shaping to shape the hole. Advances such as water guided lasers could also improve precision and repeatability.
  - High speed electro discharge machining (HSEDM) - development for shaped hole capability.
  - Alternative drilling methods – electron beam drilling (EBD), electro chemical drilling (ECD) and conventional micro drilling (CMD) could be assessed for use on combustors.
- **Near net shape manufacture**
  - Determination of process capability for size, shape, and surface roughness.
  - Development of processes for ceramic matrix composites.
  - Evaluation of alternatives to metal powder bed fusion additive manufacturing, including binder jet printing, metallic stereolithography or ceramic stereolithography.
  - Dimensional measurement and non-destructive testing of the geometrically complex near net shapes produced by additive manufacturing.
- **Manufacturing processes that enable high temperatures** is expected to continue in hydrogen gas turbines, including ceramic matrix composites and thermal barrier coatings.

The UK supply chain has limited capacity in laser drilling whereas HSEDM is more readily found, however component size and specific equipment capability may limit the options. UK suppliers for both hole manufacturing processes include ITP Aero, Preci-Spark, Winbro, Radius Aerospace, Oxford Lasers, ELE Advanced Technologies and Bromford Industries. Laser research capability resides in the Midlands at the HVM Catapult centre MTC along with the sole known UK machine manufacturer TEK4. Winbro are also a Midlands based HSEDM machine tool manufacturer. Alternative drilling methods (EBD, ECD and CMD) are less readily available globally and UK accredited aerospace suppliers could not be found – supply chain capability would need to be developed.

The UK also has emerging capability in metal additive manufacturing including Material Solutions – a Siemens company, 3TAM, the Digital Manufacturing Centre and Rolls Royce [37]. Both the of HVM Catapult MTC and AMRC research centre network have metal additive manufacturing capability. Renishaw and Wayland Additive are UK based metal powder bed additive machine manufacturers.

08. FUEL CELLS AND ELECTRICAL PROPULSION

The propulsion system of hydrogen electric aircraft will include a fuel cell powering an electric motor. Both of these technologies will present opportunities for manufacturing development. Development needed to take the fuel cell and electrical propulsion system to TRL6 is laid out in their respective roadmaps [38] [39].

From the range of fuel cell technologies available today proton exchange membrane (PEM) fuel cells are considered to have the highest potential for aircraft applications. Aerospace fuel cell stacks will be highly optimised for power-to-weight, and so will likely be bespoke to aerospace and higher cost than fuel cells used in other sectors. It is expected that in the near term the optimisation of the PEM fuel cells for aerospace applications will drive higher levels of platinum loading on the cathode of fuel cell, requiring different deposition techniques. Automated assembly at both the sub-system level and stack level will deliver repeatable quality whilst minimising cost. AMRC Cymru is building a development cell for the automation of fuel cell stack assembly to support deployment across multiple end use sectors. Steps for preparation of the membrane electrode assembly (MEA) also have potential for automation. Electrode coating is one particular area for the introduction of novel techniques. The introduction of additive manufacturing and composite materials could be routes to reducing weight, especially for the bipolar and compression end plates which can equate up to 80% of the fuel cell stack weight.

Electric motors are being developed particularly for use in automotive [23]. Automotive will require much higher production volumes than aerospace, which will drive automotive to focus on processes like wet processing that can limit rate. However, both the aerospace and automotive industries require high power densities and so will have common interest in manufacturing processes that enable this.

To achieve higher power density, higher fill factor windings such as hairpin or edge-wound topologies can be manufactured by automated bending, or potentially casting or additive manufacturing processes [24]. Electrical insulation with higher temperature capability will allow the motor to run hotter without causing longer term degradation. There is a requirement to develop automated techniques to prepare the ends of windings, and then join them to lead-outs, (i.e., copper-aluminium, or aluminium-aluminium). Some of the techniques being assessed rely on laser-based solutions; however, lasers are limited by the need for line-of-sight access.

Higher thermal efficiency can be achieved by, for example, using net shape processes that enable cooling channels to be embedded in the motor casings at closer proximity (or even within) the windings, as opposed to the current automotive standard for water jacket cooling.

The stators and rotors of electric motors are manufactured from laminated and joined thin electrical steel sheets, with electrical insulation between each sheet to reduce eddy current losses. These sheets are currently adhesively bonded, mechanically joined or welded. These joining processes could be further optimised using simulation to predict resultant material properties and the effect on performance. Higher speed electric motors also see challenges in the retention of magnets at very high operating speeds, with specific challenges being identified in robust and repeatable carbon overwrapping or similar that do not cause issues with the motor performance.

For a traditional electric motor, around half of the mass is attributed to non-active components such as the motor casing, shaft components, bearings, seals, fasteners, insulation, and adhesives. Novel motor architectures can eliminate the stator yoke, which reduces the stator iron mass providing a power density advantage. Additive and composite manufacturing have potential to reduce mass by more than 30%. For example, additive manufacturing can enable the integration of the electric motor and power electronics with shared cooling systems within a single package.

Higher power density can also be achieved by higher rotational speed of the motor. High speed motors can be improved by reducing AC losses through shaped braided structures and using soft magnetic materials. For example, soft magnetic materials by power metallurgy routes enables the tailoring of materials properties that in turn enable advanced axial flux or transverse flux motor topologies.

Aerospace certification and quality assurance processes will drive a requirement for high quality in motor manufacture. This will result in a need for more repeatable processes, including for example processes for joining electrical terminations and connectors (alternatives to crimping and brazing) with solid state processes (e.g., ultrasonic welding, friction stir welding). The need for quality will also drive towards automated assembly. As an example, insertion of pre-magnetised or post-magnetised magnets within the rotor assembly can be automated. This has safety as well as quality benefits. Potting and adhesives steps can also be automated.

Manufacturing developments are needed for fuel cells and electric motors in the following areas:

- **Near net shape manufacturing** (casting, additive manufacturing, powder metallurgy routes) to enable higher powers by reducing mass. The new manufacturing processes would enable greater design freedom to incorporate channels for cooling, consolidate parts, and vary/tailor magnetic properties through the component to improve power density. This includes material processes for new motor materials such as composites and magnesium alloys. For fuel cells novel manufacturing methods are needed for the control and disposition of electrode material onto proton exchange membranes and the manufacture of bipolar and end plates made of composite materials.

- **Novel or requalification of coating methods** used to coat components with electrical insulation with higher temperature capabilities. The development of innovative corrosion resistant coatings for components (i.e. bipolar plates, end plates) operating in highly corrosive high temperature environments.
- **Joining processes**. Especially advanced fusion welding methods for joining of motor rotor and stator stacks, reliable joining of conductive elements (solid state welding processes as replacements for crimping and brazing).
- **Automated assembly** of fuel cell stacks, fuel cell membrane electrode assemblies and for electric motors, including active (magnetic) components. The manufacturing cycle will drive the requirement for automated assembly. The maintenance and overhaul activity will drive the need for equivalent automated dis-assembly and re-assembly activities.

09. THERMAL MANAGEMENT

Thermal management will be critical to realising hydrogen-powered flight. Hydrogen heat exchangers will be needed in the gas turbine fuel distribution system to warm the hydrogen from the tank for delivery to the combustion chamber and to maximise the performance of hydrogen gas turbines. In fuel cell architectures, air radiators will be needed to dissipate the heat generated by fuel cells, heat exchangers will be required to precool the fuel cell air source and to warm hydrogen fuel source from the tank for delivery to the fuel cell. The heat exchangers will have to be lightweight structures, with thinner walls than a conventional heat exchanger. Development will be required for hydrogen heat exchangers and heat exchangers with novel architectures (e.g., air radiators for fuel cells). Development needed to take thermal management technology to TRL6 is laid out in the ATI FlyZero Thermal Management Roadmap [40].

Aerospace heat exchangers are produced by manufacturing processes such as hydroforming, welding, laser cutting and laser welding. To continue to minimise the mass of heat exchangers and to maximise their thermodynamic efficiency, the wall thicknesses of micro tubes and plates will need to keep reducing. Therefore, processes such as tube extrusion and drawing needs to be continuously developed. A number of tests will be required on the production line, including leak tests, proof tests, pressure drop tests and final performance test.

For heat exchangers, manufacturing developments are needed in:

- **Automated assembly and joining** methods with high levels of repeatability, for joining thin-walled features.
- **Net shape manufacturing** (such as casting or additive manufacturing) to enable greater design freedoms, allowing designers to minimise mass and volume, whilst maximising performance. Metal powder bed additive manufacturing process is a high potential candidate that is being pursued now by the UK supply chain companies.
- **Quality assurance through unit tests**. Hydrogen test rigs and test protocols will need to be developed, that can enable safe testing at full manufacturing production rates.

The UK has world-leading capability in the design and manufacture of aerospace heat exchangers. Companies with UK manufacturing capability include Meggitt, HS Marstons (part of Collins Aerospace), Reaction Engines and their supply chains. HiETA Technologies specialises in design and manufacture of heat exchangers produced by additive manufacturing.

10. BUILDING UK MANUFACTURING SUPPLY CHAIN CAPABILITY

Aircraft production can last decades. As an example, the first A320 entered service in 1988 and a large proportion of today's production volumes are still delivered from the same factory footprint.

In the early years of this lifecycle for hydrogen aircraft, the focus will be on development of hydrogen aerospace technologies and engineering design of hydrogen aircraft. However, the UK also needs to focus on building manufacturing supply chain capability in time to anchor longer-term production jobs.

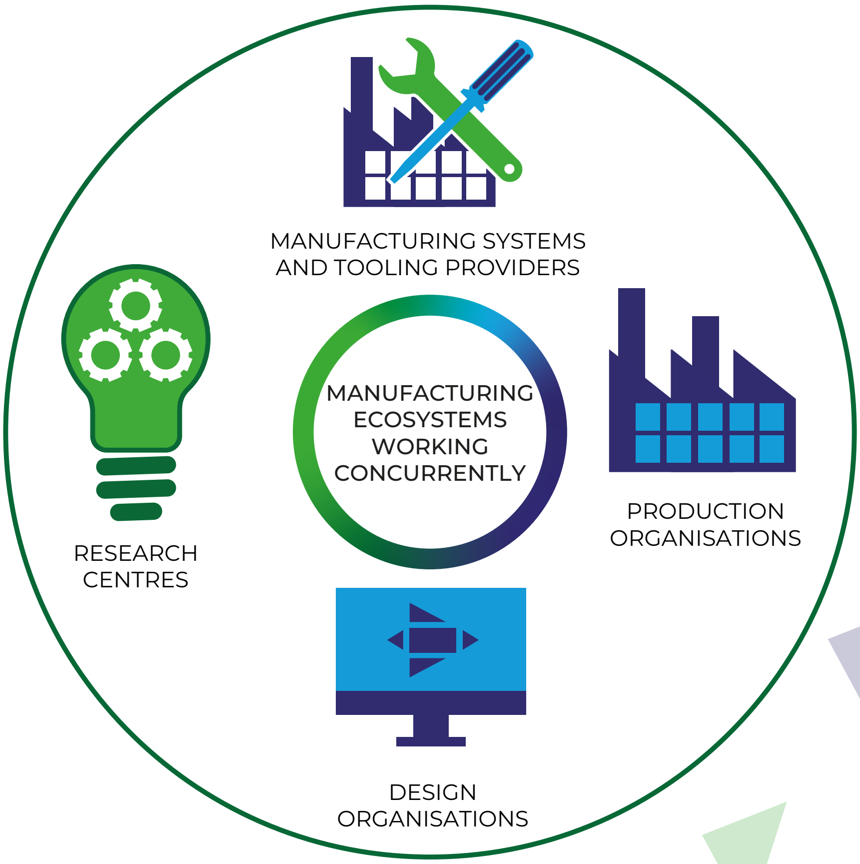


Figure 15 – Actors in a manufacturing ecosystem

Enabling an ecosystem of the manufacturing partners shown in **Figure 15** above, plus suppliers of raw materials and primary processing, can deliver innovation and collaboration between organisations who share a common goal [41]. Grouping these in a regional cluster can increase the productivity of these companies [42]. Therefore, ensuring the UK has a thriving manufacturing ecosystem can enable UK productivity and competitiveness.

UK design organisations and the UK research network is already actively considering how a move to hydrogen may impact them, so this section particularly focusses on production organisations and manufacturing systems and tooling providers.

Production organisations must develop manufacturing capability critical to realising hydrogen aircraft concurrently with the aircraft systems, but the UK is lagging other nations in its adoption of advanced manufacturing technology and so will need to accelerate to take advantage of the opportunity. Manufacturing systems and tooling providers are a critical anchor for manufacturers of end use parts, but the UK has a low market share in the manufacturing systems (see **Section 10.2**) compared to other nations.

10.1 PRODUCTION ORGANISATIONS

The UK aerospace sector has circa 3,000 companies **[43]**. 98% of enterprises registered as an aerospace business in the UK are small and medium sized enterprises (SMEs) **[44]**. The top of the aerospace supply chain is highly consolidated with few primes and tier ones.

A 2016 survey of the UK aerospace sector undertaken on behalf of the UK Department for Business found that 79% of respondents viewed developing manufacturing capability in new aircraft technologies as major opportunities for growth. The same respondents said that the UK supply chain is not currently well positioned and major investment is needed into upgrading manufacturing capability. The UK is lagging other nations in the adoption of advanced manufacturing technologies such as digital and automation, ranking 22nd in the world for adoption of robots in 2017 **[45]**.

Production organisations need support to accelerate the adoption of manufacturing technologies including raising their awareness of the technology; upskilling; access to specialist expertise; access to facilities where companies can 'learn by doing' ahead of making investment decisions; support to build the business case; and support to manage change associated with the introduction of the new technology. The Aerospace Growth Partnership (AGP), through the various working groups, are working with ADS, regional aerospace alliances, industry and HVM Catapult to improve understanding and awareness of technologies and supporting skills required in the sector with prioritised topics focused at developing SMEs. There are a number of existing government support mechanisms. The aerospace sector can access grant funding through the ATI Strategic Programme or its National Aerospace Technology Exploitation Programme (NATEP) for SMEs. The northeast pilot of the Industrial Strategy Challenge Fund's (ISCF) Made Smarter Adoption Programme aims to accelerate the adoption of digital and automation technologies by providing capital investment and support to build the business case. The HVM Catapult has programmes of support targeted at SMEs. Programmes like Aerospace UP and DRAMA have demonstrated the benefit of using a cluster body to help connect supply chain companies to access funded support from academia and research centres.

Investment in production capability can anchor jobs over the 40+ years of an aircraft lifecycle. **Figure 16** indicates the relative level of investment needed at each stage of an aircraft development cycle. Costs increase significantly on the transition to pre-production. Companies must demonstrate rate capability to win production contracts. Support is needed to prove out the rate capability of new manufacturing solutions, to build pilot lines **[46]** (lines that incorporate advanced manufacturing technologies and so enable its development up to TRL6), and to support investment in new production lines.

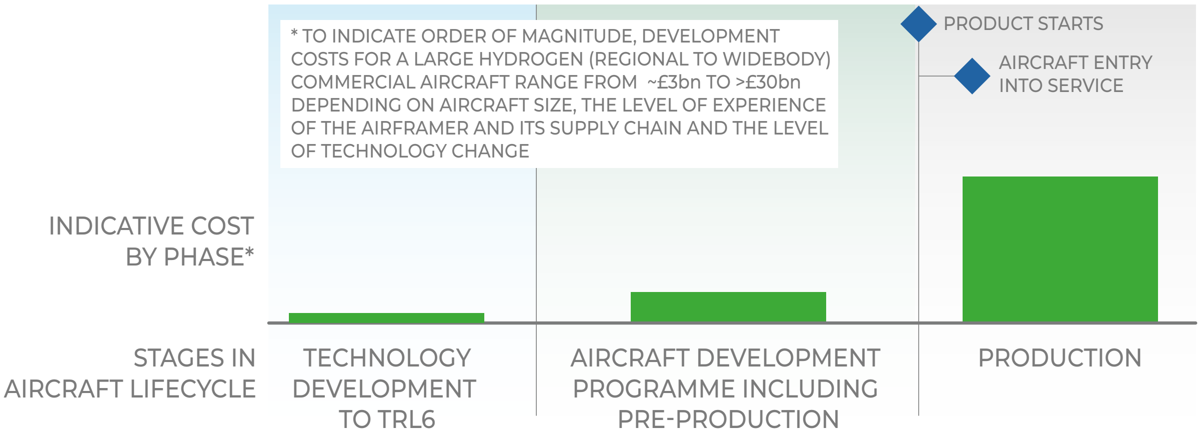


Figure 16 – Indicative cost (investment needed) at different stages in the aircraft development cycle

Companies outside the aerospace sector in space, automotive, energy, defence and other sectors have technologies with potential for application to hydrogen aircraft. The aerospace market is attractive to these companies but the barrier to entry is high. High levels of quality, reliability, and safety are required to supply to aerospace and supplier accreditation is a prerequisite for many contracts. To achieve accreditation takes resource and aerospace specific knowledge. Support for overcoming similar barriers exists in other sectors with programmes such as Fit 4 Nuclear and Fit 4 Offshore Renewables.

10.2 MANUFACTURING SYSTEMS AND TOOLING PROVIDERS

Local manufacturing systems and tooling providers who work to develop and commercialise new equipment are a key anchor for end use manufacturing. Their presence accelerates the diffusion of the technology into local manufacturers and skilled employees swap over time between system providers and production organisations.

The HVM Catapult has estimated that UK companies have <1% share of the >£100bn annual global market for manufacturing machinery and systems **[47]**, compared to 15% for Germany. The aerospace segment is ~10% (£10bn per annum). The UK is ranked 7th within Europe for production of manufacturing systems - level with Turkey and the Czech Republic.

The move to hydrogen and electric technologies is an opportunity for the UK to increase the share in this market by developing new manufacturing systems to address emerging challenges. This report has highlighted the need for special purpose machinery for unique and oversized components (especially fuel tanks), flexible tooling to support prototyping and production of oversize components and the need for equipment in additive manufacturing, metrology and robotics. There is particularly high demand for manufacturing systems integrators, who connect manufacturing, automation and inspection equipment.

The UK is well positioned to develop new manufacturing systems. The UK has a deep understanding of aerospace end use requirements and a strong engineering skill base. The UK also has a strong digital tech sector – a skillset that will be essential in developing new manufacturing systems that will have to have high levels of digital control and connectivity. UK aerospace tooling capability was recently captured in a directory by the ATI **[48]**.

The development of hardware and systems is resource intensive compared to software development. The unique IP means, however, they are harder to copy and the success rate for 'deeper' technology start-ups is higher than for software, >80% versus <25% for Silicon Valley software-based start-ups **[49]**. Manufacturing systems providers often receive significant support from academia or research and technology organisations.

Manufacturing systems and tooling providers need support in the form of expertise and facilities for prototyping; access to end user requirements and components on which they can demonstrate their technology; introduction to potential customers; commercial mentoring to help create a business plan and to win private investment; and support to scale-up their business. It is critical that manufacturing systems developers understand the end user requirements and level of evidence required at the relevant technology maturity to enable them to understand the level of effort required to commercialise.

Support for development of manufacturing systems has been limited in the past. In more recent years, the Advanced Machinery and Productivity Institute **[50]** in Rochdale has secured £22.6m from UK government to address this mission for multiple end use sectors, aiming to generate £2bn UK export capacity over 10 years and establish 30,000 high value jobs. The ATI Accelerator has supported software start-ups in manufacturing and other areas in technology demonstration, introduction to potential customers and commercial mentoring. Through Made Smarter, the HVM Catapult piloted a test bed programme to provide access to of systems and tooling providers to facilities and expertise for proof of concepts. For the UK to compete in this area with leading manufacturing nations internationally, more support of this type is needed.

11. RECOMMENDATIONS

This report has highlighted manufacturing research and development areas for the six revolutionary hydrogen aerospace technology bricks and then associated actions needed to secure a strong UK strong supply chain capability. High level recommendations for the UK manufacturing community are provided here.

Recommendation 1. Accelerate research and development into rate enabling manufacturing technologies critical to realising hydrogen-powered flight.

This report has highlighted the manufacturing challenges and opportunities which exist on the route to delivering hydrogen aviation. Areas of manufacturing technology development identified in this paper are required to support the FlyZero technology bricks are summarised in **Figure 17**. By 2050, each major OEM is anticipated to supply narrowbody aircraft at a rate of over 100 per month. Ensuring the manufacturing technology developments, highlighted below, are rate capable is essential to securing an earlier fleet to market, which maximises decarbonisation.

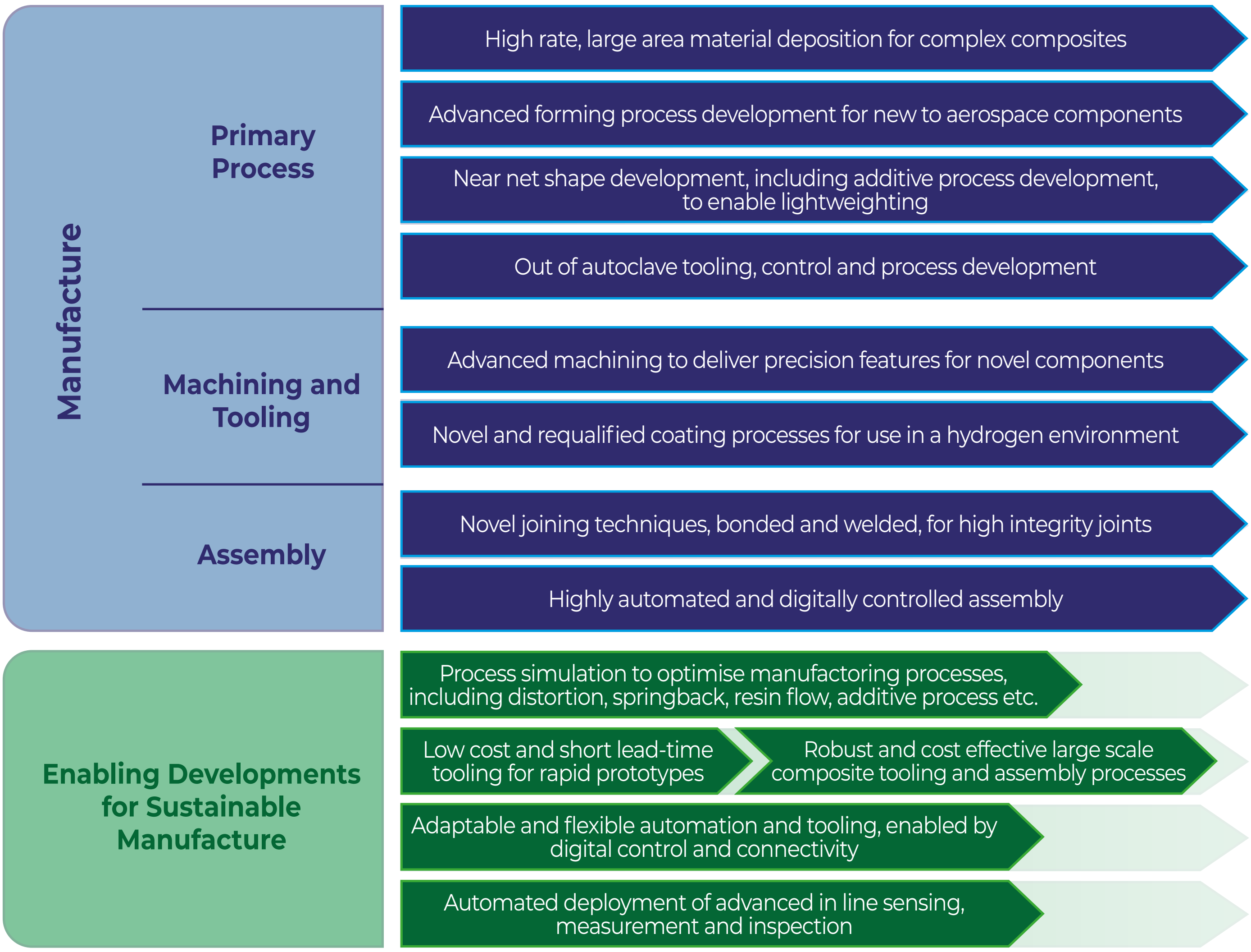


Figure 17 – Areas of manufacturing technology development identified in this paper are required to support the FlyZero technology bricks

Many of these manufacturing developments are also highlighted in the ATI Technology Strategy, ATI roadmaps and Insight papers [1] [2] [3] [4] [5] and the forthcoming HVMC Aerospace Manufacturing and Materials roadmaps. There is also commonality in manufacturing challenges across sectors. Electric motors and systems have strong applications in automotive and funding for industrialisation is available through UKRI Driving the Electric Revolution (DER) challenge. Fuel cells also have strong applications in automotive. Cryogenic storage tanks and fuels systems have strong synergies with the space sector. Fuel cells, tanks and fuel systems could be the subject of future cross-sector funding initiatives.

Manufacturing development and demonstration beyond technology readiness level 6 (TRL6), including pilot line demonstrations, will also be critical to securing OEM confidence to grow manufacturing in the UK.

Suggested actions:

- Accelerate research and development into rate enabling manufacturing technologies, including those identified in this report. This can be delivered through collaboration between industry, research centres and academia with support from by the High Value Manufacturing Catapult, EPSRC, Innovate UK and the Aerospace Technology Institute.
- Launch cross-sector funding targeted at product and manufacturing developments for areas of overlap that are not yet addressed by initiatives in the UK. These areas are fuel cells (automotive and energy sectors) and tanks and fuel systems (space sector).
- Provide funding and support to help build pilot lines (lines that incorporate advanced manufacturing technologies and so enable its development). This development can be supported by the UK Catapult network, research organisations and academia as well as industry.

Recommendation 2. Build manufacturing supply chain capability relevant to hydrogen in the UK tiered aerospace supply chain to anchor production in the UK.

The UK has a strong tiered aerospace supply chain. The technological disruption of hydrogen is an opportunity to improve market share but also potentially a threat as other nations target aerospace as a route to high value jobs. The UK needs aerospace accredited supply chain companies with high levels of productivity and with facilities and competency to deliver advanced manufacturing processes.

The UK aerospace supply chain could be strengthened by funding for industrialisation to accelerate the transition to a hydrogen aerospace industry. An equivalent fund exists for the UK automotive sector already; the Advanced Propulsion Centre works to accelerate the transition to an electrified UK automotive industry and has an Automotive Transformation Fund to support post TRL 6 investments, to support the industrialisation and scale-up of the supply chain by funding large-scale capital-focussed projects. There are also schemes with demonstrated success internationally. For example, Germany's Operational Programme for Economic Regional Development in Brandenburg supports supply chain innovation and strengthening. Delivery of this type of funding in the UK exists in part through devolved administrations and LEPs but strengthening this with an "Aerospace Transformation Fund" or similar will support the world-leading research and development work carried out in the UK to translate into manufacturing jobs, securing 40 plus years of aerospace production.

Suggested actions:

- Accelerate investment and adoption of advanced manufacturing equipment by UK aerospace tiered supply chain. Cluster bodies, research organisations, knowledge transfer organisations and funding bodies need to collaborate to deliver programmes that cover awareness campaigns; upskilling; access to specialist expertise; access to facilities where companies can 'learn by doing' ahead of making investment decisions; support to build the business case; and support to manage change associated with the introduction of the new technology.
- Fund economic development activity in the supply chain, enabling companies to make the capital investment required to support production of hydrogen aircraft components and systems, and anchor high value jobs, and continually innovate to retain UK competitiveness.
- Help new companies enter the aerospace sector by providing support to attain aerospace accreditations through programmes used in other sectors such as e.g., Fit 4 Nuclear.

Recommendation 3. Support the foundation and scale-up of UK enterprises that develop manufacturing systems and tooling, creating an indigenous UK base for manufacturing equipment.

Manufacturing systems and tooling providers are a critical anchor for manufacturers of end use components. This is a particular area of weakness in UK manufacturing; the UK has only a <1% share in the global manufacturing systems market and is 7th in Europe. However, it is one that the UK can address through its deep understanding of aerospace, strong engineering base and strength in digital technologies.

Suggested actions:

- Identify a pipeline of opportunities for manufacturing systems and tooling development. The ATI could support this by connecting end user requirements and solution providers. This could be done in collaboration with other sectors with common requirements, such as defence and power generation.
- Deliver programmes, like those launched by The Advanced Manufacturing and Productivity Institute, designed to support the foundation and scale-up of UK manufacturing systems and tooling providers. Cluster bodies, research organisations, knowledge transfer organisations and funding bodies need to collaborate to deliver programmes that provide access to expertise and facilities for prototyping; access to components on which they can demonstrate their technology; introduction to potential customers; commercial mentoring to help create a business plan and to win private investment; and support to scale-up their business.

Recommendation 4. Reduce emissions embodied during manufacturing at the same time as moving to aircraft with zero-carbon tailpipe emissions.

All sources of energy and emissions for aerospace need to be reviewed and optimised to address the aerospace sectors carbon footprint as part of a national energy strategy. As other sectors speed their transition to zero carbon and then aerospace develops zero emission aircraft the embodied energy and emissions for manufacturing will potentially become a much greater contributor for the sector. This will need to consider energy and emissions from raw materials, processing, operations, maintenance, repair and end of life need to be addressed. Supply chains, factories and processes must become carbon neutral and resource efficient, including a sustainable supply of feedstock material.

Suggested actions:

- Design carbon neutral end-to-end processes and supply chains in parallel to future aircraft, thereby ensuring emissions from the whole value chain are addressed (scope 3 emissions) in parallel with emissions from industry's own factories (scope 1 and 2 emissions).
- Develop standards for accounting for emissions through supply chains and digital tools to help monitor and reduce them. Delivery will require collaboration between industry, research organisations and academia.

12. REFERENCES

1. ATI, "ATI Insight - Issue 17 - Near Net Shape Manufacturing: Applications in Aerospace", 2021.

2. ATI, "ATI Insight - Issue 9 - Composite Material Applications in Aerospace", 2018.

3. ATI, "ATI Insight - Issue 8 - Additive Manufacturing: Applications in Aerospace", 2018.

4. ATI, "ATI Insight - Issue 5 - Product Verification", 2017.

5. ATI, "Aerospace aluminium shape casting roadmap", 2021.

6. FlyZero, "Technology Roadmaps (FZO-IST-MAP-0012)", 2022.

7. FlyZero, "Lifecycle Impact (FZO-STY-POS-0034)", 2022.

8. FlyZero, "Advanced Materials (FZO-IST-POS-0036)", 2022.

9. FlyZero, "Culture and Digital Tools (FZO-IST-POS-0038)", 2022.

10. House of Commons Library, "Manufacturing: international comparisons", 2018.

11. US Department of Commerce International Trade Administration, "United Kingdom - Country Commercial Guide - Aerospace and Defense", 2021.

12. ATI, "ATI Annual Review 2018-19", 2019. [Online]. Available: **https://www.ati.org.uk/wp-content/uploads/2021/08/ati-annual-review-2018-19.pdf**

13. Catapult Network, "Embodied emissions & manufacturing - headline case for action - aerospace", 2021.

14. Airbus, "Airbus increases its innovation footprint in Spain to develop new hydrogen technologies", [Online]. Available: **https://www.airbus.com/en/newsroom/press-releases/2021-12-airbus-increases-its-innovation-footprint-in-spain-to-develop-new**

15. Boeing, "Boeing Breakthrough in All-Composite Cryogenic Propellant Tank Advances Technology Readiness", [Online]. Available: **https://boeing.mediaroom.com/news-releases-statements?item=130996**

16. FlyZero, "Cryogenic Hydrogen Fuel System and Storage - Roadmap Report (FZO-PPN-COM-0027)", 2022.

17. AMRC, "Manufacturing Challenges for Liquid Hydrogen Metallic Storage Tanks for FlyZero (FZ_SoW_0055)", 2022.

18. NCC, "NCC - FlyZero Cryogenic Tank Manufacture Review (FZ_SoW_0055)", 2022.

19. NASA, "First Liquid Hydrogen Tank Barrel Segment for the SLS Core Stage Completed at Michoud", [Online]. Available: **https://www.nasa.gov/exploration/systems/sls/sls-barrel-at-michoud.html**

20. Arienespace, Ariane 5 User's Manual Issue 5 Revision 3, 2020.

21. NASA, "External Tank", [Online]. Available: **https://science.ksc.nasa.gov/shuttle/technology/sts-newsref/et.html**

22. Airbus, "Airbus establishes Zero-Emission Development Centres in Germany and France", [Online]. Available: **https://www.airbus.com/en/newsroom/press-releases/2021-06-airbus-establishes-zero-emission-development-centres-in-germany-and**

23. Fusion for Energy, "Welding ITER's vacuum vessel components help signing contracts with ArianeGroup and Solar Orbiter", [Online]. Available: **https://techtransfer.fusionforenergy.europa.eu/index.php/welding-iters-vacuum-vessel-components-help-signing-contracts-with-arianegroup-and-solar-orbiter/** [Accessed 2022].

24. Lockheed Martin, "Giant satellite fuel tank sets new record for 3-D printed space parts", [Online]. Available: **https://news.lockheedmartin.com/2018-07-11-Giant-Satellite-Fuel-Tank-Sets-New-Record-for-3-D-Printed-Space-Parts#assets_all**

25. Relativity Space, "How Relativity is Revolutionizing 3D Printed Tank Design", [Online]. Available: **https://www.relativityspace.com/headlines-news/2020/12/21/how-relativity-is-revolutionizing-3d-printed-tank-design**

26. "Cranfield unveils highest profile WAAM parts to date", [Online]. Available: **https://3dprintingindustry.com/news/cranfield-unveils-highest-profile-waam-parts-to-date-for-bae-systems-and-thales-alenia-space-150215/**

27. Airbus Defence and Space, "Additive manufacturing of fuel tanks", in IQPC Additive Manufacturing for Aerospace & Space , 2020.

28. Virgin Orbit, "Composite Tanks 002", [Online]. Available: **https://virginorbit.com/p1000089/**

29. Composites World, "Rocket Lab all-composite Electron launch vehicle", [Online]. Available: ***https://www.compositesworld.com/articles/rocket-lab-all-composite-electron-launch-vehicle***

30. Lockheed Martin, "Lockheed Martin Looks To Space With Australian-Developed Composite Tanks", [Online]. Available: ***https://lockheedmartinau.mediaroom.com/Lockheed-Martin-looks-to-space-with-Australian-developed-composite-tanks***

31. MT Aerospace, "MT Aerospace AG sets CFRP milestone: Hydrogen tank for rocket propulsion proves itself in tests", [Online]. Available: ***https://www.mt-aerospace.de/news-details-en/mt-aerospace-ag-sets-cfrp-milestone-hydrogen-tank-for-rocket-propulsion-proves-itself-in-tests.html***

32. Boeing, "Performing under pressure", 2022. [Online]. Available: ***https://www.boeing.com/features/2022/02/performing-under-pressure.page***

33. NCC, "NCC's Core Research Programme 2021/22 aiming to solve industry's biggest advanced materials challenges", 2021. [Online]. Available: ***https://www.nccuk.com/news/ncc-s-core-research-programme-2021-22-aiming-to-solve-industry-s-biggest-advanced-materials-challenges/***

34. GKN Aerospace, "Leading the Way in Composite Technology", [Online]. Available: ***https://www.gknaerospace.com/en/our-technology/2017/leading-the-way-in-composite-technology-2/***

35. R. S. G. Slayton, "Radical innovation in scaling up: Boeing's Dreamliner and the challenge of socio-technical transitions", Technovation, vol. 47, no. January, pp. 47-58, 2016.

36. Airbus, "www.airbus.com", [Online]. Available: ***https://www.airbus.com/en/newsroom/press-releases/2021-09-airbus-begins-assembly-of-first-future-eco-wing-prototype***

37. AIN online, "Additive Manufacturing Gains Altitude as Technology Matures", [Online]. Available: ***https://www.ainonline.com/aviation-news/air-transport/2021-07-13/additive-manufacturing-gains-altitude-technology-matures***

38. FlyZero, "Fuel Cells - Roadmap Report (FZO-PPN-COM-0033)", 2022.

39. FlyZero, "Electrical Propulsion Systems Roadmap Report (FZO-PPN-COM-0030)", 2022.

40. FlyZero, "Thermal Management - Roadmap Report (FZO-PPN-COM-0019)", 2022.

41. M. E. Porter, "Clusters and the new economics fof competition", Harvard Business Review, 1998.

42. P. L. S. D. B. Wellener, "Accelerating smart manufacturing", 2020. [Online]. Available: ***https://www2.deloitte.com/us/en/insights/industry/manufacturing/accelerating-smart-manufacturing.html***

43. Department for Business, Energy and Industrial Strategy, "Aerospace Sectort Deal", 2020. [Online]. Available: ***https://www.gov.uk/government/publications/aerospace-sector-deal/aerospace-sector-deal***

44. ADS, "Industry Facts & Figures 2021 - Extended", 2021. [Online]. Available: ***https://www.adsgroup.org.uk/industry-issues/facts-figures-2021/*** *[Accessed 2022].*

45. Midlands Manufacturing Resilience Commission, "Manufacturing Confidence", 2022.

46. Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (European Commission) , TNO, "Pilot Production in Key Enabling Technologies: Crossing the Valley of Death and Boosting the Industrial Deployment of Key Enabling Technologies in Europe", 2015.

47. High Value Manufacturing Catapult, "Aerospace Manufacturing Accelerated", 2020.

48. ATI, "ATI Tooling Directory", 2021.

49. EARTO, "How to exploit the untapped potential of RTOs' deep-tech start-ups in Europe", 2017.

50. "Advanced Manufacturing and Productivity Institute (AMPI) receives funding boost for its innovation initiative", 2021. [Online]. Available: ***https://www.ampi.org.uk/news***

51. FlyZero, "Midsize Aircraft Concept Report (FZO-AIN-REP-0010)", 2022

52. ATI, "ATI NNS Insight Paper", 2021

53. GKN Aerospace, "GKN Aerospace and partners launch ASCEND to accelerate high volume composite technologies", [Online]. Available: ***https://www.gknaerospace.com/en/newsroom/news-releases/2021/gkn-aerospace-and-partners-launch-ascend-to-accelerate-high-volume-composite-technologies/?linkId=100000036077164***

54. FlyZero, "Aerodynamic Structures Technical Report (FZO-AIR-REP-0014)", 2022.

55. Research Centre for Non-Destructive Evaluation (RCNDE), "UK Research Centre in Nondestructive Evaluation", 2022. [Online] Available: ***https://rcnde.ac.uk/***

56. FlyZero, "Hydrogen Gas Turbines and Thrust Generation - Roadmap Report (FZO-PPN-COM-0023)", 2022

12.1 LIST OF ABBREVIATIONS

AC	*Alternating Current*
ADS	*Aerospace Defence Security and Space*
AFP	*Automated Fibre Placement*
AFRC	*Advanced Forming Research Centre*
AGP	*Aerospace Growth Partnership*
Al	*Aluminium*
AM	*Additive Manufacturing*
AMPI	*Advanced Manufacturing and Productivity Institute*
AMRC	*Advanced Manufacturing Research Centre, The University of Sheffield*
APC	*Advanced Propulsion Centre*
ATI	*Aerospace Technologies Institute*
ATL	*Automated Tape Laying*
CFRP	*Carbon Fibre Reinforced Polymer*
CMD	*Conventional Micro Drilling*
CO_2	*Carbon Dioxide*
COC	*Combustion Outer Case*
Cu	*Copper*
DER	*Driving the Electric Revolution*
DRAMA	*Digital Reconfigurable Additive Manufacturing facilities for Aerospace*
EB	*Electron Beam*
EBAM	*Electron Beam Additive Manufacturing*
EBD	*Electron Beam Drilling*
ECD	*Electro Chemical Drilling*
EPSRC	*Engineering and Physical Sciences Research Council*
ESA	*European Space Agency*
GTAW	*Gas Tungsten Arc Welding*
H_2	*Hydrogen*
HP	*High Pressure*
HSEDM	*High Speed Electro Discharge Machining*
HVM	*High Value Manufacturing*
HVMC	*High Value Manufacturing Catapult*
IP	*Intellectual Property*
ISC	*Integrally Stiffened Cylinder*
K	*Kelvin*
LEP	*Local Enterprise Partnership*
LH_2	*Liquid Hydrogen*
Li	*Lithium*
LP	*Low Pressure*
MEA	*Membrane Electrode Assembly*
MTC	*Manufacturing Technologies Centre*
NAMRC	*Nuclear Advanced Manufacturing Research Centre*
NASA	*National Aeronautics and Space Administration*
NATEP	*National Aerospace Technology Exploitation Programme*
NCC	*National Composites Centre*
NDT	*Non-Destructive Testing*
OEM	*Original Equipment Manufacturer*
OOA	*Out of Autoclave*
PEM	*Proton Exchange Membrane*
RT	*Radiographic Inspection*
RTM	*Resin Transfer Moulding*
RTO	*Research and Technology Organisation*
SAF	*Sustainable Aviation Fuel*
SLS	*Space Launch System*
TBC	*Thermal Barrier Coating*
TBD	*To Be Determined*
TRL	*Technology Readiness Level*
TWI	*The Welding Institute*
UK	*United Kingdom*
UKRI	*UK Research and Innovation*
US	*United States*
UT	*Ultrasonic*
VPPA	*Variable Polarity Plasma Arc*
VSM	*Value Stream Map*
WAAM	*Wire Arc Additive Manufacturing*

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